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Review Article

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A new dawn: The impact of digital technologies in oral and maxillofacial pathology

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Abstract
The rapid evolution of digital technology in all walks of the life is an important indicator that a different future is waiting for us. Technology has become a mainstay of daily life and is being increasingly used in education, research as well clinical activities with new innovations aiding healthcare and increase our knowledge, productivity and efficiency. There is no doubt that the healthcare sector, including dental sciences will be influenced by these rapid changes with many standard procedures likely to change. This is supported by the fact that some medical and dental specialties such as radiology have already made the digital leap. Digital pathology is an emerging area which has started to transform education and workflow in pathology. In this review, we will discuss how these novel and 'disruptive' technologies are likely to change education, training and diagnostic work flow in oral and maxillofacial pathology.

Keywords: artificial intelligence, digital pathology, education, image analysis, machine learning, oral and maxillofacial pathology

1. Introduction

Digital pathology (DP) has started to transform training, education and the conventional ways of working in pathology. There has been an explosion of research and development in this area over the last few years and it appears quite likely that DP will become a part and parcel of the oral and maxillofacial pathology workflow beginning from the biopsy accession to signing the report in near future. In addition to digital reporting, this workflow includes laboratory information management systems (LIMS), digital dictation and voice recognition tools as well as digital image analysis (Griffin and Treanor, 2017; Williams et al., 2018). A significant body of evidence has shown that transition to DP has numerous advantages over conventional light microscopy including improvements in safety, quality and efficiency in pathology laboratories. This is prudent at a time when there are significant workforce shortages in pathology laboratories across the world and expert consultations are becoming the norm.

The use of digital technology in pathology began in the 1960s with the first use of telepathology via real-time "television microscopy" (Weinstein, 1986). The term telepathology was first used in the 1980s allowing remote diagnosis using digitized/analogue video or a still image (Weinstein et al., 2012). This technology has been used successfully for primary diagnosis, intraoperative consultations (frozen section), rapid cytology, second-opinion practice consultation, archival review, quality assurance, multidisciplinary meetings (MDTM) and patient consultations (Pantanowitz et al., 2014). However, it has numerous limitations including suboptimal resolution, lack of standardization of file formats, loss of image quality due to compression as well as associated costs which continue to remain high. The advent of DP has rendered 'conventional' telepathology almost obsolete. High resolution slide scanners have now been around for almost 20 years with continuous technological improvements allowing capture of images from glass slides at a high magnification resulting in a whole slide image (WSI). Numerous scanners have now been approved and validated for diagnostic work by regulatory bodies and several studies have shown DP to be non-inferior to conventional light microscopy (Snead et al., 2016). Advent of low-cost scanners as well as high throughput scanners along with an increase in computational power has further accelerated digital deployment in the field of pathology. These advances in DP have the potential to revolutionize oral and maxillofacial pathology (OMFP) practice by transforming education, clinical training, case sharing and diagnostic workflow.

2. Workflow

DP has the potential to help improve clinical workflows in many ways. Digital techniques can be used in a number of processes from specimen reception/booking to archiving the pathology report. The process starts with barcode application to the specimen forms and containers reducing misidentification errors (Zarbo and D'Angelo, 2007) and

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providing electronic identification of the biopsy specimen. The macroscopic/gross features of the specimen can also be recorded digitally by the pathologist and uploaded in a secure manner allowing immediate remote transcription. This is further complemented by use of digital photographs. Even the standard procedures of tissue embedding and glass slide preparation have changed with the advent of automated microtomes and autostainers. Once the glass slides have been obtained, they can be scanned in batches, linked with the LIMS and immediately assigned to pathologists for reporting. Acquisition of a high-resolution digital image removes the need for physical transport of slides, ‘immortalises the staining’, reduces the need for storing glass slides and prevents the risk of glass slides getting broken or lost. The workflow becomes much more efficient and lean by reducing waste and streamlining processes providing a good audit trail and reducing errors. After digitization, the WSI can be assigned to pathologists who can report the cases from their workstations or remotely (Randell et al., 2014). Even at that stage, digital dictation as well as voice recognition tools have been widely adapted to aid reporting. DP access and implementation also means that interesting cases can be easily saved for teaching sets and MDTMs. At the end of the workflow, the reports can also be signed out electronically and stored digitally reducing the need for printing and posting and avoiding loss of confidential patient information. Hence a fully digital system from start to finish can offer safety, quality, flexibility and efficiency in any pathology setup.

2.1. Digital slides

The digitization process involves a robotic microscope that can obtain WSI by scanning sections of the slide at different magnifications and focus distances to facilitate a sufficient depth of field comparable to a microscope (Zarella et al., 2019). Once an image has been captured, it is digitally stitched to produce a composite virtual image mimicking the whole slide, which can be viewed on a digital screen by a pathologist (Indu et al., 2016) (Fig.1). The WSI can have a magnification of up to x40 and multiple slides can be viewed at the same time by multiple people. They can integrate with the LIMS and also make simplify slide sharing and collaboration. The scanning times are continually improving and the size of the produced images are also reducing due to improvement in image compression methods. Furthermore, WSI acquisition also facilitates more quantifiable and accurate information from tissue sections. A number of free WSI viewing software are available on the internet, almost all of which have features allowing measurement of lesions, distance from margin, annotations and export as still images or snapshots. Having said that, there is an initial cost associated with a scanner setup, service contracts for software upgrades as well as certain computing and networking requirements for smooth running of the system however the improvement in efficiency and turnaround times still make a compelling case for DP implementation.

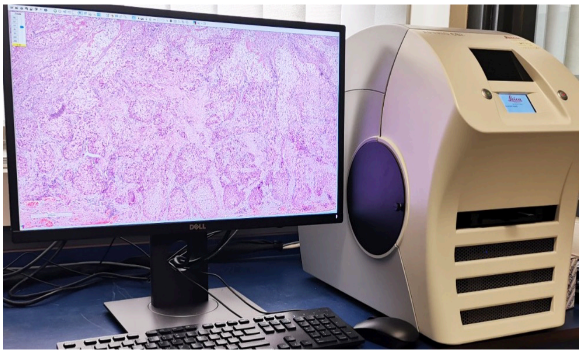

Fig. 1. A representative image showing a digital slide scanner and associated workstation

As previously mentioned, WSI produced using digital scanners have now been evaluated in a number of studies, all of which show that DP is equivalent to glass slides for diagnostic purposes (Mukhopadhyay et al., 2018). A recent systematic review has also shown a considerable amount of concordance between diagnosis made by pathologists on glass and digital slides (Williams et al., 2017; Araújo et al., 2019). Despite its widespread use and validation in general histopathology, use in OMFP remains limited with only one small validation study to date (Araújo et al., 2018). How far DP has come is shown by the fact that most of the regulatory pathology bodies now have recommendations and guidelines for its use and application including the Royal College of Pathology UK (Cross et al., 2018) and the College of American Pathologists (Hipp et al., 2017).

The disadvantages of digital pathology include expensive equipment, the need for secure platforms allowing exchange of images/documents and laboratory infrastructure and information systems that are not yet ready to support digitalization for each pathology laboratories.

2.2. Image analysis

The application of digital image analysis in pathology is rapidly evolving. Propriety image analysis software systems have been available for a while for evaluation of immunohistochemical (IHC) markers and have been shown to improve the consistency and accuracy of scoring but have largely been used in research to date (Helin et al., 2016). WSI are large images containing a wealth of information ideal for application of image analysis tools which can reduce the subjectivity to provide more meaningful and accurate dimensions and quantitative scores to aid patient management. This can include variables such as tumour size, depth of invasion, distance from margins or scoring of personalised/ therapeutic IHC markers such as HER2 and PD-L1. Numerous open-source software (such as QuPath, Cytomine and Orbit) have also emerged recently as really valuable tools for researchers and clinicians allowing quantification of a wide range of features in pathology images and WSI (Marée et al., 2016; Bankhead et al., 2017; Stritt et al., 2020) (Fig. 2).

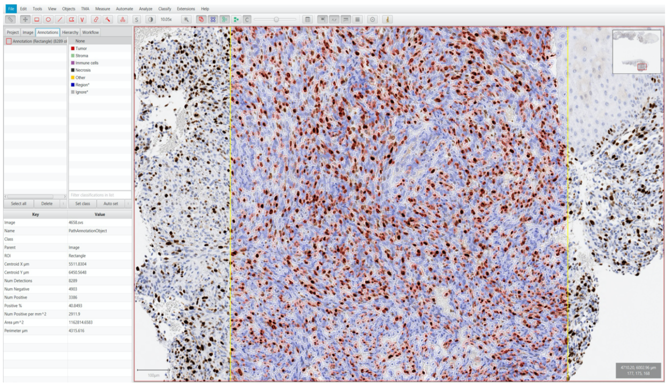

Fig. 2. Ki67 scoring in an OMFP specimen using QuPath. Red cell=positive, blue cells= negative. Percentage positivity = 40%

2.3. Artificial intelligence and deep learning

Development in whole slide scanner technology and computational power and reduction in scanner costs have led to a large number of glass slides being scanned and archived digitally. These multi-gigapixel digital images are ideal for application of artificial intelligence (AI) not only to aid the pathologist in terms of interpretation and workload reduction but also to maximize the amount of information gleaned and facilitate discovery of novel 'digital biomarkers' and morphologic patterns to predict the prognosis. AI and Deep Learning (DL) have been widely used to predict disease behavior in breast (Ehteshami et al., 2018), lung (Coudray et al., 2018), thyroid (Guan et al., 2019), colorectal (Weis et al., 2018) and prostate (Arvaniti et al., 2018) cancers. In numerous studies, AI has shown similar (and in some case better) performance compared to experienced pathologists removing subjectivity and variability by producing standardization and quantitative outputs (Kourou et al., 2015; Vu et al., 2019).

Application of AI and DL to OMFP has been somewhat limited compared to other specialties. Recently, an automated AI-based tumour infiltrating lymphocyte score used for oral squamous cell carcinoma (OSCC) patient stratification has been reported (Shaban et al., 2019). Attempts have also been made in a handful of studies to explore the potential of AI in oral potentially malignant disorders (including dysplasia) and oropharyngeal squamous cell carcinoma. Figure 3 demonstrates an example of automated identification of OSCC, stroma and immune cells in a WSI resulting in a quantitative measurement which can be compared with other clinicopathological variables. The advent of open-source image analysis tools and reported results of the studies to date show that AI has the potential to be a diagnostic/prognostic aid in OMFP but also highlight the need for further larger and multi-centric studies to harness the true potential of AI.

Despite the recent surge in AI related publications and research funding, translation of AI algorithms for clinical and prospective use in pathology remains a problem and is fraught with numerous obstacles and challenges such as validation, interpretability, pathologist engagement, acceptance of patients and clinicians and regulatory approval (Jiang et al., 2020).

However, considering the vast amount of research that has emerged in this area within the last few years, it is likely that these problems will be overcome eventually and AI based tools will become a part of pathology practice as a useful adjunct.

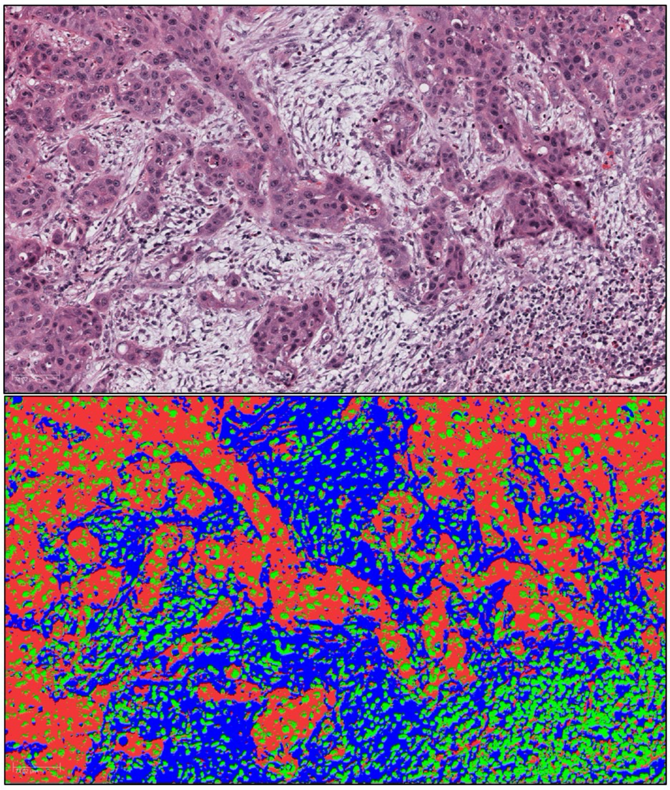

Fig. 3. H&E and overlay images showing automated detection of tumour/OSCC (Red), stroma (blue) and immune cells (green). Image generated using Orbit Image Analysis Software

2.4. Digital pathology in education

In an age with such advanced technology, changes in education systems are inevitable and essential. This has been highlighted prominently during the COVID-19 pandemic where digital learning and education tools have proven invaluable allowing people to work flexibly and remotely. This is supplemented by the fact that access to information in the current times is much easier than it has ever been. Even access to large digital achieves of pathology slides and data sets is becoming increasingly common (e.g. The Cancer Genome Atlas/TCGA) and proving to be a huge educational resource for students and trainees. Publicly available DP platforms have made sharing of WSI really easy and such initiatives have been strongly complemented by the widespread use of social media by pathologists. It is now possible to access WSI in digital media for many pathology publications shown by the fact that the WHO Classification series has established a digital platform to start providing WSI of the images used in the books. In addition, many pathology associations upload interesting cases with clinical information, radiological images and WSI to engage students, residents/trainees and pathologists. Among these associations, the British Association for Oral and Maxillofacial Pathology (BSOMP) has been a trail blazer for OMFP, publicly sharing a highly interesting OMFP case of the month on its website and social media accounts since April 2018 covering a range of odontogenic, mucosal, salivary and dental pathologies (https://www.bsomp.org.uk/cotm).

A number of web based digital pathology platforms have also emerged to provide educational tools to students, trainees and specialists (e.g. Pathpresenter, Kiko XP and Open Zoom etc.). Pathpresenter.net is one of the leading example of a digital pathology education system (https://pathpresenter.net/#/). It is a platform created by pathologists for sharing of digital educational content and research data. It also has a very useful OMFP section with examples of some classical pathologies. Such platforms can also be used for presentations, lectures and quizzes for students/trainees removing the need to use microscopes and facilitating learning. This is complemented by the fact that the current and next generation of students and pathologists are technology savvy preferring to use digital tools and 'smart devices' to view WSI (Fig.4). One criticism of using virtual microscopy is that it prevents students from learning microscope-handling skills. This might be true, but this is a separate goal from the analysis and interpretation of tissue sections where the advantages of virtual microscopy clearly outweigh the disadvantages.

3. Conclusion and the future

Development of digital technologies has already made a great impact on our lives. These days, especially when the Covid-19 pandemic has ground the world to a halt and with social distancing being the most effective way of protection, examples of this digital technology revolution can be seen everywhere with virtual meetings, on-line education, remote working from home, virtual patient consultations as well as use of DP and remote reporting indicating that a new dawn is already here. It is almost certain that even more education institutions and pathology laboratories will make the transition to DP in the near future as this digital future appears to offer an equally effective and alternative learning, teaching and working opportunity for all of us.

Fig. 4. The students using their phones to see WSI simultaneously with the screen in a pathology practical lesson

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Review Article

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Contemporary imaging modalities for temporomandibular joint: An update and review

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Abstract

There are different imaging methods used in the evaluation of bone structure, disc, ligaments and muscles that make up temporomandibular joint (TMJ). The aim of this review is given information about choice of suitable imaging methods for TMJ diseases from past to present. In the past, conventional radiographs have often been used for TMJ imaging, but nowadays magnetic resonance imaging is the gold standard for soft tissue imaging and disc position determination. Another new technology, ultrasonography can be used for disc displacement, effusion, diagnosis of intraarticular defects. Cone beam computed tomography is used for the evaluation of cortical and trabecular structure of bone components of TMJ, developmental anomalies and traumatic injuries affecting TMJ, pathological changes such as osteophyte, erosion, fractures, ankylosis, glenoid fossa-condyle relationship. Nowadays, in parallel with the developing technology, no singular imaging method is used for TMJ imaging and evaluation is performed with several imaging methods. Imaging methods should be selected by evaluating the factors such as radiation dose, contribution to diagnosis and treatment plan, easy applicability.

Keywords: cone beam computed tomography, imaging, magnetic resonance imaging, temporomandibular joint, ultrasonography

1. Introduction

Temporomandibular Joint (TMJ) is one of the most complex joints of the body that functions in chewing, swallowing and speaking functions (Okeson, 1996). In the diagnosis of TMJ disorders, clinical examination results such as anamnesis, clicking or crepitations, mandible movements should be evaluated together with radiological findings. Different imaging methods are used to examine the anatomical structures of TMJ. Some selection criteria are taken into account in determining the imaging method to be used. In view of the patient's history and clinical findings, considering the contribution of radiological examination to the diagnosis and treatment plan, preventing the patient from being exposed to unnecessary radiation dose is important in choosing the imaging method (Brooks et al., 1997).

The aim of this review is to examine the radiographs used in the imaging of bone structure, disc, ligaments and muscles of TMJ from past to present and give information about choice of suitable imaging methods for TMJ diseases.

2. Imaging for temporomandibular joint

2.1. Conventional radiography

When any pathological condition is considered after clinical evaluation of the cases, direct radiographic methods are firstly recommended by the American Academy of Pediatric Dentistry (1990) and American Academy of Oral and Maxillofacial Radiology (Brooks et al., 1997). It is easy to use and low radiation dose, visualization of many anatomical structures in a single plan, being inexpensive, detecting the developmental anomalies of TMJ and bone damage due to trauma or arthritis are the reasons of choice. In contrast, guidance for specific diagnosis of TMJ patients is limited and it is difficult to obtain direct information on the condition of the soft tissues of the joint. (Fallon et al., 2006). Transcranial, transpharyngeal and transorbital projections are used to obtain limited information about different parts of TMJ bone anatomy (Chilvarquer et al., 1988). In studies comparing transcranial radiography with MRI, transcranial radiography was recommended for initial radiological examination because of its low cost and easy applicability (Menezes et al., 2008).

2.2. Panoramic radiography

Panoramic radiographs allow condyle fractures, joint findings due to syndromes, tumors, cysts, osteomyelitis, highly degenerative changes in the condyle such as hyperplasia, hypoplasia and aplasia, as well as changes in bone structure such as osteophyte, erosion and sclerosis. Some panoramic radiography devices have special TMJ imaging programs. These radiographs, in which the image of both joints in open and closed position can be observed on a single film, are called

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mouth open-closed TMJ or lateral panoramic graph (Brooks et al., 1997; Tvrdy, 2007). Ease of use, being a non-invasive technique and ease of storage of radiographs are the advantages of this technique. However, since the joint is only visualized in a single plane, the mandibular fossa and articular eminence cannot be observed at the desired level. Cephalometric and panoramic radiographs are inadequate in determining the asymmetric relationship between the two TMJs in the sagittal plane, differences in volume and form of the condyles, variations between the incline and height of the articular eminence, and the position of condyles in the glenoid fossa (Chilvarquer et al., 1988; Katsavrias, 2003).

2.3. Arthrography

Arthrography is to obtain an indirect image of the disc by injecting radiopaque contrast agent into the lower or upper joint cavity or both joint cavities under fluoroscopic guidance. Then, images are taken with conventional radiographs or tomography. It gives information about the form, localization and function of the disc. Disc perforation, ligament of the disc, capsule tears and disc adhesions can also be visualized with this technique (Petrikowski, 2004). The greatest advantage of arthrography is that the clinician can monitor the movements of the joint during fluoroscopic examination (Katzberg, 1980). In the absence of MRI, arthrography can be used to diagnose anterior disc displacements (Tyrdy, 2007). However, it does not provide reliable information about the lateral and rotational displacement of the disc and the hard tissue cannot be evaluated well due to the radiopaque material (Isberg, 2001). The disadvantages of arthrography include being expensive, invasive, high dose radiation exposure to patients, technical training and experience, rarely observed allergy to contrast agent, risk of infection of the procedure, possibility of facial nerve paralysis due to excessive injection of local anesthetic to the condyle and condyle neck region and discomfort in the TMJ site for one or two days postoperatively (Som and Curtin, 1996).

2.4. Arthroscopy

The first arthroscopic intervention into the temporomandibular joint was made by Ohsnishi in 1975 (Sangeetha et al., 2012). This technique has been developed over time and has evolved into use for both diagnostic and therapeutic purposes (McCain, 1988). Today, arthrocentesis and arthroscopy techniques are included in the TME disorders treatment protocol as minimally invasive methods that complement each other (Nitzan et al., 1991).

Arthroscopy is indicated in cases such as disc displacement without reduction, degenerative joint diseases and synovitis (Pharaboz and Carpentier, 2009). It has been reported that it is more sensitive than MRI in the diagnosis of pathologies such as joint disc deformation or erosion, disc inflammation (Gonzalez-Garcia et al., 2008). On the other hand, it is contraindicated in cases such as ankylosis, operated joints, excessive disc resorption and tumor (Kayar, 2019).

In the literature, it has been reported that the opening of TMJ obtained by arthroscopy is greater in the comparison between arthroscopy and arthrocentesis (Israel, 1999). It has been stated that arthroscopy is a viable option before open surgery in TMJ dysfunctions that do not respond to conservative methods (Kayar, 2019).

2.5. Computed tomography (CT)

Due to the superposition of adjacent anatomical structures, imaging of joint structures that already have a complex anatomical structure can be misleading on two-dimensional radiographs (Laderia et al., 2005). Laderia et al. (2005) reported that two-dimensional panoramic radiographs were inadequate to show morphological and bone changes in TMJ and that they could not be used effectively in the diagnosis because they obscured the radiographic findings at a high rate. Computed tomography (CT) can be used to examine the three-dimensional structure of the bone components of the TMJ, TMJ anatomy, diffuse fractures and pathological changes in TMJ detailed. Since the images are taken in cross-section by CT, it is not possible for the parts outside the region of interest to be superposed. It is useful in determining TMJ pathologies such as ankylosis, neoplasms, stage of bone involvement in some arthritis, complex fractures, dislocation and ectopic bone growth (Brooks et al., 1997).

Clinical and cadaver studies have shown that CT is an appropriate method for evaluating bone morphology (Westesson et al., 1987; Tanimoto et al., 1990). However, CT is not a preferred method for examining the disc. In CT scans, the disc can be confused with the tendon of the lateral pterygoid muscle. Furthermore, the disadvantage of the technique is that the device is expensive and the scanning process is long (Christiansen et al., 1987).

2.6. Cone Beam Computed Tomography (CBCT)

Due to developing technology, CBCT which works with conical X-rays has been developed for imaging of bone structures in maxillofacial region (Scarfe et al., 2006). With this technique, which provides three-dimensional imaging with reconstruction, high diagnostic quality images can be obtained with a short exposure time of 10-70 seconds and a lower radiation dose than helical computed tomography (Honda et al., 2006; Scarfe et al., 2006).

CBCT; it is used for the evaluation of condyle bone structure changes in TMJ, developmental anomalies and traumatic injuries affecting TMJ, pathological changes such as osteophyte, erosion, fractures, ankylosis, and determination of condyle position in open-closed mouth position (Krishnamoorthy et al., 2013). In addition, cortical and trabecular structure of bone components of TMJ, joint space, glenoid fossa-condyle relationship, bone changes in patients with soft tissue pathology can be used for examination (Barghan et al., 2012; Yadav et al., 2015). Studies showing that CBCT provides accurate and realistic results in linear measurements of TMJ are also available in the literature

(Hilgers et al., 2005; Zhang et al., 2012). The selection of the appropriate field of view in TMJ evaluation with CBCT is important for obtaining diagnostic images and reducing the patient dose. The right and left TMJ imaging procedure has been shown to produce a lower effective dose compared to CBCT images obtained using a large imaging area (Lukat et al., 2013).

It has been shown in the literature that the quality of the images obtained may vary due to different scanning protocols when evaluating TMJ with CBCT. Yadav et al. (2015) stated that the images obtained with 360-degree rotation were the gold standard in the evaluation of TMJ but caused the patients to take approximately twice as much as the 180-degree rotation dose. In addition, they reported that both the 180- and 360-degree gravitation protocol were approximately effective in detecting large and small erosive bone defects. Patel et al. (2014) stated that the smaller voxel dimensions are more effective in detecting condyle defects. Libirizzi et al. (2011) reported that small FOV areas should be preferred in cases where TMJ erosions are the primary objective of the assessment. However, if orthodontic treatment or orthognatic surgery is planned and there is no clinically identified TMJ disorder, they have shown that a larger FOV area should be selected instead of a small FOV. Zhang et al. (2013) reported that there was no significant difference between standard FOV (8x8x8 mm) and large FOV (150x110x80 mm) areas to differentiate condylar defects and therefore, a larger FOV area should be preferred in terms of less radiation dose in TMJ imaging, in contrast to Libirizzi et al. (2011).

Barghan et al. (2012) reported that hard tissue changes in TMJ can be detected by CBCT in inflammatory joint diseases. In another study, they showed that MRI was insufficient for imaging of osseous ankyloses detected by CBCT (Alkhader et al., 2010). It has been shown in the literature that CBCTs are effective in detecting fracture lines in the TMJ region (Palomo and Palomo, 2009; Sirin et al., 2010; Barghan et al., 2012).

In addition to all these advantages, there are some missing points about TMJ imaging of CBCTs. One of the most important deficiencies in this regard is the lack of Hounsfield Unit, and bone density cannot be measured. In addition, due to the low soft tissue contrast, it fails to evaluate the articular disc. Especially in pediatric patients, artifacts may occur due to patient movement. CBCTs may also fail to detect changes in deeper areas in patients of growing age (Alkhader et al., 2010).

2.7. Ultrasonography (US)

Ultrasonography (US) is a non-invasive, low-cost, easy-to-use imaging method performed using sound waves (Tvrdy, 2007). US may be used for disc displacements, effusion, diagnosis of intraarticular defects and evaluation of treatment results in TMJ. However, in imaging the structural changes in bone in the condyle, its specificity is lower than MRI (Manfredini et al., 2005; Bonafé et al., 2012). In US, it is possible to obtain information about narrow joint space, joint disc position, joint fluid and ligaments adhesions by using 7.5-12 MHz linear transducer in TMJ imaging (Tvrdy, 2007).

Uysal et al. (2002) showed that perfect agreement between MRI and US in the diagnosis of TMJ internal derangements, and MRI and US can be used to define the disk and its position, as well as the presence of TMJ internal derangements. Emshoff et al. (2002) stated that the accuracy of prospective interpretation of high-resolution US of internal derangement, disk displacement with reduction, and disk displacement without reduction was 95%, 92%, and 90%, respectively. Additonally they found that there was one false-positive finding was found for internal derangement. Manfredini et al. (2003) reported that US showed a good diagnostic capability to detect TMJ intra-articular effusion and disc displacement when compared to a standardized clinical assessment. Also it can be suggested that US could represent a promising imaging technique in the study of temporomandibular joint.

The main disadvantage of US is that the position of the joint disc cannot be clearly determined. As the sound waves strike the hard tissues in front of them and show abnormal deviations, it is quite difficult to identify the joint disc located between the two hard tissues (Hayashi et al., 2001). However, multiplanar examination is not possible and, major deficiency of TMJ sonography is the inability to visualize the medial part of the joint (Aksoy and Orhan, 2010). Sensitivity of US was found to be significantly lower than MRI in open and closed imaging of the mouth (Bonafé et al., 2012).

2.8. Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is a noninvasive technique in which images are obtained using magnetic field and radiofrequency waves. Due to the high level of soft tissue contrast obtained by MRI, supporting structures of TMJ, masticatory muscles, joint disc shape, position and pathologies in the disc are evaluated. It also gives an idea about synovial fluid quality (Nogami et al., 2013; Shi et al., 2014). MRI is useful in cases where imaging techniques based on ionizing radiation such as panoramic radiography and CT are insufficient in dentistry (Şatır and Yılmaz, 2020). MRI has been an option for the evaluation of TMJ disc displacement cases. Due to the absence of radiation and the high details of soft tissue images, MRI has become superior to other imaging modalities (Liu et al., 2017). At the same time, open-closed mouth position images by evaluating the position of the disc with the joint, to provide valuable information about the condition of the joint, soft tissues and hard tissues can be evaluated, providing three-dimensional and multi-sectional imaging, tissue characterization, sortable as advantages of the method (Kondoh et al., 1998; Nebbe et al., 1998).

MRI is a gold standard in soft tissue imaging and disc position determination (Klatkiewicz et al., 2018). Yang et al. (2017) reported that MRI was very useful in the evaluation of anterior disc displacement, whereas Kaimal et al. (2018) reported that MRI was more successful in the specificity of

TMJ diseases compared to panoramic radiographs. Many studies of the position of the disc have shown a high correlation between MRI-acquired images and the anatomical studies of TMJ (Hansson et al., 1989; Tasaki and Westesson, 1993). Hansson et al. (1989) studies showed that 85% of the disc position, 77% of the disc configuration and 100% bone abnormalities were determined by MRI, and Tasaki et al. (1993) showed that 95% accuracy in evaluation of disc position and disc configuration and 93% accuracy in detecting changes in bone structure.

The disadvantages of the method are; disc perforations cannot be obtained as well as arthrography, the bone structure of the joint does not provide accurate information for the evaluation of CT, early degenerative lesions cannot be detected. In addition, it cannot be used in people with cardiac pacemakers, ferromagnetic foreign bodies in vital tissues, metal heart valve prostheses, pain simulator wires implanted for pain control, fear of confined spaces, difficulty in standing, and patients with poor cooperation (Tasaki and Westesson, 1993).

3. Conclusion

There are different imaging methods used in the evaluation of bone structure, disc, ligaments and muscles that make up TMJ. Conventional X-ray methods, CT and CBCT are preferred for the evaluation of bone components of TMJ. MRI is the preferred imaging modality for the evaluation of disc, ligaments and muscles in the TMJ structure. US, which is a widely used imaging method in dentistry, can be used for disc displacement, effusion, diagnosis of intraarticular defects and evaluation of treatment results. Nowadays, in parallel with the developing technology, a single imaging method is not used for TMJ imaging and evaluation is performed with several imaging methods. Imaging methods should be selected by evaluating the factors such as radiation dose, contribution to diagnosis and treatment plan, easy applicability, and treatment planning and follow-up of TMJ disorders.

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Clinical outcomes and complications of CAD-CAM fabricated complete dentures: An update and review

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Abstract

For decades, conventional complete dentures (CD) have been a promising treatment for edentulous patients. The introduction of digital technology in CD fabrication streamlines and simplifies the treatment process and offers new and specific applications for the completely edentulous patients. Computer-aided design/computer-assisted manufactured (CAD/CAM) CD protocols can improve efficiency and offer specific applications in specific situations to improve patient care, satisfaction, and convenience. The aim of this review is to assess and evaluate the clinical outcomes and complication of CAD/CAM fabricated CD systems and to provide information about currently available systems for dental practitioners.

Keywords: CAD-CAM, complete denture, clinical outcome, complication

1. Introduction

Edentulism, or the absence of teeth, contributes to disability, impairment, and handicap that significantly affect the general health and overall quality of life of an individual (Viola et al., 2013). Complete denture (CD) is the most common prosthodontic therapy in edentulous patients with anatomical, psychological or financial constraints contradicting implant therapy; many essential therapeutic variables have not yet been scientifically validated (Abduo, 2013). The use of complete dentures for rehabilitation of edentulous patients has acceptable outcomes for most patients (Muller, 2014).

For decades, conventional CD's have been a promising treatment for edentulous patients. In addition to having advantages such as verifying each stage and customizing teeth positions during the construction of complete dentures before delivery, the existence of various disadvantages should also be taken into accounts such as multiple appointments, uncertain laboratory costs and time (Bidra et al., 2013).

A numerical control device, PRONTO, was introduced in the late 1950s which indicates beginning of computer-assisted design/computer-assisted manufacturing (CAD/CAM) era. The very first CAM software program to be developed by Dr. Patrick J. Hanratty, considered as the father of CAD/CAM (www.cadazz.com, 2020). CAD technology is a widely term which refers the use of computers to aid in the creation, analysis, and manufacture of design (Dankwort et al., 2004). The major components of CAD/CAM technology are listed below (Alghazzawi, 2016):

1. Data acquisition unit for acquiring the data of anatomical or dental structures by using intraoral scanners or indirectly digitalizing of a stone model
2. Softwares; used in designing virtual restorations for manufacturing.
3. Computerized manufacturing device; is used for manufacturing the restorations.

CAD/CAM technology based on two main system are subtractive manufacturing and additive manufacturing. The subtractive manufacturing is a process by which 3D objects are created by machining to cut material away from a solid block material achieve the desired geometry as CNC (computerized numerical control) machine. The subtractive manufacturing is widely used in dentistry, especially in prosthodontics. However, limited number of authors have reported the use of CAD/CAM technology for complete dentures (Maeda et al., 1994; Kawahata et al., 1997; Busch et al., 2006; Sun et al., 2009; Zhang et al., 2011; Kanazawa et al., 2011; Goodacre et al., 2012; Inokoshi et al., 2012).

In prosthodontics, the subtractive manufacturing is widely used. However, limited number of authors have reported the use of CAD/CAM technology for CD's (Maeda et al., 1994; Kawahata et al., 1997; Busch et al., 2006; Sun et al., 2009; Zhang et al., 2011; Kanazawa et al., 2011; Goodacre et al., 2012; Inokoshi et al., 2012). This is possibly occasioned by because of complicated manufacturing of CDs. Because many factors have an important effect on them as multiple steps of

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recording, transferring, analyzing, and afterward replacing of artificial substitutes for gingiva and teeth, all of which must be in harmony with patient's mouth and face. All these determinants need the dentist's technical and artistic skill, which is less handy adapted to CAD/CAM than intracoronal or tooth-supported restorations.

The very first scientific article on the use of a CAD/CAM systems for CD production was published by Maeda et al., (1994), and these first CAD/CAM fabricated CDs were made by additive rapid prototyping (RP) technology, from photo-polymerized acrylate material using a 3-D laser lithographic (LL) machine (Maeda et al., 1994). Since then, because of the complexity of the procedures for fabricating CDs, it took almost 20 years for the emergence of the first commercially available denture systems. Katadiyil et al. (2013) presented the procedures for the production of CDs for the first two commercial CAD/CAM systems (AvaDent & Dentca) which are available in the market. The fabricating process of digital CDs consists of scanning the definitive impressions or casts and a maxillomandibular record, designing the denture base and arranging the artificial teeth by using a software program, and then manufacturing the denture by using either an additive (3D-printing) or subtractive (computerized numerical control milling) technique (Kattadiyil et al., 2013; Bilgin et al., 2015; Alghazzawi, 2016; Wimmer et al., 2016). The digitalized process can not only reduce the clinical appointments and chair time but also improve visualization and detection of the edentulous arch morphology and also decrease the polymerization shrinkage of the polymethyl methacrylate (PMMA) (Steinmassl et al., 2017). In conventional fabrication techniques, factors such as detailing the accuracy of CAD/CAM fabricated CDs, and reliable in vivo studies are scarce and have used a subjective rating scale to assess the retention and fit of dentures, making blinded evaluation impossible (Kattadiyil et al., 2015; Schwindling and Stober, 2016).

There are several advantages of CAD/CAM fabricated CDs over conventional CD's.

1. Reduced travel expense for the patient due to fewer appointments (Bidra et al., 2013).
2. The adaptation of CAD/CAM fabricated CDs to underlying tissues are good (Bidra et al., 2013).
3. Reduced micro-porosity of prepolymerized PMMA blocks (Steinmassl et al., 2017).
4. The decrease in accumulation of Candida albicans compared to conventional processing technique (Bidra et al., 2013).
5. The storage of digital files which allows fabrication of new prosthesis when dentures are lost or damaged (Infante et al., 2014).

There are some limitations and disadvantages of the current commercial manufacturing systems that need to be considered.

6. It is challenging to assess the vertical dimension, maxillo-mandibular relation, lip support and maxillar incisal edge position.

7. It is almost impossible to establish the mandibular occlusal plane.

8. Patients have minimal opportunity to participate in the procedure.

9. High investment costs and laboratory costs compared to conventional techniques (Bidra et al., 2013).

Recently there are six commercial workflows for digital complete dentures on the market: AvaDent (Global Dental Science), Ceramill Full Denture System (Amann Girrbach AG), Baltic Denture System (Merz Dental GmbH), DENTCA/Whole You (DENTCA, Inc.; Whole You, Inc), Wieland Digital Denture (Ivoclar Vivadent, Inc). And Vita Vionic (VITA Zahnfabrik).

2. Wieland digital denture (Wieland dental + technikivoclar vivadent)

Wieland Digital Denture protocol is able to finalize a digital denture delivery in four patient visits. Conventional impression trays are used to perform alginate impressions in the first visit. Also jaw relation and vertical records are determined by a centric tray and occlusal plane is determined using a special provisional transfer arch (UTS CAD). Impression trays with the jaw record and occlusal plane information are milled to be used for functional impression in second visit. If needed jaw record and occlusal plane adjustments can be done regarding the compensation values of UTS CAD transfer arch. Next step of second visit is gothic arch registration via functional impression and gnathometer CAD. Third visit is an optional try-in session, if needed dentures milled from PMMA are prone to minor adjustments and delivery to patient possible at third or fourth visit.

2.1. AvaDent digital dentures (Global dental science)

Global Dental Science offers complete digital dentures delivery in three visits. The workflow ensures to finalize the denture in two sessions if try-in session is skipped. Vertical dimension is determined by measuring two points on nose and chin and process is followed by functional impression taking by individual thermoplastic trays. Centric relation is recorded by gothic arc as well as vertical dimension is reproduced taken into account the lip support and occlusal plane with anatomical measuring device (AMD) or wax rim. At second appointment it is possible to perform a PMMA try-in which is optional. If the clinician doesn't prefer a try-in session, visualizing the final denture by fixing cellophane resembling teeth to the AMD is possible.

2.2. Whole you nexteeth (Whole You; Formerly DENTCA)

The workflow is similar to the previous ones. At first session vertical height is evaluated and recorded with the help of reference marks on upper and lower lips. Special trays are used for functional impression. Vertical occlusal dimension is then needing to be reproduced by using the integrating stylus in the lower tray, placed for final adjustments in patient. Gothic arch recording is performed on a plane adapted in the upper tray. Lip support and occlusal plane information is provided automatically from impression. Clinician may add other anatomical reference information like incisor edge length. For esthetic and functional try-in 3D printed acrylic try-in dentures can be used. The system then produces a milled denture with bonded teeth.

2.3. Baltic denture system (Merz Dental)

Baltic Denture System uses bite rims with relined occlusal arches to obtain the ideal 3D position. These occlusal arches have prefabricated different size tooth set-ups that can be adjusted. During first session, the vertical occlusal dimension is obtained and functional impressions are performed. By supporting the BD Upper Key (a bite rim resembling the final maxillary dental arch) with silicone impression material or thermoplastic impression compound, the occlusal plane, incisor length, and lip support are determined. When the maxillary dental arch has been adjusted to the ideal position, the BD Lower Key (a bite rim resembling the final mandibular dental arch) is interlocked with the BD Upper Key by click mechanism and, again, supported with silicone impression material to reach the previously determined vertical dimension and the centric maxillo-mandibular relation. Since the BD Keys resemble the final dental arches, the adjusted keys also serve as try-in dentures so that the final dentures can be placed at the next appointment.

2.4. Ceramill full denture system

The digital workflow starts with the digitization of maxillary and mandibular casts and virtual positioning of teeth and waxing of polished surfaces (Wimmer et al.,2016). Bases of dentures are milled from wax and teeth are placed in the sockets on base. Any anatomical features can be designed and mills on wax. Afterwards dentures are produced conventionally.

2.5. Vita vionic (Vita zahnfabrik)

In VITA VIONIC the digital design and production can be facilitated by non-system-inherent scanners, software, and milling machines. The conventional production protocol is defined in five steps and can also be finalized with reduced sessions only in three sessions. The simplified workflow can be summarized as anatomical and functional impression, vertical dimension and centric relation and denture delivery. Try-in dentures can be milled from Vita wax.

3. Clinical outcomes of CAD-CAM complete dentures

Several researches investigated clinical outcomes of CAD/CAM fabricated CDs based on patient centered outcomes and time efficiency. Kattadiyil et al. (2015) stated dramatically increased retention when comparing milled maxillary CAD/CAM fabricated CDs with the conventional CD manufactured for the same patient. In a pilot cohort study of satisfaction–stability, retention and adaptation relationship were reported that 50% of patients did not rate as either good or excellent Bidra et al. (2016). Schwindling and Stober (2016) stated that milled maxillary CAD/CAM fabricated CDs were slightly more retentive than maxillary injection molding CDs. Saponaro et al. (2016) reported that in 48 (2.08%) patients; one had impaired phonetics and 3 (6.25%) stated poor aesthetic results with their CAD/CAM fabricated CDs. Kattadiyil et al. (2015) and Schwindling and Stober (2016) found no remarkable differences between milled CAD/CAM fabricated CDs and other kind of CDs in view of phonetics and esthetics. Bidra et al (2015) stated great feedbacks for esthetics and phonetics with CAD/CAM fabricated CDs.

Bidra et al (2016) reported 15% (3/20) of patients was dissatisfied of CAD/CAM fabricated CDs was (two of hysterical, and one of exacting had not satisfaction). Saponaro et al. (2016) assessed requirements of post-insertion adjustment visit in their study, 6/48 (12.5%) patients did not require any post-insertion adjustment visit, 16/48 (33.33%) patients needed merely 1 post-insertion visit, 14/48 (29.16%) patients needed 2 visits, and 12/48 (25.00%) needed 3 or more visits. In regard of these data, post placement adjustment visits resulted in a mean number of 2.08 (Saponaro et al., 2016). Bidra et al. (2016) stated in their study that a mean of 3.3 denture adjustments were needed more than 1 year for the 14 patients, of which 1/14 (7.14%) patients needed a notable number of visits for denture adjustments. In their study, some researchers reported that 14.28% of patients requested additional (3rd) appointment, while others reported an average of 2.39 appointments required for the nominal 2-appointment protocol (Bidra et al., 2016; Saponaro et al., 2016). Similarly, Schwindling and Stober (2016) reported an average of 5.4 appointments for the 4-appointment protocol.

Kattadiyil et al. (2015) achieved 80% satisfaction in their study with 15 patients, and similarly Bidra et al. (2016) achieved 79% satisfaction in their study with 14 patients. Other disadvantages mentioned in the studies related to CAD/CAM fabricated CDs have been reported as the need for immediate reline, disparities with OVD, problems with aesthetics, dental layouts and phonetics. (Kattadiyil et al., 2015; Saponaro et al., 2016; Bidra et al., 2016; Schwindling and Stober, 2016).

The current literature has shown the benefits that CAD/CAM fabricated CDs offer: fewer patient visits, digitally saved files for easier remakes, improved denture base adaptation, and improved retention, to name a few (Goodacre et al., 2012; Baba, 2016; Bidra et al., 2013, 2016). One of the most important advantages observed about CAD/CAM fabricated CDs is that fewer appointments (2) are required compared to the traditional method (5 appointments). Researchers reported an average of 2.39 appointments for patients treated by dentists during their postgraduate and predoctoral training. (Saponaro et al., 2016).

In a study related to the production time of CAD/CAM fabricated CDs, the researchers stated that they saved a significant amount of time (approximately 205 minutes) compared to CDs prepared by the traditional method. It was reported that students were able to easily produce CAD/CAM fabricated CDs during the 2-appointment period under the guidance of the faculty during their predoctoral education (Kattadiyil et al., 2015).

In another study, it was stated that the time spent in the clinic in the production of CAD/CAM fabricated CDs decreased, but contrary to this advantage, the time spent in communication with the laboratory increased in order to achieve a successful result (Bidra et al., 2016).

Schwindling and Stober (2016) concluded that dentists who do not have sufficient experience with CAD/CAM fabricated CDs use may need additional appointments in a study on a 4-appointment CAD-CAM system that includes a trial placement appointment. In addition, in their pilot study, they reported that an average of 5.4 appointments were required to complete the production period.

In many studies, advanced initial fit and retention, attributable to polymerization shrinkage deficiency, has been identified as an important advantage of milled denture bases. (Kattadiyil et al., 2015; Saponaro et al., 2016; Bidra et al., 2016; Schwindling and Stober, 2016; Goodacre et al., 2016).

Fernandez et al. (2016) stated that the archiving of CAD/CAM fabricated CDs is an important advantage compared to traditional CDs. The electronic archiving of all clinical data from the patient, together with the design of the manufactured prostheses, which enables making spare or new prostheses, in case of breaking or losing them, without clinical appointments. Bilgin et al. (2016), in their research, stated that microbial colonization should reduce with milled denture bases.

Similarly, milled denture bases have shown significantly higher short-term retention, (Kattadiyil et al., 2015) but long-term data were available in only 1 study of 1-year duration (Bidra et al., 2016).

Al-Helal et al. (2016) reported that there was considerable improvement in retention to the CAD/CAM fabricated CDs compared with the traditional heat-polymerized CD's after 24 h storage in water before the testing appointment. The clinical outcomes demonstrated a considerable improvement in retention for the CAD/CAM fabricated CDs compared with the traditional group. The authors suggested that feasible explanation for this might be the raised intensity of prepolymerized acrylic resin block, which offers higher dimensional stability and is not surely affected by hydration. He also noted that the arch form and type had no influence on the retention of either type of denture base.

Goodacre et al. (2016) compared the denture base adaptation of CAD/CAM and conventional (pack and press, fluid resin, or injection) CD's an in vitro study and they concluded that CAD/CAM technology procreated the best accurate and reproducible dentures of the 4 tested techniques.

Al-Rumaih (2016) compared the retention of conventional and digitally milled CD's. He concluded that denture adhesive effectively compensates for potential differences in retention between conventionally and digitally designed denture bases.

Three common types of complication have been reported by Saponaro et al. (2016) lack of denture retention, incorrect centric relation (CR) and inaccurate vertical occlusal (VDO) dimension. The authors indicated that these complications could have been due to the overall quality of the impressions and the operator experience.

Srinivasan et al. (2017) compared the trueness of the intaglio surface CD's produced by different techniques (injection molding, flask-pack-press and CAD/CAM). they reported all techniques seems to remain within a clinically acceptable range CAD/CAM group showed the highest compression values (with the exception of the tuberosities), especially in the vestibular flange area. The vestibular flange (tighter inner seal) compression may be linked to improved retention.

Accordingly, the CAD/CAM technique would be considered the best processing technique in comparison with traditional techniques. The results of Goodacre et al. (2018) for denture tooth movement demonstrated that techniques requiring compression during processing (pack-and-press, injection) showed increased positive occlusal tooth movement compared with techniques not involving compression (fluid resin, CAD-CAM bonded, CAD-CAM monolithic), meaning that it would cause an increase in the patient's OVD.

3.1. Complications of CAD-CAM complete dentures

Several researches investigated complications of CAD/CAM fabricated CDs such as lack of retention, necessity to relines, occlusal vertical dimension and centric relation errors, occlusion and tooth arrangement errors, esthetic and phonetic problems, tooth wear, additional visits to protocol, postinsertion adjustments, overall patient dissatisfaction and remake needed.

Saponaro et al. (2016) in a retrospective study, they stated that 16.66% of patients had inadequate prosthetic retention at the delivery appointment of the prosthesis. Bidra et al. (2016) in a prospective study, 50% of the patients stated that they did not feel sufficient prosthetic retention at delivery, and that 1 patient experienced significant retention loss after 1 year of follow-up. While Schwindling and Stober (2016) reported that 40% of their patients had prosthetic retention problems, in contrast, Kattadiyil et al. (2015) reported no problems with CAD/CAM fabricated CDs retention in a study with 15 patients.

Saponaro et al. (2016) found that 4 of the 48 participants had incompatibility in their occlusal vertical dimension. Besides, Schwindling and Stober (2016) stated that 2 of the 5 patients had an inadequate vertical dimension. Kattadiyil et al.

(2015), found that wrong centric relationship record had been taken from one of the 15 participants. Likewise, the centric relationships of 3 of the 48 participants involved in the study of Saporano et al. (2016) were wrong. Bidra et al. (2016) noted that a higher proportion of centric relationship errors were revealed by 14.28% and extra sessions were conducted to confirm.

In their study, Schwindling and Stober (2016) attempted to establish bilateral balanced occlusion in the participants, but the need for intraoral adjustment was revealed in each participant. Although a rehearsal session was conducted to obtain a suitable occlusion, at least a single tooth for 2 of the 5 participants required to be corrected.

Saponaro et al. (2016) achieved inadequate aesthetic results in 3 of the 48 participants. Schwindling and Stober (2016) needed extra arrangements (no parallels of occlusal plane with Camper plane and interpupillar line, narrowed buccal corridors, midline deviation, and excessive support of lips) to improve esthetics in all 5 participants. Kattadiyil et al. (2015) however, reported that there is no significant difference between conventional and digital complete dentures in terms of esthetics.

Saporano et al. (2016) reported that they had regulated phonetics of one of the 48 participants (2.08%) by applying heat-processed palatal reline due to the lack of palatal contour. Schwindling and Stober (2016) stated that one of the 5 participants had difficulty with pronouncing the letter "S" at first, but the situation improved without any alteration afterwards. A significant amount of wear on acrylic teeth of 3 of 14 participants was observed as a result of 1-year observation in the study conducted by Bidra et al. (2016).

Saponaro et al. (2016) stated that 17 of the 48 participants needed more than 2 sessions for CAD/CAM fabricated CDs; the 2-visit protocol was able to perform with an average of 2.39 visits. For 2 participants' rehearsal session was deemed necessary. Schwindling and Stober (2016) were able to complete their 4-session protocols with an average of 5.4 sessions. Saponaro et al. (2016) reported that 62.5% (30 participants) needed a postinsertion adjustment for 1 or 2 sessions and 29.16% (14 participants) needed for 3 or more sessions of 48 patients. On the other hand, Bidra et al. (2016) stated that an average of 3.3 sessions of postinsertion adjustment had needed after 1-year follow-up.

Kattadiyil et al. (2015) stated that 3 of 15 participants preferred conventional full prosthetics than CAD/CAM fabricated CDs. It was reported that in the study of Bidra et al. (2016) 6 of the 17 participants and in the study of Saporano et al. (2016) 4 of the 19 participants had dissatisfaction with CAD/CAM fabricated CD treatment. Kattadiyil et al. (2015) reported that the lower jaw prosthesis of one of the 15 participants was renewed because anterior open bite was observed. Saponaro et al. (2016) stated that the replacement of dentures was necessary for 5 of the 48 participants, as 2 of them had excessive OVD.

4. Conclusion

The use of CAD/CAM technology to fabricate complete dentures has positive benefits for both the patient and practitioner. Because the required clinical records can be obtained in one appointment and the dentures completed for a second appointment, there is less clinical time involved in the treatment. Therefore, it should be possible to reduce the cost of care for patients while still providing quality dentures using state, of-the-art dental materials. Elimination of the polymerization shrinkage inherent in conventionally processed completed dentures enhances the fit of the dentures base. Additionally, having a repository of digital data allows for rapid fabrication of spare or replacement dentures.

As we switch to the world of CAD/CAM dentures, competency in making acceptable impressions, determining the appropriate OVD, capturing accurate records, applying esthetic principles and intervention for behavioral modification when required will continue to play a predominant role, even as the applications for this new technology continue to expand.

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Review Article

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What do we expect to visualize on the radiographs of mronj patients?

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Abstract

Medication related osteonecrosis of the jaws (MRONJ) is a common complication of the bisphosphonates and other anti-resorptive drugs which are mainly used for osteoporosis, malignancy related hypercalcemia and distant bone metastases. While some imaging modalities are not successful at detecting Stage 0 MRONJ patients, some modalities such as Magnetic Resonance Imaging (MRI), can detect early MRONJ lesions. Early diagnosed MRONJ lesions are relatively easier to maintain and treat; thus, early diagnosis plays huge role in treatment. In this review main imaging modalities which are used in dentistry were evaluated regarding MRONJ.

Keywords: bisphosphonate-associated osteonecrosis of the jaw, cone-beam computed tomography, magnetic resonance imaging, multidetector computed tomography, panoramic radiography, positron-emission tomography, single photon emission computed tomography

1. Introduction

Medication related osteonecrosis of the jaws (MRONJ) is a progressive necrosis of the maxilla and mandible due to bone-modifying agents, angiogenic drugs and other medications. Clinical features of MRONJ are reported as: Presence of an exposed bone area which does not heal within eight weeks (Ruggiero et al., 2014; Unsal et al., 2017; Dunphy et al., 2020; Kim et al., 2020; Limones et al., 2020; Morishita et al., 2020). Also, the patient must have a history of bone-modifying agents (BMAs) such as bisphosphonates, denosumab or angiogenic inhibitor drugs (AID) and the patient must not have any radiotherapy at the maxillofacial region. Although the pathogenesis of MRONJ is not completely understood there are hypothesizes which suggest that MRONJ is related in remodeling and healing of the jaws. Mechanisms that frequently mentioned are inhibition of osteoclast differentiation, inhibition of angiogenesis, induced apoptosis of osteoclasts, reduction of bone turnover (Ristow et al., 2015; Berg et al., 2016; Brierly et al., 2019). Oral malodor, erythema, soft tissue ulceration, which is persisted for more than 8 weeks, neuropathy, jaw pain, mucosal swelling, trismus, exposed bone or a non-healing extraction socket, paresthesia and suppuration are the common clinical signs and symptoms of MRONJ (Brierly et al., 2019; Rao et al., 2019; Sarmiento, 2019; Steel, 2019; Dunphy et al., 2020; Jasper et al., 2020; Limones et al., 2020; Morishita et al., 2020; Wadia, 2020).

Five different hypotheses were suggested for the pathophysiology of the MRONJ since the first osteonecrosis of the jaws cases were reported; however, the exact pathophysiology is not determined yet (Marx, 2003; Aghaloo et al., 2015). Proposed hypotheses were regarding; the inhibition of bone remodeling process, infection/inflammation hypothesis which tries to find an answer to if exposed bone induces bacterial biofilm or if bacteria induced the exposed bone and infection, angiogenesis inhibition, toxicity of soft tissues and acquired immunity dysfunction (Christodoulou et al., 2009; Sedghizadeh et al., 2009; Filleul et al., 2010; Kumar et al., 2010; Santos-Silva et al., 2013; Bae et al., 2014; Aghaloo et al., 2015).

The clinical signs of the MRONJ are well reported in the literature, however, only several studies concentrated on the early radiographic signs of MRONJ. This manuscript focuses on MRONJ's radiographic appearances in various imaging modalities (Berg et al., 2016; Subramanian et al., 2017; Wazzan et al., 2018; Shibahara, 2019; Zirk et al., 2019).

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2. Imaging modalities and MRONJ

2.1. Orthopantomography (OPG)

OPG which has relatively lower radiation dose, comparing to 3D imaging techniques, is useful especially for routine radiographic examinations. The most common radiological findings that can be visualized at early MRONJ defects are widening of the periodontal ligament space, thickening of the lamina dura, narrowing of the mandible canal and sclerosis of the trabecular bone. If MRONJ occurs after tooth extraction, a persistent non-healing extraction socket (Fig. 1.) is often seen at OPG image. Advanced MRONJ defects induce sequestrum formation which indicates necrotic bone island. Sequestrum is seen as a radiopaque calcified area within a radiolucent lesion which is completely separated from the healthy trabecular bone (Fig. 2.). Periosteal new bone formations can also be seen on OPGs. Osseous sclerosis is found at almost all MRONJ patients and increased mandibular inferior cortical bone thickness is also another significant parameter in MRONJ patients (Berg et al., 2016).

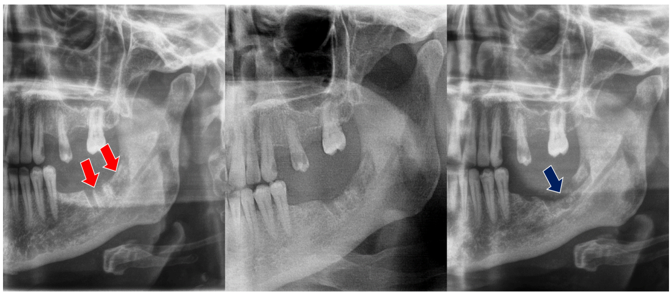

Fig. 1. Cropped panoramic radiographs of a 49-year-old female patient. Persistent non-healing extraction socket's (red arrows) transformation to sequestrum (blue arrows) is seen at mandibular left molar region

Stockmann et al. (2010) stated that the detectability of MRONJ is 96% for CT while 54% for OPGs, thus, it should not be forgotten that MRONJ may be detected on some OPGs, but advanced assessments should be done with.

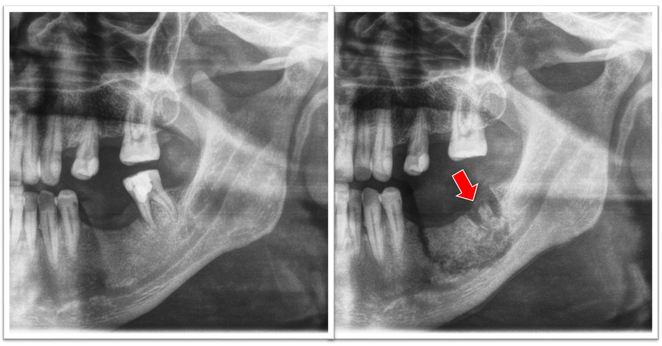

Fig. 2. Cropped panoramic radiographs of a 60-year-old female patient. Sequestrum formation as a radiopaque calcified area within a radiolucent lesion (red arrow) which is separated from the healthy trabecular bone is seen

2.2. Cone-beam computed tomography (CBCT)

CBCT, which has conical X-rays instead of fan beam X-rays, has high diagnostic quality images with lower radiation dose than CT. CBCT is also superior to OPG since there is no superpositions of adjacent anatomical structures and bucco-lingual evaluations can be performed. CBCT is better at visualizing early changes in both trabecular and cortical bone comparing to all 2D imaging modalities (Berg et al., 2016; Subramanian et al., 2017; Unsal et al., 2017; Goller-Bulut et al., 2018; Zirk et al., 2019).

CBCT can demonstrate increased bone density which is the most common initial change in MRONJ patients (Fig. 3). Since the slice thicknesses of CBCT images are usually thinner than CT images, small bone alterations can be easily detected with CBCT. CBCT images does not have diagnostic soft tissue contrast which makes it impossible to evaluate associated thickening and edema of soft tissues (Subramanian et al., 2017; Goller-Bulut et al., 2018; Zirk et al., 2019).

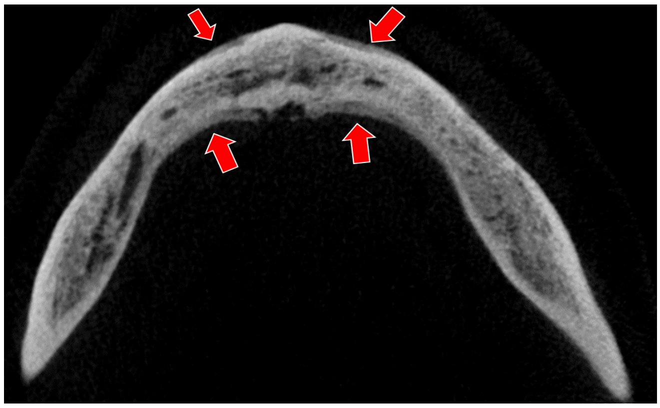

Fig. 3. Osteosclerosis is seen at axial CBCT slice. Parallel/solid periosteal reactions are also seen at buccal and lingual cortical plates (red arrows)

Common CBCT findings of initial MRONJ lesions are (Berg et al., 2016; Subramanian et al., 2017; Goller-Bulut et al., 2018; Zirk et al., 2019):

- Narrowing of bone marrow space
- Osteolysis with sclerosis at surrounding trabecular bone
- Parallel/solid periosteal reactions

Common CBCT findings of advanced MRONJ lesions are (Fig. 4.) (Berg et al., 2016; Subramanian et al., 2017; Goller-Bulut et al., 2018; Zirk et al., 2019):

- Cortical bone erosion and trabecular bone destruction.
- Pathologic fractures
- Buccal and lingual cortical plate destructions at advanced stages
- Parallel/solid periosteal reactions

2.3. Computed tomography (CT)

Relatively higher radiation dose and longer scanning process are the limitations of CT comparing to CBCT. However, CT images have diagnostic soft tissue contrast, thus, edema and thickening of soft tissues can be evaluated with CT. It should not be forgotten that most of the CT units have bigger voxel sizes than CBCT units which makes it almost impossible to evaluate minor alterations at trabecular bone (Berg et al., 2016).

2.4. Magnetic resonance imaging (MRI)

Following the studies by Lauterbur and Mansfield, MRI was developed for clinical use in 1980s. The principle of MRI relies on a large magnet which affects hydrogen nuclei in the human body and aligns them in the active magnetic field. After a radiofrequency pulse is directed to patient some hydrogen nuclei will resonate and after this radiofrequency is taken away the energy will be released from the patient. This energy is detected by the coils and a distribution pattern of those nuclei, an image will be reconstructed (Orhan and Rozylo-Kalinowska, 2019).

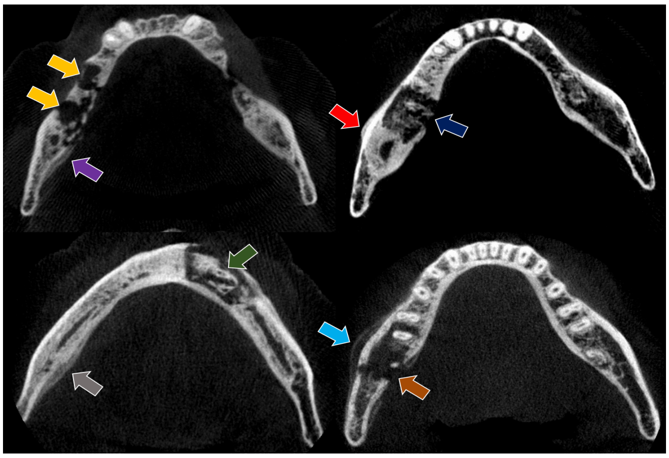

Fig. 4. Axial CBCT slices of four different MRONJ patients. A: Non-healing extraction sockets (yellow arrows), cortical destruction and parallel periosteal reaction (purple arrow) at lingual cortical plate are seen. B: Parallel periosteal reaction (red arrow) at buccal cortical plate, cortical destruction at lingual cortical plate and sequestrum (blue arrow) formation are seen. C: Osteosclerosis, sequestrum formation (green arrow), cortical destruction at buccal cortical plate and parallel periosteal reaction (gray arrow) at lingual cortical plate are seen. D: Cortical destruction at lingual cortical plate (brown arrow), parallel periosteal reaction (cyan arrow) at both lingual and buccal cortical plates are seen

Comparing to other imaging modalities MRI has a high soft tissue contrast which makes it superior in TMJ disc evaluations and other examination regarding soft tissues. However, due to long scanning times, possible injuries due to ferromagnetic objects and high installation costs it is still less common than other imaging modalities in dentistry (Orhan et al., 2005; Orhan et al., 2006; Orhan and Rozylo-Kalinowska, 2019).

Although MRONJ mainly involves the jaws which are hard tissues, exposed bone areas show hypointense regions in T1/T2 weighted images and inversion recovery (IR) images since those osteonecrotis areas have lower water content. However, unexposed, and affected areas show hypointense regions in T1 and hyperintense regions in T2-IR images since those osteomyelitic areas have higher inflammation content (Fig. 5.). In other words, it is possible to state that early MRONJ defects will have hyperintense areas in T2 sections and after osteonecrosis those areas will have hypointense areas due to lack of water content. Contrast-enhanced MRI sections reveal more extensive alterations comparing with CBCT and clinical examination (Stockmann et al., 2010; Berg et al., 2016).

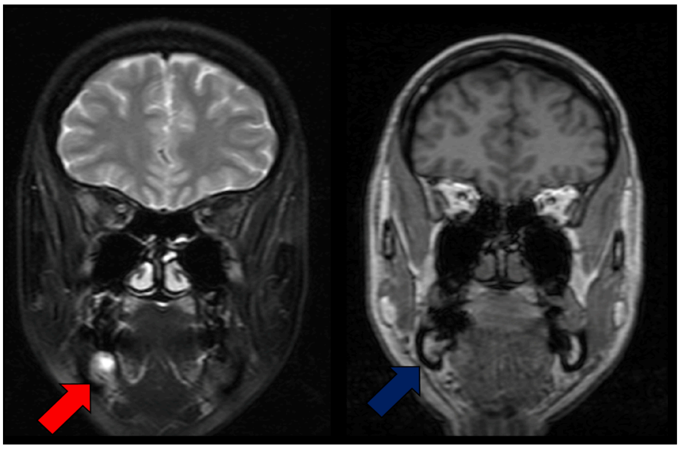

Fig. 5. Coronal T2-W (a) and T1-W (b) MRI images of a 64-year-old female patient. As it is seen in early MRONJ patients, T2-W slice reveals hyperintense osteomyelitic areas with high inflammation content (red arrow). Relevant area was seen hypointense in T1-W slice (blue arrow)

Early MRI finding of MRONJ is the loss of T1 hyperintensity of fatty bone marrow both in maxilla and mandible. Advanced MRI findings of MRONJ are soft tissue edema, bone destruction and inferior alveolar nerve thickening. MRI with contrast agents has high detectability for MRONJ lesions but extent of the detection is a concerning area (Stockmann et al., 2010; Berg et al., 2016).

2.5. Ultrasonography (USG)

Although USG is an advanced imaging modality that has superiority for superficial soft tissues examination, it is not possible to evaluate MRONJ cases since exposed bone areas lack soft tissues. No USG study has yet been done for stage 0 MRONJ cases with USG.

2.6. Single photon emission computed tomography (SPECT)

SPECT is an advanced nuclear imaging technique which is a combination of computed tomography images and signals which were gained from scintigraphy. SPECT scans the distribution of radionuclides such as Tc-99m within both hard and soft tissues with gamma cameras (White and Pharoah, 2014). This allows the distribution of the radionuclide to be displayed in a three-dimensional manner offering better detail, contrast, and spatial information than planar nuclear imaging alone.

SPECT imaging is a functional imaging which is useful especially for bone scans. Several studies were done for MRONJ patients with SPECT and common findings were reported as (Miyashita, et al., 2015; Berg et al., 2016; Miyashita et al., 2019; Miyashita, et al., 2019):

- MRONJ lesions showed focal abnormal activity with an increased radionuclide uptake at periphery and decreased radionuclide uptake at the center of the defect.
- 99Tcm-MDP and 99Tcm-DPD did not show any significant differences in detecting pathologies, so,

both nuclides can be used for MRONJ.

- MRONJ should not show an uptake in the necrotic zone, but due to associated infection, a nuclide uptake may be seen.
- Clinically asymptomatic MRONJ lesions showed significant nuclide uptake which is a promising improvement for SPECT.
- A study showed that 65.7% of the MRONJ patients have increased nuclide uptake so it should not be forgotten that SPECT is not as dependable as CBCT-MDCT or MRI images.

2.7. Positron emission tomography/computed tomography (PET/CT)

PET is also an advanced nuclear imaging modality which relies on radionuclides which emit positrons. In this modality, positron-source radionuclides given to the body lose their substance properties due to the annihilation and F-18, C-11, N-13, and O-15 radionuclides that emit positrons are generally used. The most used radionuclide is F-18 it is used for labeling FDG. Since FDG is a metabolic analogue of glucose the uptake is higher in tissues which requires more energy like cancer cells. But malignant cells do not always have high FDG uptakes which should be considered in differential diagnosis. Higher uptakes can also be seen in active infections and inflammations such as MRONJ, collagen diseases and granulomatous lesions. PET is a common imaging modality for detecting primary bone tumours, osteomyelitis, and metastases (Koenig, 2011; White and Pharoah, 2014; Kitagawa et al., 2019).

PET has limitations in MRONJ patients since the necrotic areas without blood flow and hypermetabolism will not show increased glucose metabolism; however, infected areas can be seen because of inflammatory processes. In other words, early detection and assessment of inflammatory processes can be imagined which may visualize an initial MRONJ (Fig. 6.). PET/CT can detect diffuse and local metabolic changes and these changes can be compared with the contralateral side of the mandible or maxilla for the reference (Berg et al., 2016; Fleisher et al., 2016).

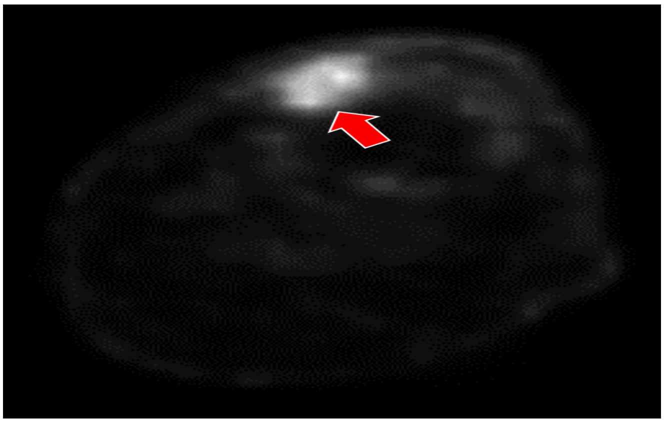

Fig. 6. PET image of a 44-year-old female Stage-0 MRONJ patient. Note the increased glucose metabolism at mandibular right molar region (red arrow)

2.8. Fluorescence-guided bone resection/visually enhanced lesion scope (VELscope)

This newly technique is published as: 100 mg of doxycycline will be received by the patient twice a day for 10 days. This will let the bone to have a high doxycycline uptake which will appear as green at VELscope images. Necrotic bone will not have an uptake therefore no/very little fluorescence is shown. Even in a patient who received only a single 100 mg shot of doxycycline one hour pre-operatively, it was possible to distinguish between necrotic and healthy bone using the VELscope. This technique is used as a guide especially before surgical procedures such as resection (Berg et al., 2016).

Tomo et al. (2020) conducted a review in which they evaluated 18 different studies (218 patients) regarding the VELscope-guided surgical management of MRONJ patients and stated that this method is promising at delimitating the surgical margins of MRONJ resections. It was also reported that inadequate necrotic bone debridement can be avoided with using VELscope.

2.9. Key differential diagnosis

2.9.1. Chronic suppurative osteomyelitis

Chronic suppurative osteomyelitis, osteoradionecrosis and MRONJ share same radiographic features since all of them are characterized with necrotic bone lesions. Medical anamnesis of chronic suppurative osteomyelitis patients lack history of head and neck radiotherapy and BMA/AID drug usage. Radiographs of these patients mostly reveal an odontogenic infection such as apical lesions (Koenig, 2011; White and Pharoah, 2014).

2.9.2. Osteoradionecrosis (ORN)

ORN is a complication of head and neck radiotherapy which is characterized by exposed necrotic bone. As it was mentioned above, radiographic features are same with MRONJ. Medical anamnesis is key in differential diagnosis (Koenig, 2011; White and Pharoah, 2014).

2.9.3. Distant metastasis to jaws

Distant metastases to jaws are unique and present only 1-3% of all oral malignant neoplasms. They can occur in jawbones or oral soft tissues. The main difference between metastatic lesions and MRONJ is metastatic lesions are characterized with ill-defined osteolytic lesions usually without osteosclerosis. Breast and prostate cancers metastases occasionally appear as purely sclerotic changes which may cause a diagnostic challenge. Irregular soft tissue mass is frequently seen with metastatic lesions (Koenig, 2011; White and Pharoah, 2014).

3. Conclusion

Since osteosclerosis is the first radiographic finding in OPG/CT and CBCT images, patients with intense osteosclerosis should be followed-up routinely. If any functional imaging was performed, for follow-up or diagnostic purposes, it should not be forgotten that high nuclide uptake is one of the findings of clinically asymptomatic MRONJ lesions. Also, unexposed MRONJ lesions show hypointense regions in

T1 images and hyperintense regions in T2-IR images due to higher inflammation content. Various imaging modalities have different radiographic findings for initial MRONJ lesions; thus, dentists should be aware of these alterations in order to take preventive measures.

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Applications of contemporary imaging modalities in orthodontics

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Abstract
The validity of orthodontic diagnosis and treatment planning depends on the accuracy of the photos, models and radiograps to be obtained from the patient. One of the most important parts of diagnosis and treatment planning is the use of appropriate imaging method. Although lateral cephalometric radiographs are still the most preferred imaging method, other methods such as hand-wrist radiographs, panoramic radiographs, cone beam computerized tomography (CBCT), magnetic resonance imaging (MRI), and ultrasound are also frequently used. For this reason, it is important to know the advantages and disadvantages of all imaging methods for orthodontists in order to select the most suitable method for the patient. Although 2D imaging modalities are still frequently preferred in terms of their accessibility, CBCT use may come to the fore when precise imaging of hard tissues is desired. In cases where TMJ region and soft tissues are to be imaged, the use of MRI and ultrasound should be considered. Orthodontists should follow up the up-to-date usage areas of the developing imaging methods.

Keywords: CBCT, contemporary imaging, digital imaging, orthodontics, 3D Imaging

1. Introduction

Orthodontic treatment aims to position the dentition within the skeletal and soft tissue environment for optimal facial and dental aesthetics. Although the design of primitive orthodontic appliances dated back to ancient times, systematic identification of orthodontics was carried out by Kingsley in the 1800s (Kingsley, 1880; Profitt, 2013). The occlusion concept, which simply expresses contact between teeth, was introduced in the late 1800s, and the classification of this relationship was carried out by Edward H. Angle, the father of modern orthodontics (Angle, 1899; Angle, 1907). This classification, which was mainly based on the relationship of molar teeth, had been effective in the transition of orthodontic treatments to a more advanced stage. Nevertheless, it was observed that satisfactory results could not be achieved due to incompatibilities in the jaw and facial structures even if ideal occlusion was achieved. With the spread of lateral cephalometric radiographs after World War II, it had been shown that the problem in Class II and Class III malocclusions was not only due to the placement of the teeth, but also the position of the jaws was effective in this case. Therefore, the treatments started to target not only the correction of the teeth but also the correction of the skeletal structure (Profitt, 2013).

The validity of orthodontic diagnosis and treatment planning depends on the completeness of the material to be obtained from the patient. One of the most important parts of diagnosis and treatment planning is the use of appropriate imaging method. Although lateral cephalometric radiographs are still the most used imaging method, other methods such as hand-wrist radiographs, panoramic radiographs, cone beam computerized tomography (CBCT), magnetic resonance imaging (MRI), and ultrasound are also frequently used. The important thing is that the orthodontist should decide which radiographs are required to suit the needs of each patient.

2. 2D imaging modalities

2.1. Lateral cephalometric radiographs

Cephalometry was a tool used by anatomists for measuring skulls and studying craniofacial development long before the emergence of orthodontic science (Chaconas and Fragiskos, 1991; Uzel and Enacar, 2000). For the first time, Pacini (1922) obtainted lateral cephalometric films by fixing the individuals' heads with bandages, and made some dimensional and angular measurements on these films for anthropometric purposes and investigated certain indices. Later in 1931, standardized remote X-ray techniques were developed by Hofrath in Germany to examine the results of prosthodontic reconstruction, and by Broadbent in the USA to study craniofacial growth. In this way, cephalometry had entered clinical use and had become one of the most important tools of orthodontic clinic and

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research (Uzel and Enacar, 2000; Quintero et al., 1999; Profitt, 2013; Hans et al., 2015).

After the cephalometry entered the orthodontic literature in 1931, analysis methods were developed one after another. Researchers such as Tweed, Downs, Steiner, Sasounni, Ricketts, Jarabak and Fizzell, McNamara created cephalometric analysis methods (Uzel and Enacar, 2000). Cephalometric films are generally obtained in the head position, where the Frankfort Horizontal plane, clinically detected, is parallel to the ground, where the head is fixed with the ear and nasion sticks of the cephalostat. Cephalometric analysis is carried out according to the various reference planes obtained using intracranial points on these films. Some hard tissue reference points used in cephalometric analysis are exemplified in Fig. 1.

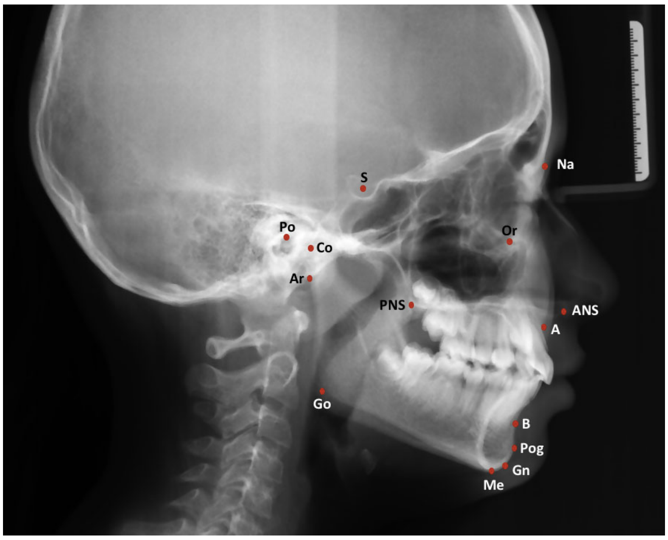

Fig. 1. Examples for cephalometric hard tissue landmarks. A: The deepest point of concavity on the maxilla between ANS and prosthion. B: The deepest point of concavity on the mandibular symphysis between infradentale and pogonion. Na: Nasion, the most anterior point of the front nasal suture. S: Sella, the midpoint of sella turcica. Go: Gonion, point of intersection of the ramus plane and the mandibular plane. Me: Menton, the midpoint on the inferior border of the mental protuberances. Pog: Pogonion, the most anterior point of the bony chin in the median plane. Gn: Gnathion, the most anteroinferior point on the symphysis. ANS: the most anterior point of anterior nasal spine. PNS: the most posterior point of posterior nasal spine. Po: Porion, The most superior point of the meatus acusticus externus. Co: Condylion, most posterior/superior point on the condyle of mandible. Or: Orbitale, most inferior point on margin of orbit. Ar: Articulare, junction between inferior surface of the cranial base and the posterior border of the ascending rami of the mandible

Cephalometric analysis methods are used for orthodontic diagnosis, to determine facial growth patterns, to evaluate changes during and after orthodontic treatment. (Ülgen, 2001; Kayasu and Köklü, 2012). Current uses of cephalometry are (Gill and Naini):

Morphological analysis: Orthodontic anomalies arise not only from the positional disorders of the teeth, but also from the size and position of jaws and facial structures. Cephalometric analysis methods are frequently used to make the correct diagnosis. Various linear and angular measurements are used for this purpose. Thus, the relationship between the jaws with each other and the cranial base can be evaluated in both sagittal and vertical directions. Cephalometric analysis is used not only for the evaluation of skeletal structure but also for the evaluation of dental relations and soft tissue (Holdaway, 1983; Bergman, 1999).

Analysis of facial growth pattern: Accurate diagnosis of facial growth pattern is to determine the treatment timing and the appropriate treatment method. It is not possible to stop growing, but it is possible to direct it with appropriate treatment mechanics. Therefore, various measurements can be used to determine the treatment method that will not conflict with the patient's growth model and can give an effective result (Erverdi, 2017).

Evaluation of treatment results: Cephalometric analysis can be used not only in diagnosis, but also to evaluate the effect of functional appliances and other treatment mechanics,

Evaluation of impacted teeth: Although panoramic radiographs and 3D imaging methods are frequently preferred for this purpose, cephalometric radiographs can also be used to have an idea about the bucco-lingual positions of anterior teeth.

Evaluation of skeletal maturation: It is very important to determine the skeletal development of the individuals to treat the anomalies related to the lower and middle face areas at the appropriate time. In treatments targeting growth modifications, the most appropriate period is considered to be the pubertal peak period. Although different methods are used to evaluate the skeletal maturation of individuals, one of the most frequently used methods is the evaluation of cervical vertebra maturation stages (CVMS) on lateral cephalometric radiographs. CVM stages were first introduced by Lamparski (1972). Then Baccetti et al. (2002) developed the method, by examining the shape and size of the bodies of the cervical vertabrae 2-4. They have identified five maturation stages. Baccetti et al. (2005) evaluated CVM phases in six groups in another study (Fig. 2). Studies showed that this method was reliable in predicting individual growth and evaluating the growth spurt of the mandible (Hassel and Farman, 1995; Flores-Mir et al., 2006; McNamara and Franchi, 2018). The most important advantage of the method is that it does not need any other material in addition to cephalometric radiographs, it is easy to apply and practical. However, it should be kept in mind that it is subjective because of visual evaluation (Türköz et al., 2017).

2.2. Hand-wrist radiographs

One of the most frequently used methods for determining skeletal maturation is the evaluation of hand-wrist radiographs. The presence of a large number of bones in the region and its ability to provide detailed assessment often make it preferred compared to other methods (Bowden, 1976; Fishman, 1979). Evaluation of skeletal maturation using hand-wrist radiographs can be performed with two approaches.

First approach is based on comparison of radiographs for determining the skeletal age of individuals using hand-wrist atlas. The atlas of Greulich and Pyle (1959) contains hand and wrist radiographs, taken from girls and boys, from birth to adulthood, with an interval of six months. Each bone of the patient's hand-wrist is compared with the corresponding bones in the atlas and is assigned an age in months. In this atlas, again for girls and boys separately; separate tables are given for skeletal age as normal, retarded or accelerated. These tables show how many percent of the child's growth is completed at each age. In Tanner et al. (1983) method, specific ossification centers in the hand and wrist (radius, ulna and certain metacarpal and phalanges) are evaluated and classified for certain stages. The total bone age is determined by calculating the score obtained from each bone.

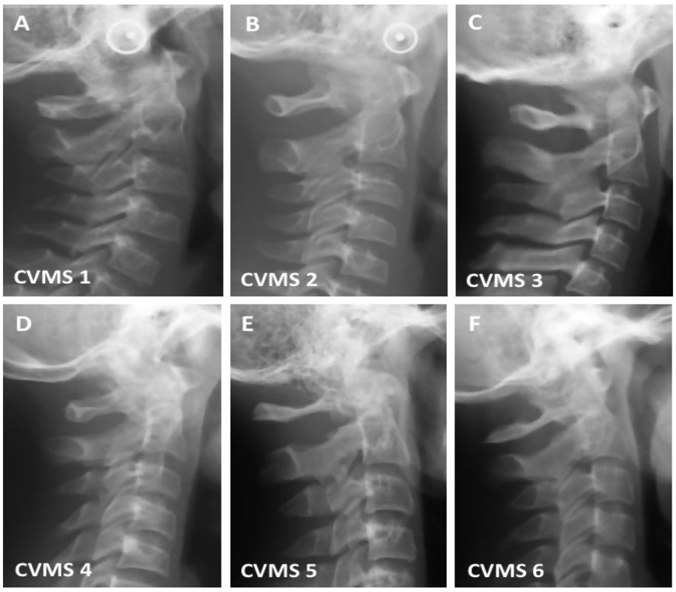

Fig. 2. Cervical vertebrae maturation stages. A. CVMS 1: Inferior surfaces of all vertebras are flat and get narrower from posterior towards anterior. B. CVMS 2: Formation of a concavity at the lower border of the second vertebra has started and anterior heights of the vertebras have increased. C. CVMS 3: Lower border of the third vertebra is also becoming concave. D. CVMS 4: Lower border of the fourth vertebra is also concave and slight concavity is observed at the fifth and sixth vertebras. Also, vertebras are now rectangular in shape at this stage. E. CVMS 5: Concavity of the fifth and sixth vertebras has distinctively deepened, vertebras are rectangular in shape and the gap between them has decreased. F. CVMS 6: Length of the vertebras exceeds their width and concavities are deep (Baccetti et al., 2002)

The second approach aims to reveal the skeletal development period of the individual by evaluating the formation of various hand bones and the epiphysis/diaphysis relationship on hand-wrist radiographs. The expansion of the epiphyses is associated with diaphysis and is an ongoing process. The epiphysis first emerges as the ossification center in the middle of the diaphysis and begins to expand to the sides. The capping phase is the phase between the expansion of the epiphyses and their union with the diaphysis. The formation of the sesamoid bone begins on the medial of the proximal phalanx of the thumb (Fishman, 1982). The formation of the sesamoid bone occurs about 1 year before the pubertal peak. Pubertal peak growth is considered as the period when the epiphysis of the medial phalanx of the 3rd finger is capping through the diaphysis (MP3cap). The evaluation of the growth period by evaluating ulnar, radius, carpal, metacarpals, phalanges, and the sesamoid bone on hand-wrist radiographs was examined by various researchers and various classifications was introduced (Bjork and Helm, 1967; Bowden, 1976; Fishman, 1982). These methods aimed to determine the treatment approach by evaluating the skeletal maturation of the individual, not the calculation of the skeletal age. Examples of hand-wrist radiographs showing various stages are presented in Fig. 3.

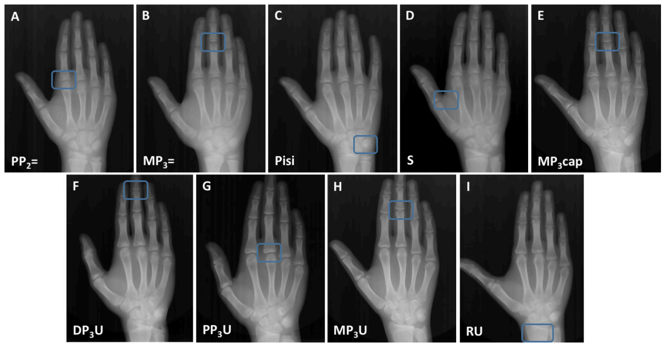

Fig. 3. Stages of maturation according to the hand wrist radiographs. A. PP_2= (equality of epiphysis and diaphysis of proximal phalanx of the 2nd finger), B. MP_3= (equality of epiphysis and diaphysis of medial phalanx of the 3rd finger), C. Pisi (ossification of os pisiforme), D. S (formation of the sesamoid bone), E. MP_3cap (epiphysis of medial phalanx of the 3rd finger covering diaphysis), F. DP_3U (fusion of epiphysis and diaphysis of distal phalanx of the 3rd finger), G. PP_3U (fusion of epiphysis and diaphysis of proximal phalanx of the 3rd finger), H. MP_3U (fusion of epiphysis and diaphysis of medial phalanx of the 3rd finger), I. RU (Fusion of radial epiphysis with diaphysis)

2.3. Panoramic radiographs

Panoramic radiography is the technique that provides a single tomographic image of the facial structures containing both the maxillary and mandibular dental arches and the tissues that support them. Panoramic radiographs have the advantages of being able to apply in patients who cannot open their mouth, showing teeth, mandible and maxillary and a large part of other facial bones together, having a much lower radiation dose compared to full mouth periapical films, and completion in a short time (Orhan and Aksoy, 2015).

Panoramic radiographs are frequently used for orthodontic diagnosis and treatment planning. Panoramic radiographs provide an extensive examination of the patient's temporomandibular joint, including all maxillary and mandibular arches. These radiographs can be used to detect dental anomalies, to detect hypodontia and supernumerary teeth, and to evaluate impacted teeth. (Graber 1967; Altug and Erdem, 2007). Panoramic radiographs can also be used to detect variations in root morphology and resorption (Apajalahti and Peltola, 2007). Diagnostic features of panoramic radiographs for the evaluation of skeletal pattern were evaluated by various researchers (Akçam et al., 2003; Nohadani and Ruf, 2008). Although some parameters were shown to be useful, their reliability was found to be low. Therefore, cephalometric radiographs should be preferred in determining the skeletal pattern. Panoramic radiographs are also helpful in assessing the quality and quantity of alveolar bone for placement of temporary anchorage devices (TAD) and implants, and in determining their distance to vital structures.

3. 3D imaging modalities

Three-dimensional (3D) imaging methods have found widespread use in orthodontics, as in other areas of dentistry in recent years. It has been frequently emphasized in previous studies that two-dimensional images are insufficient to reflect the three-dimensional cranial system. 2D imaging methods may be insufficient to reflect anatomical asymmetry, and errors in head positioning can cause distortion of the image (Hans et al., 2015). For example, while determining the "mandibular plane" used in cephalometric analysis, an imaginary plane is created by averaging the right and left lower borders of the mandible. Especially in such cases where bilateral structures are averaged, it is difficult to make accurate evaluation of the patient (Palomo et al., 2005). Therefore, 3D imaging modalities are becoming increasingly common in the visualization of both hard and soft tissue, in orthodontic practice.

3.1. Computed Tomography (CT)

CT was developed by Godfrey Hounsfield in 1972 and basically consists of a well-collated X-ray tube that produces a fan-shaped X-ray, scintillation detectors that measure the number of photons that pass through the patient, and orientation chambers. Since CT allows the imaging of normal and abnormal soft tissues and bone tissues, it is useful in the evaluation of temporomandibular joint (TMJ) diseases, the evaluation of syndromes and deformities associated with craniofacial region and the decision of treatment plan before maxillofacial and orthognathic surgery. Compared to conventional imaging methods, CT is advantageous for allowing the 3D examination of structures without superposition of surrounding tissues, having high contrast resolution which allows two tissues with different physical density to be separated more easily, having no distortion and magnification. Meanwhile, the need to use contrast agents to display soft tissues, high radiation dose, and reduced image quality due to the scattering in the image caused by metallic objects are considered to be the main disadvantages of CT imaging (Orhan and Aksoy, 2015).

3.2. Cone Beam Computed Tomography (CBCT)

The high cost and the high radiation dose of conventional CTs prevented their use in dentistry routine in spite of method's high image quality. Mozzo et al. (1998) introduced CBCT to overcome these disadvantages of CTs. Today, CBCT is frequently preferred as a routine clinical procedure because it takes up less space, its cost is much lower than CT and the radiation dose is less (Erten and Yılmaz, 2018). For CBCT imaging, instead of the fan-shaped X-ray used in CT, the cone-beam X-ray photons are used. The shape of the beam can be circular or rectangular. Unlike the multiple rotation used to obtain images in a spiral CT, a single 360º rotation is sufficient to display the relevant area in the CBCT. In this way, X-rays are used more efficiently, and 3D images are obtained with the use of much less X-ray components (Orhan and Aksoy, 2015).

Ionizing radiation is a known human carcinogenic factor and its biological effects are more important in young patients because of their higher radiosensitivity. Although the radiation dose to which the patient is exposed is much lower in CBCTs, indications for the use of CBCT should be well established in orthodontics, especially in the pediatric population. American Academy of Oral and Maxillofacial Radiology (AAOMR) (2013) stated that exposure of patients to ionizing radiation must never be considered “routine” and it is important to perform a thorough clinical examination prior to performing or ordering any radiographic study.

Oenning et al. (2018) introduced the DIMITRA (dentomaxillofacial pediatric imaging: an investigation toward low-dose radiation-induced risks) project and justified the importance to move from the principles of ALARA (As Low as Reasonably Achievable) and ALADA (As Low as Diagnostically Acceptable) to ALADAIP (As Low as Diagnostically Acceptable being Indication-oriented and Patient-specific). In this report, it is reported that CBCTs can be used for the evaluation of impacted and supernumerary teeth. Binita et al. (2010) stated that CBCTs can provide more detailed information in the initial diagnosis of pathologies such as impacted and supernumarary teeth than traditional radiographs. CBCTs may also be preferred in cases where it is necessary to determine bone quality and distance to anatomical structures such as placing temporary anchorage devices or evaluating orthodontic treatment results.

Another area in which CBCTs are used in orthodontics is the determination of root resorptions. Dudic et al. (2009) evaluated the resorption of 275 teeth in 22 individuals with panoramic radiographs and CBCTs. They concluded that apical root resorption after orthodontic tooth movement is underestimated when evaluated on panoramic radiography. CBCT can be considered as a useful diagnostic method compared to conventional radiography. There are many craniofacial anomalies that affect facial morphology and the development of the maxilla/mandible. In craniofacial syndromes, the response to treatment varies depending on the pathogenesis of the underlying anomaly. Another area in which CBCT is beneficial is the ability to display defects in detail in anomalies such as cleft lip and palate and provide detailed imaging of craniofacial morphology in the presence of the syndrome associated with cranial region (Garib et al., 2012;

Dalessandri et al., 2011). Depending on the superiority of CBCTs in hard tissue imaging, CBCT can be preferred to visualize the bone component of temporomandibular joint region such as glenoid fossa, condyle morphology, articular eminence (Sümbüllü et al., 2012; Ejima et al., 2013).

The upper airway affects the growth and development of the jaws. Determination of airway dimensions is limited in conventional 2D cephalometric images. Meanwhile, CBCT allows 3D visualization and volumetric analysis of the upper airway and provides reliable results (Zimmerman et al., 2019). In adults with skeletal incompatibility between the jaws, ideal treatment is orthognathic surgery. Especially in recent years, 3D imaging methods and softwares produced for this purpose have increased remarkably for orthognathic surgery planning and follow-up. Sharath Kumar et al. (2017) stated that 3D virtual head models are accurate and realistic tools for documentation, analysis, treatment planning and long term follow up for orthognathic surgery procedures and may provide a realistic prediction model.

With the introduction of CBCT in craniofacial imaging, it provided detailed/ 3D imaging and measurement opportunities in many areas of orthodontics. However, the accuracy of the measurements obtained from CBCT should be investigated when used in these areas. While investigating the accuracy and consistency of the linear and angular measurements of the CBCT, it was compared with the measurements made with the help of a skull caliper. Although there were minor differences in some measurements, it has been reported that cephalometric radiographs created from images taken with CBCT can be used instead of conventional methods (Van Vlijmenet al., 2010). Navarro et al. (2013) compared the manual, digital and lateral CBCT cephalometric analyzer. According to their results, all evaluated methods were reliable and valid, however, the lateral cephalograms from the CBCTs proved the most reliable. In another study, Cattaneo et al. (2008) aimed to compare conventional and cone-beam computed tomography generated cephalograms. They concluded that CBCT-synthesized cephalograms can successfully replace conventional radiographs. Many studies reported that CBCTs may be an alternative to conventional radiographs and are superior in many ways. However, when deciding on the imaging method, the simplest technique which providing the necessary information, but protecting the patient rom unnecessary radiation, should be preferred.

3.3. Magnetic Resonance Imaging (MRI)

MRI is based on the principle of creating a signal by inserting hydrogen atoms, which are densely present in water and adipose tissue, into a strong magnetic field by vibrating with radiofrequency (RF) energy (Oyar, 2008). The absence of ionizing radiation, taking images on any desired plane without changing the patient's position, and having a high soft tissue discrimination power have made MRI an important imaging method in medical practice. However, the technique's high sensitivity to movement, high cost of the imaging and the difficulty for claustrophobic patients was demonstrated as factors limiting the use of MRI. (Brown and Semelka, 1999; White et al., 2000; Könez, 1995).

The fact that different tissue densities can be displayed with high contrast sensitivity without giving ionizing radiation to the patient has extended MRI applications especially in the examination of soft tissues (Orhan et al. 2006; Ozbek et al, 2016). MRI is accepted as the gold standard in the imaging of the TMJ region along with the arthrography (Orhan et al., 2005; Orhan et al., 2006) (Fig. 4). The advantages such as high diagnostic quality of MRI in the TMJ region, being pain-free and non-invasive, and no ionizing radiation to the patient have allowed it to be used for the evaluation of spatial changes occurring in the joint area with functional orthopedic treatment (Ruf and Pancherz, 1998; Pancherz et al., 1999; Ruf et al., 2002; Cesur et al., 2020).

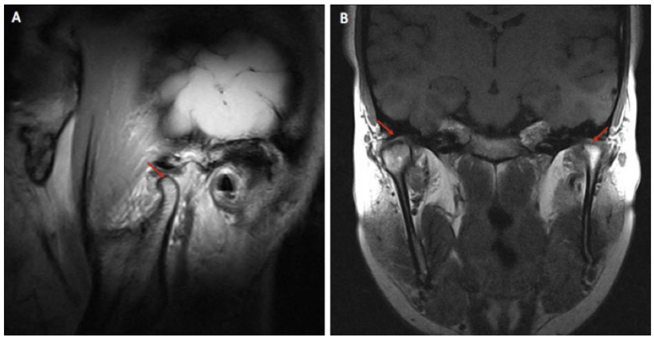

Fig. 4. Imaging of the TMJ region and mandibular condyle in sagittal (A) and coronal (B) sections on MR images

Method's high ability in soft tissue imaging also allows the visualization of masticatory muscles. Orhan et al. (2005) determined an increase in signal intensity ratio (SIR) in lateral pterygoid and temporal muscle activity in patients with disc displacement. Boom et al. (2008), on the other hand, examined the relationship between masseter and medial pterygoid muscle volumes and the vertical size of the face and stated that there was a strong correlation between these muscles and the posterior facial height. MR imaging of the masticatory muscles is exemplified in Fig. 5. Studies conducted in recent years revealed that, MRI also enables cephalometric analysis (Eley et al., 2012; Eley et al., 2013; Markic et al., 2014; Heil et al., 2017). Markic et al. (2014) compared the efficacy of panoramic radiography, cephalometric radiography, MRI, CBCT and CT using cadaveric human heads in evaluating the length of the mandibular ramus and condylar process, and reported that all 3D imaging methods gave similar results. Accordingly, the researchers recommended the use of MRI as it is non-ionizing. Eley et al. (2012) described a low flip angle gradient echo MRI sequence which provides high image contrast between bone and other tissues but reduces the contrast between individual soft tissues. This permits the ‘‘black bone ’to be easily distinguished from the uniformity of the soft tissues. They claimed that “Black Bone” MRI offered an improved method of cephalometric landmark identification over routine MRI sequences, and provides a potential non-ionizing alternative to CT for three-dimensional cephalometrics (Eley et al., 2013).

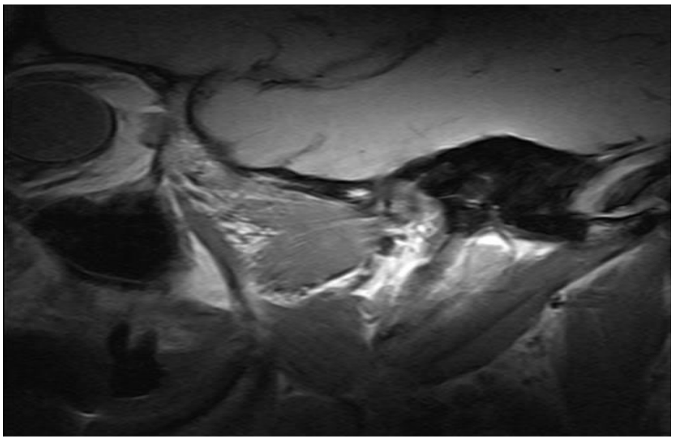

Fig. 5. MR imaging of the lateral pterygoid muscle in sagittal section

3.4. Ultrasound

Ultrasonography (USG) is an imaging technique that uses sound waves to examine soft tissue and parenchymal organs. This technique uses sound waves with frequencies well above the audible sound frequency (2-20 MHz). (Aldrich., 2007). Ultrasonography (USG) has been utilized in several areas of medicine. Recently, it has found use in dentistry for reasons such as being non-invasive, non-ionizing and enabling dynamic imaging. Although data on the use of orthodontics have increased in recent years, its use is still limited. USG can be used for purposes such as the evaluation of masticatory muscles (Close et al., 1995; Raadsheer et al., 1996; Bertram et al., 2001) (Fig. 6), the imaging of the TMJ region (Gateno et al., 1993) (Fig. 7), the evaluation of tongue volume and function (Shawker and Sonies, 1984; Wojtczak, 2012), the visualization of upper airway (Singh et al., 2010), the determination of soft tissue thickness at orthodontic miniscrew placement sites (Cha et al., 2008; Parmar et al., 2016), the evaluation of midpalatal suture (Sumer et al., 2012; Gumussoy et al., 2014) after RPE/SARPE procedures and the examination of changes in periodontal tissues (Zimbran et al., 2013).

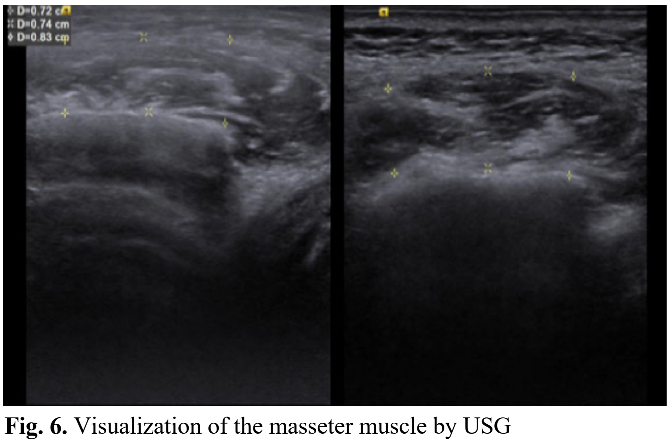

Fig. 6. Visualization of the masseter muscle by USG

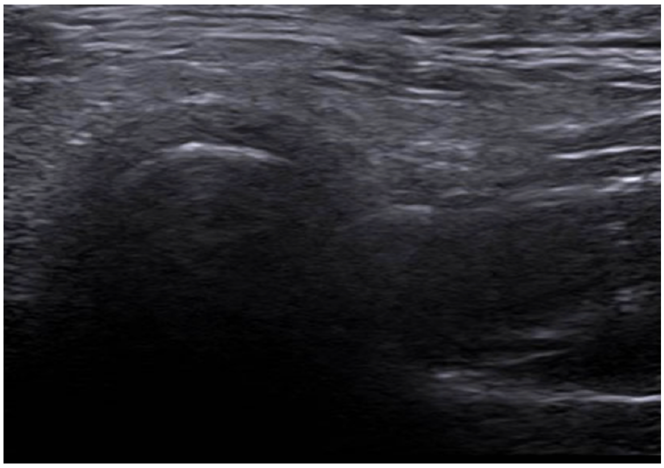

Fig. 7. Displaying the TMJ region by USG

USG is very useful in displaying the thickness and areas of the masticatory muscles and allows cross-sectional measurement of the muscles (Raadsheer et al., 1996; Close et al., 1995; Bertram et al., 2001). With USG, the length, thickness, cross-sectional area and volume measurements of the muscles can be performed (Durao et al., 2017). The most obvious disadvantage of the technique is that it allows only superficial muscles to be displayed. Therefore, ultrasound imaging of the lateral and medial pterygoid muscles is more difficult (Eren and Görgün, 2016). Another limitation of the technique is that the probe cannot cover the entire cross-sectional area of the muscle. For this reason, many researchers measured the ultrasonographic thickness of the muscles instead of the cross-sectional areas (Kliaridis and Kalebo, 1991; Raadsheer et al., 1994; Raadsheer et al., 1996). In addition to the evaluation of masticatory muscles, USG is also used for the evaluation of tongue thickness, volume and function. 2D USG imaging is used for tongue function evaluation such as swallowing and speech as well as for estimating tongue thickness, and tongue volume (Shawker and Sonies, 1984; Wojtczak, 2012). 3D USG is performed for the evaluation of tongue function (Bressman et al., 2005).

In orthodontic treatment, miniscrews, placed inside the alveolar bone, are especially useful in cases where anchorage is critical. One of the factors affecting the stability of miniscrews is the thickness of the surrounding soft tissue. Cha et al. (2008) and Parmar et al. (2016) evaluated gingival tissue thicknesses with the help of USG and concluded that evaluation of the gingival tissues could help in selecting a proper miniscrew in orthodontic practice. In the current literature, there are also studies showing that USG use in the evaluation of midpalatal suture after RPE or SARME in patients with transversal maxillary deficiency (Sumer et al., 2012; Gumussoy et al., 2014). Although the results of these studies showed that the technique could be useful in imaging midpalatal sutures, it had not been possible to obtain certain results.

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Review Article

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Digital imaging and dental record

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Abstract
One of the most important developments in the field of radiology is that the imaging process has started to take place in the digital environment. The advantages of digital radiography increase the interest of dentists in digital radiography, and nowadays digital systems are replacing conventional systems. The most important reasons for the increase of using the digital systems are the fast access to the image, the quality of the image, and the easy storage and transmission of the image. Nowadays, clinicians can digitize anything and recall it with the patient. This article presents a review of digital imaging and dental record. The history of digital imaging, direct and indirect digital imaging methods, digital sensors, and dental records were reviewed.

Keywords: dental records, digital imaging, image analysis, image processing

1. Introduction

1.1. The history of digital radiology

Digital radiography (DR) is considered one of the most important developments in the field of dentistry in recent years. DR systems consist of a conventional X-ray machine, a receiver (sensor or screen) instead of a film, and a computer with suitable software. A high-resolution monitor complements the system (Wenzel and Gröndahl, 1995). The first digital X-ray sensor used in dentistry was invented by Francis Mouyen in the mid-1980s (RVG, Trophy Radiologie, Croissy Beaubourg, France). The event that inspired the invention of dental intraoral sensors has been a challenge for Mouyen during his student years as he moved between departments for radiographic procedures during endodontic treatment (Farman, 2003; Farman, 2006).

1.2. Digital imaging system

Digital imaging includes X-ray interaction with electrons in sensor pixels, converting analog data to digital data, computer phase, and showing of the apparent image on a computer monitor. Data obtained by the sensor is transmitted to the computer in analog form. The computer operates on the binary number system that two digits (0 and 1) are benefited from represent data. These digits are determined as bits and they create words eight or more bits termed as bytes. The total number of bytes for 8-bit is calculated as 256 (2^8). The analog-to-digital converter becomes analog data to numerical data depending on the system of the binary number. The signal voltage is calculated and transferred a number from 0 indicating black to 255 indicating white based on the voltage intensity. The numerical assignation translates into 256 shades of gray. The eye of the human can determine about 32 gray levels (Bushong, 2001). Some digital systems sample the raw data with a resolution that is more than 256 gray values as 10 bit or 12 bit (van der Stelt, 2000).

When conventional radiographs are examined on a negatoscope, the structure of the different densities of silver grains is perceived by the eye as different layers of gray. In the digital system, many photosensitive small elements are used instead of silver halide crystals for image recording. Different gray layers are produced in the light emitted from the computer screen to reflect the image. In the analog image, while the silver grains are randomly distributed in the emulsion, the digital image contains a large collection of pixels (image elements) in an organized matrix of rows and columns. Since these picture elements are small, they cannot be seen with normal magnification (van der Stelt, 2000; Ludlow and Mol, 2004). There are some features required in a digital imaging system (Farman and Farman, 2005):

- The diagnostic quality of the generated image should be good
- The radiation dose used should be equal to or lower than

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the film

- Digital radiography techniques should be compatible with conventional X-ray devices
- It allows information flow within Digital Imaging and Communication in Medicine (DICOM) standards
- The time required for all operations must be less than or equal to the film

1.3. Digital sensors

Digital images can be obtained either directly or semi-directly using a detector or indirectly by scanning and converting an existing conventional radiograph into a digital image (Kamburoğlu and Paksoy, 2010).

1.3.1. Indirect method

In the indirect method, a film-based radiograph is needed. A device is used to scan or take a photograph of a film-based radiograph. A camera or scanner can be used for the indirect method. By using digital cameras, a digital image can be created directly. One disadvantage is that the camera may be handheld, and the camera shakes and poor-quality images may occur. This disadvantage can be avoided by using a tripod camera (Langland et al., 2002).

Scanners provide a fast and easy way of converting radiographs to images. The scanner passes a light beam through the radiograph to a chip termed as a charge-coupled device (CCD) CCD that converts the light to a digital image (Langland et al., 2002).

1.3.2. Directed method

In the direct method, films are not required. The digital image is obtained by the sensor (Langland et al., 2002). Direct digital systems are real-time solid-state detectors. Generally, direct digital systems use a CCD and complementary metal-oxide-semiconductor / active pixel sensor (CMOS/APS) technology. Semi-direct detectors are phosphor plates (photostimulable phosphor storage plate) (Whaites, 2002; Langlais, 2004).

Charged coupled device (CCD)

CCD sensor includes a sensor that is placed in the patient's mouth. A cable leads from the sensor to an interface, which is connected to a computer in the operatory. The CCD also includes a pixel array on a silicon chip (Dhir et al., 2014).

CCD is an integrated circuit that consists of a grid of small transistor components converting X-ray to an electron. When X-ray photons reach to transistor component, electrons are trapped in the wells according to the number of striking X-rays. The transistor is arranged in a grid formation. Each component describes as a pixel of the final image. After exposure, the components are read, stored electron charge is converted into brightness value and a digital image is formed (Langland et al., 2002).

The scintillation screen and fiber-optic plate made CCD thicker. Patient comfort reduced due to the thick sensor. However, the size of modern CDD sensors is similar to No.2 periapical film and has a thickness as lower as 3 to 5 mm (Langland et al., 2002).

Complementary metal-oxide-semiconductor (CMOS)

CMOS sensor is an option to CCD sensor and does not require charge transfer that increases sensor reliability and lifespan. Additionally, less system power to operate and lower cost is needed (Parks and Williamson, 2002).

Photostimulable phosphor plates (PSP)

Phosphor plates contain a barium fluor halide phosphorus layer. Repeatedly used plate, photon generated by X-ray absorption and stores its energy. The image plate is then scanned by a laser beam in a reader. The energy in the phosphorus layer is released in the form of light detected by a photomultiplier. Thus, the information is transferred to the computer and observed on the monitor (Akdeniz, 2000; Whaites, 2002; Langlais, 2004). To obtain the best quality images, it is ideal to scan phosphor plates in the first ten minutes. Plates should be stored in a light-tight environment if longer periods are to be expected and no scanning is possible within the first ten minutes (Akdeniz et al., 2005).

At least 50% of the radiation dose is required by using PSP than a film. Using a lack of film processing repeatedly and wide exposure range are important advantages. Another advantage of the phosphor plate is that it has film dimensions and is not connected to the computer by a cable (Langland et al., 2002). The PSP is placed in a plastic pouch to prevent oral saliva contamination and to control infection (Dhir et al., 2014).

1.4. Extraoral digital imaging

Extraoral digital imaging can be accomplished utilizing direct or indirect digital imaging systems. There are several panoramic systems available that use either linear array CCD or PSP plate sensors. The cost of the sensor, the time needed to capture the image data, and file size are all considerations that must be evaluated when considering a digital panoramic system. In either case, the method is like conventional panoramic radiography, but the receptor, processing, display, and storage differ from film-based imaging (Farman and Farman, 2000).

The PSP for extraoral imaging is a similar size to conventional film. There is an excessive costto produce an area array the size of a panoramic film using either CCD or CMOS. As a result, the trade-off is describing the smallest size of an array that can capture an extraoral image. The panoramic radiography design of the CCD or CMOS area array is less complex because of capturing only a small part of the image (Parks and Williamson, 2002).

1.5. The factors affecting digital image quality

The higher the visibility of anatomical and pathological structures on an image, the higher the quality of that image (Çağlayan and Harorlı, 2020).

1.5.1. Resolution

A quality image is provided by clearly showing the smallest structure that the system can view. Resolution is the capacity to distinguish two objects close to each other. The concepts of "contrast resolution" and "spatial resolution" are mentioned in digital images (Udupa et al., 2013; Harorlı, 2014; Hellén-Halme et al., 2016; Toraman Alkurt and Demirel, 2016).

1.5.1.1. Contrast resolution

Changes in anatomical or pathological structures create images of different tones and intensities due to different absorption of x-ray. The ability to distinguish different densities in the image is called "contrast resolution." (Udupa et al., 2013; Hellén-Halme et al., 2016). The contrast resolution of digital systems is higher than conventional radiography (Harorlı, 2014; Toraman Alkurt and Demirel, 2016).

1.5.1.2. Spatial resolution

Spatial resolution is the capacity to distinguish details in an image. It can also be defined as the ability to show two different structures standing side by side. The higher the number of distinguishable structures per unit area in an image, the higher the dimensional resolution of that image. When calculating the resolution, special test materials that consist of gaps of the same width as the radiopaque lines are used. In this test, a line and a space adjacent to it are called a "line pair" (Seely et al., 2008; Harorlı, 2014; ToramanAlkurt and Demirel, 2016). At least two pixels are required to analyze the line pair, one dark line, and one light line. Resolution is measured in units of line pair per millimeter (line pair / mm "lp / mm") (Çağlayan and Harorlı, 2020).

The thinner line pair a viewing system can separate, the higher the spatial resolution of that system. The resolution of periapical films (including E-group) is about 20 lp / mm (Mısırlı and Orhan, 2016). The resolution of the sensors varies between 7-27 lp / mm. The spatial resolution of phosphor plate systems values ranges from 10-21 lp/mm (Harorlı, 2014;Toraman Alkurt and Demirel, 2016).

1.5.2. Noise

These are changes caused by the imaging system that impair the image quality but cannot be completely prevented. Noise degrades the quality of the image, gives it a mottled appearance, and prevents low contrast objects from being seen. Since scintillation crystals equivalent to ranforsator are used in some digital systems, structural speckling that may occur in them is among the noise sources. Noise sources are divided into electronic noise and digitalization noise (Harorlı, 2014; Kaya, 2014; Özcan and Yurdabakan, 2017).

Electronic noise is the distortion created by all electronic components in the image (Harorlı, 2014; Kaya, 2014).

Digitization noise is the grayscale coding difference caused by the display of an image obtained with high bit depth in a low bit depth environment. For example, if an image obtained with 10 bits (1024 shades of gray) is displayed on a monitor with 8 bits (256 shades of gray), one of every four grayscale levels obtained will be distributed into grayscale in the display environment, and as a result, the image will be distorted. For this reason, systems should be designed at bit depths that are as high as possible, yet still compatible (Harorlı, 2014; Kaya, 2014).

1.5.3. Dynamic range

In digital radiology, the dynamic range determines the system's capacity to convert changing photon energies into images. Systems that can transform the information carried by photons with minimum and maximum energy into images are systems with a wide dynamic range (Harorlı, 2014; Toraman Alkurt and Demirel, 2016).

1.6. Image processing

Operations to improve, correct, analyze, or modify an image are known as image processing. The aim is to create more selectable images for the human eye or to obtain data by analyzing the image content (Mol, 2000). It is possible to obtain more pleasing images with subjective reinforcement. Nowadays many of the software packages offer image processing techniques. The selection of the appropriate one of these techniques is determined by the imaging model, diagnostic objective, and observation conditions (Analoui, 2001).

Diagnostic areas that clinicians expect to benefit from using image processing in digital systems are mostly the diagnosis of caries, periodontal and periapical lesions, and bone lesions. With the automation of the processing, a faster and more accurate diagnosis will be possible (Li et al., 2006).

When an image is captured, it is digitized, various computerized enhancements may be performed on the image. Density and contrast can both be changed. Density can be changed by adding or subtracting the same value to each pixel. Contrast can also be changed by a difference in the gradient of the gray level on the image. Other image enhancements are the inversion of the grayscale that can be explained by the displacement between black and white, magnification, and pseudocolor enhancement (Parks and Williamson, 2002).

Filters that smooth the image, eliminate high-frequency noise. Image sharpening filters eliminate low-frequency noise or sharpen by strengthening the boundaries between different intense zones (edge reinforcement) (Ludlow and Mol, 2004).

1.7. Image analysis

Image analysis operations are designed to extract diagnostically relevant information from the image which can range from simple linear measurements to fully automated diagnosis. An example of image analysis is the measurement of a distance in a digital image (Dhir et al., 2014).

Using automatic measuring tools, length, angle, and area calculations can be made on the digital image. The easiest way to do this is to specify measurements as pixel numbers. Another method is to use millimeters or inches as units of measurement. To convert pixel measurements to actual length measurements, it is necessary to calibrate the magnification factor of the sensor used (van der Stelt, 2005).

1.8. Advantages and disadvantages of digital imaging

There are some advantages such as 50-70% less radiation dose, decreased time between exposure and image acquisition, manipulation ability, clear diagnostic image, lack of radiograph chemical processing, and ease of electronically storing patient records (Lačević and Vranić, 2004). Disadvantages can be stated as size, shape, thickness, and rigidity of the sensor, lower image resolution, high cost, unknown use time of the sensor, difficulties for infection control (Miles,1993; Farman et al., 1995). The sterilization of CCD sensors cannot be done. Saliva contamination to the sensor and electrical cable should prevent cross-contamination (Parks and Williamson, 2002). During CCD use, mistakes and retakes of images may occur because of patient discomfort (Versteeg et al., 1998). Versteeg et al. (1998) reported horizontal placement errors, particularly in molar regions, and vertical angulation errors, in the anterior regions where the incisal area was cut off and not visible. 28% of CCD images were found as unacceptable and retakes were required compared to 6% for films.

2. Dental record

A dental record is a detailed document including the disease history, clinical examination, diagnosis, and treatment planning of a patient. Dentists are obliged by law to have sufficient dental records. With increased public awareness of the legal issues surrounding health care and increased concern for cases of malpractice, comprehensive knowledge of dental registration issues is required for any practitioner. The ability of clinical practitioners to produce and maintain accurate dental records is a legal obligation as well as quality patient care. A dental record provides continuity of care to the patient and is critical in the event of a claim for malpractice insurance (Lawney, 1998).

Comprehensive and accurate records are a vital part of the practice of dentistry. Good record-keeping is essential for good clinical practice and an indispensable skill for practitioners. The main purpose of keeping dental records is to provide quality patient care and follow-up. Dental records can also be used for forensic purposes (Charangowda, 2010). Teeth are less affected by physical and external factors than other organs and can maintain their shape and structure for a long time. Many studies have been conducted on the identification of teeth since they can often be found with the corpse, they survive more than other body tissues after death and show differences even in identical twins (Fischman, 1985; Agnihotri et al., 2008; Jayawardena et al., 2009).

According to the Australia Guidelines on Dental Records (2010);

- General principles;
- A dental record should be made during or after an appointment as soon as possible
- Entries on a dental record should be made in chronological order
- Entries on a dental record should be accurate and concise
- The dental records should be easily understandable by third parties (in particular another dentist). Access by third parties is subject to the application of the provisions of confidentiality legislation
- Dental records should be retrievable promptly when required
- Dental records should be stored securely and protected against loss or damage including the safe backup of electronic records
- Dentists should be aware of the local privacy laws governing the maintenance of records that must be kept for 7-10 years
- All comments should be in objective and non-emotional language
- Dentists should be aware of the requirements of the Board's Code of Conduct in 3.16 regarding the closure of an application. The rules require the transfer or proper management of all patient records according to the legislation governing health records in the jurisdiction
- Corrections to records should not remove the original information
- A dentist who conducts the treatment should not delegate responsibility for the accuracy of medical and dental information to another person.
- Determine patient details
- Information for the record;

1) Patient details

- Determine patient details
- Completed and current medical history, including adverse drug reactions

2) Clinical information

a) Accurate documentation;

- Visit date
- Descriptive details of the practitioner providing the treatment
- Information about the type of examination
- The patient complaint
- Patient history
- Clinical findings and observations

- Diagnosis
- Treatment planning and options
- Patient consent, client, or consumer
- All procedures carried out
- Instrument batch (tracking) control identification, where relevant
- A prescribed, administered, or given drug/drug or any other therapeutic agent used (name, amount, dose, instructions)
- Details of advice provided.

b) Unusual treatment sequelae
c) Radiographs and other relevant diagnostic data; digital radiographs should be easily transferable and available in high-resolution digital media
d) Other digital information such as CAD-CAM restoration files
e) Instructions to laboratories and communication with laboratories

3) Other information

- All referrals to other practitioners and other practitioners
- Any communication with or relating to the patient, customer, or consumer
- Details of dental record contributors
- Fee estimations or quotations (Australia Guidelines on Dental Records, 2010).

Most clinicians believe that record keeping is sufficient. There is an inconsistency between the dentist's perception of the adequacy of dental registration and the proposed structure and guidelines. When pieces of evidence from studies in the United States, Australia, Scandinavia, and the United Kingdom are examined, it is true. It has been found that the basic clinical entries that may affect the delivery of basic dental care are lacking in many records. The frequency of enrollment for patients whose treatment is financed under government regulations is much worse than for patients whose treatment is privately funded (Osborn et al., 2000; Morgan, 2001). In the study of Osborn et al. (2000), it was reported that Minnesota dentists' perception of the sufficiency of their dental records, 85% of dentists expected their records were sufficient but, 9-87% of the time information was observed to be absent when compared with the American Dental Association (ADA) criteria. Astekar et al. (2011) reported that only 38% of the dentists in Rajasthan were aware of the importance of keeping dental records. Preethi et al. (2011) found that it was found that 21% did not keep any dental records and that only 12% maintained full dental records among dental clinicians in Chennai.

In the article reported by the College of Dental Surgeons of British Columbia (1996), dental records should be protected from unauthorized use or disclosure, even to family members, except where required by law or where the patient expressly consents to them in writing. All dental records must be safely stored and never left unattended. If an electronic system is used to enter patient records, a login name and password must be available to access the data. All original records of the patient are the exclusive property and responsibility of the treating dentist and must be in custody. If the patient is moved to a different dental office, a copy of the records should be transferred to the new practitioner.

Patients do not have the right to have original records. However, they have the right to access complete dental records and to have a copy, and the dentist is obliged to submit these copies, even in case of disagreements or fees (Devadiga, 2014).

According to the Records Management Code of Practice for Health and Social Care (2016), the retention period of general dental services records is 10 years. It has been reported to be reviewed and destroyed if no longer required.

3. Conclusions

Digital imaging is a powerful method for dentists with the features of being reliable and versatile. So, this technology expands the diagnostic and image-sharing opportunities of dental radiology (Dhir et al., 2014).

Nowadays, keeping patient records in dentistry does not meet the guidelines in many ways. If patient records need to be improved by adopting the transition to electronic record-keeping, the profession should seek to expand traditional record-keeping formats to overcome the practical problems of keeping dental records accurate and contemporary. Adopting the use of digital voice recording can provide an easily accessible and easy to use solution (Brown, 2015).

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Review Article

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Computer-aided dental manufacturing technologies used in fabrication of metal frameworks

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Abstract

Metal alloys have been used for many years as framework material of dental restorations. The conventional lost-wax and casting method, which was very popular in fabrication of metal frameworks, is now being replaced by computer-aided manufacturing technologies. Computer-aided manufacturing methods offer many advantages, such as standardization and quality in manufacturing, precise fit of restorations, and improved mechanical strength. Digital technologies used in fabrication of metal frameworks are simply classified as subtractive and additive computer-aided manufacturing systems, and each has their own subdivisions, which show differences in the used technology. This review summarizes computer-aided systems used in fabrication of metal frameworks in terms of use in dental practice, advantages, and disadvantages and provides clinical recommendations.

Keywords: computer-aided manufacturing, digital dentistry, metal frameworks, metal manufacturing

1. Introduction

The use of metal alloys as a framework under superstructure material has always been a choice for dentists due to their excellent mechanical properties (Kaleli and Saraç, 2017b). Manufacturing of metal frameworks in the professional sense first started with the introduction of the lost-wax casting method, which was adapted from the jewelry industry (Van Noort, 2012), and this old technology is still used for fabricating metal frameworks (Kaleli and Saraç, 2017a). However, casting of base metal alloys has some drawbacks. Casting process involves several time-consuming steps, of which each need technical sensitivity (Sun and Zhang, 2012). Moreover, cast frameworks may show some impurities within the structure, which negatively affect the mechanical properties (Willer et al., 1998; Pasali et al., 2018).

Dentistry is continuously evolving, and more and more dentist join to this field day by day, and dental laboratories have to use high performance manufacturing technologies to meet the commercial needs. With the introduction of computer-aided design and computer-aided manufacturing systems (CAD-CAM), a new era has begun in metal manufacturing. CAD-CAM systems simply work as follows: (1) the computer-aided impression (CAI) data, which is obtained by intra-oral scanners (IOSs) or laboratory model scanners, (2) is processed by the CAD software, (3) and then the final design is turned into a physical part by the CAM unit (Alghazzawi, 2016). This digital workflow has overcome the problems resulted from casting imperfections and have offered easier, faster, and more predictable manufacturing solutions as well as improved mechanical properties of metal frameworks (Sun and Zhang, 2012; Van Noort, 2012; Alghazzawi, 2016; Braian et al., 2018). The computer-aided manufacturing systems used in dentistry are classified as subtractive manufacturing technologies and additive manufacturing technologies, and each system has advantages and disadvantages when compared with each other (Van Noort, 2012; Alghazzawi, 2016). This review illuminates the current computer-aided manufacturing systems used in fabrication of metal frameworks (Fig. 1) in terms of manufacturing time, laboratory cost, ease of application, preferability, and clinical recommendations.

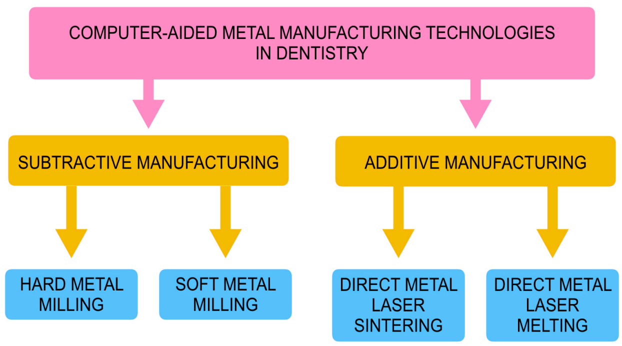

Fig. 1. Computer-aided metal manufacturing technologies in dentistry

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2. Subtractive metal manufacturing

Subtractive manufacturing is simply based on the milling technology, of which uses sharp cutting tools to cut solid metal blocks under the control of computer software. This technology reduces overall manufacturing time, and dental restorations with complex geometries, which are difficult to be made by using conventional workflow, could be easily fabricated (Van Noort, 2012). However, the accuracy of the milling process is limited by the diameter of the milling equipment (Örtorp et al., 2011; Bosch et al., 2014). Any surface detail smaller than the smallest milling bur, which is in the bur tool set, will be over milled and hence result in missed geometrical details in the final restoration (Alghazzawi, 2016).

The milling process of metal alloys can be either dry or wet milling, which depends on the alloy system (Alghazzawi, 2016). In the past, only fully sintered hard alloys (FHA) were used, which needed wet milling (Alghazzawi, 2016). The FHA blanks are fabricated under standardized conditions so that they lack structural defects, porosities, and residual stresses (Braian et al., 2018). Therefore, metal frameworks, which are fabricated by using FHA blanks, have high-level of structural homogeneity and improved mechanical properties (Willer et al., 1998; Braian et al., 2018). Titanium (Ti) metal blanks are mainly used for fabricating custom implant abutments and bars, whereas the cobalt-chromium (Co-Cr) metal blanks are mainly used for fabricating single or multiple-unit metal frameworks of fixed dental restorations (Alghazzawi, 2016). In particular, the hard metal milling provides improved fit in fabrication of full-arch implant-supported metal frameworks, which involves both teeth and gingival parts (Srivastava and Bidra, 2020). However, the milling of base metal alloys takes too much time and their hardness leads to rapid abrasion of milling tools, which increases the laboratory cost (Sun and Zhang, 2012; Krug et al., 2015; Park et al., 2016). As a solution, manufacturers have come up with new commercial manufacturing strategies (Park et al., 2016). Today, pre-sintered soft alloys (PSA) are available for fabrication of metal frameworks (Park et al., 2016; Kim et al., 2017; Pasali et al., 2018), and these wax-like metal blanks need dry milling (Stawarczyk et al., 2014; Alghazzawi, 2016; Park et al., 2016). The PSA blanks are manufactured by compressing Co-Cr metal powders under isostatic pressure (Lambert et al., 2017), and they can be easily milled with minimum abrasion of milling equipment (Krug et al., 2015; Park et al., 2016; Kim et al., 2017). Moreover, the manufacturing process is completed sooner when compared to hard metal milling (Krug et al., 2015; Park et al., 2016; Kim et al., 2017). Following the milling process, the PSA frameworks are sintered to full density under argon protective gas atmosphere, and this sintering process results in an approximately 10% to 11% contraction within the structure, which is similar to sintering process of pre-sintered zirconia restorations (Stawarczyk et al., 2014; Park et al., 2016; Kim et al., 2017; Pasali et al., 2018). Soft metal alloys may be considered as cost-efficient for metal-ceramic restorations; however, only Co-Cr soft metal alloys are available in the market. Therefore, they are not indicated for fabricating custom implant abutments and bar structures because of that titanium is the first option for custom solutions in implant-supported metal frameworks (Lambert et al., 2017).

Yet, subtractive manufacturing is a wasteful process because the amount of removed material is more than that used in the final metal product. Moreover, the subtractive milling technologies are not efficient in contouring of undercuts and complex internal geometries due to limited access of the milling tools associated with the size of milling burs and the working axis of the milling machines (Van Noort, 2012; Revilla-León and Özcan, 2017). Material waste and missing details associated with milling process can be minimized by using additive manufacturing methods (Van Noort, 2012).

3. Additive metal manufacturing technologies

The American Society for Testing Materials (ASTM) defines the additive manufacturing as the process of joining materials to make parts from 3D model data, usually layer upon layer (Van Noort, 2012). Unlike subtractive manufacturing, additive manufacturing strategies eliminate the waste of raw material and provides fabrication of actual parts, which have complex structural geometries (Sun and Zhang, 2012; Van Noort, 2012; Alghazzawi, 2016; Revilla-León and Özcan, 2017). Several additive manufacturing systems are used in dental applications; of these, laser sintering technologies stand out for metal manufacturing (Sun and Zhang, 2012; Van Noort, 2012; Revilla-León and Özcan, 2017). In the laser sintering system, the CAD data is segmented to multiple layers at micron level, and each layer is fabricated by using a high-power laser source that transmits the laser beams to the powdered metal particles on the surface layer and hence fuses them together. This process continues layer by layer until the fabrication of metal frameworks is completed (Santos et al., 2006; Sun and Zhang, 2012).

Laser sintering machines, which are used for dental applications, can be classified according to their melting method as follows: (1) direct metal laser sintering (DMLS), (2) direct metal laser melting (DMLM). DMLS is based on partial melting of metal particles, whereas DMLM is based on complete melting of metal particles (Ekren et al., 2018; Ucar and Ekren, 2018; Kaleli et al., 2019a; Kaleli et al., 2019b; Kaleli and Ural, 2020). The final product reaches higher density when the process is based on complete melting (Santos et al., 2006; Ekren et al., 2018; Kaleli and Ural, 2020). Regardless of the melting strategies, all metal frameworks are subjected to additional heat treatment in normalization furnaces, which is defined as annealing, after the fabrication process is completed (Revilla-León and Özcan, 2017; Tulga, 2018). This post-processing procedure provides improved ductility, relief from internal stresses, structural homogeneity. Although the duration and temperature range of the annealing process varies depending on the sintering parameters, alloy powder, and laser sintering machines (Tulga, 2018), a common point for all annealing programs is that the process should be conducted under protective gas atmosphere to decrease the interparticle distance and bilayer thickness (Ayyıldız et al., 2013; Tulga, 2018).

The laser sintering is conducted under control of several processing parameters, which affect the mechanical properties of final product. One of the important parameters is the layer thickness of sintering process (Kaleli et al., 2019a; Kaleli et al., 2019b; Kaleli and Ural, 2020). The laser sintering systems used in metal manufacturing generally work with the principle of powder-bed fusion. In powder-bed fusion system, the powdered metal particles are swept onto the build platform by the rake, which is a metal, ceramic, or polymer-coated bar. After the laser beam wave passed, the building platform is lowered, and a new layer is swept onto the build platform. This processing parameter simply determines how much metal powder will be swept onto the build platform between each laser wave (Sames et al., 2016). The layer thickness directly affects the manufacturing time. The duration of the laser sintering process considerably decreases when the layer thickness is increased (Sames et al., 2016); however, this brings up a new challenge. When the layer thickness exceeds a certain threshold, which is higher than the penetration depth of laser source, the "balling effect" may occur. This phenomenon is defined as "porosity" or "delamination" that causes a poor interlayer bond between the fresh powder and previously sintered layer (Gu and Shen, 2009). As for dental applications, the laser sintering process is conducted approximately with a layer thickness of 20 μm (Koutsoukis et al., 2015), and this cannot be further decreased because of that setting the layer thickness lower than 20 μm increases the porosity within the structure (Mazzoli, 2013). Another important processing parameter is the laser scanning speed, which is mostly under the operator's control (Kaleli and Ural, 2020). Increasing the laser scanning speed decreases the manufacturing time (Senthilkumaran et al., 2009); however, the linear energy density of the laser input decreases as well, and this results in a balling effect and transverse shrinkage distortion in the interparticle zone (Wang et al., 2007; Zhang et al., 2012). On the other hand, if the laser scanning speed decreases too much, the high energy of the laser input may cause rapid evaporation of the raw metal particles (Lu et al., 2017). Dental laboratories have their own manufacturing considerations, which are mostly based on cost and manufacturing time. Nevertheless, the best manufacturing strategy is to follow the manufacturer's guidelines.

The laser sintering is a cost-efficient and rapid manufacturing method for dental laboratories. Yet, one of the important disadvantages of this system is the support removal followed by finishing procedures. The laser sintered metal frameworks are fabricated on lattice support structures (Fig. 2), which prevents metal frameworks from deformation caused by gravity or growth stress (Sames et al., 2016).

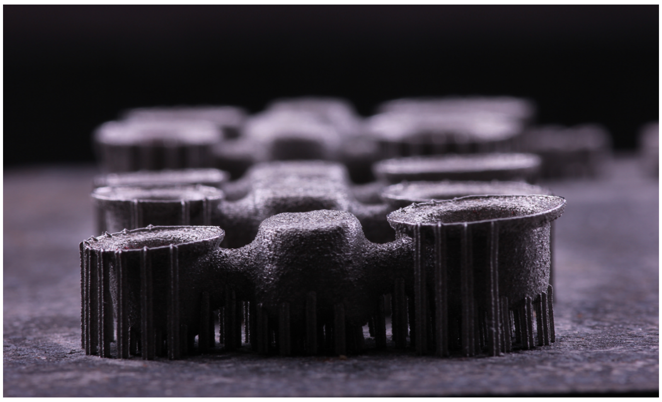

Fig. 2. Laser-sintered metal framework on lattice supports

After the fabrication and subsequent annealing processes, the supports are removed by using tungsten carbide burs. However, the computer-aided manufacturing continues with conventional manual manufacturing. Moreover, the raw metal powder undergoes rapid melting and then annealing, and these thermal processes may affect the adaptation of metal frameworks. Furthermore, the laser sintering systems are unable to create smooth or planar frameworks like milling technologies (Fig. 3). Therefore, laser sintering systems are not preferred particularly in fabrication of full-arch implant-supported frameworks or custom implant-supported solutions (Ciocca et al., 2019).

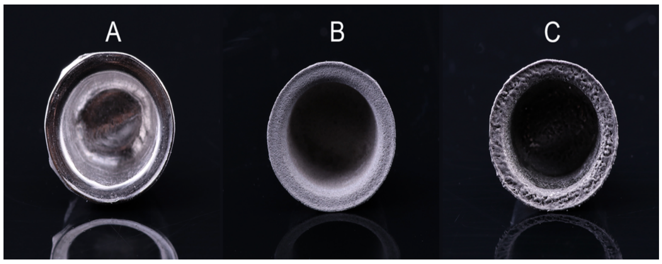

Fig. 3. Metal frameworks fabricated with different Computer-aided manufacturing technologies: hard metal milling (a), soft metal milling (b) and direct metal laser melting (c)

Recently, a new manufacturing solution, which is called hybrid manufacturing, has been proposed to fabricate implant-supported metal frameworks. In the hybrid manufacturing system, the main part of the metal framework is fabricated by using laser sintering machine, and the following finishing process is completed by 3D processing manufacturing machines using milling to refine the over-contoured areas. This new manufacturing strategy promises to combine the advantages of both laser sintering and milling technologies (Ciocca et al., 2019).

4. Conclusion

The clinicians should consider advantages and disadvantages of both subtractive and additive manufacturing methods, and they should select the manufacturing method according to the cases. Laser sintering technologies offer economical solutions when compared to milling technologies. Nevertheless, milling systems are more preferable in custom implant solutions. Using only one manufacturing system may not be efficient for all cases.

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Review Article

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Digital smile design as a communication tool for predictable clinical results: An update and review

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Abstract
Increasing aesthetic preferences and technological changes in dentistry have occurred over time, resulting in predictable, more aesthetic and more functional results. First, the development of digital dentistry, especially the CAD/CAM systems, following these developments, the ability to make smile designs with the effect of digitalization in anterior restorations led to the emergence of reliable and more guaranteed restorations for both the patient, dentist and dental technician. This review summarizes the information and offers suggestions with features to be considered in digital smile design and digital smile design software.

Keywords: dental aesthetic, digital dentistry, digital smile design, smile design software

1. Introduction

These days patients prefer dental and medical treatments for aesthetic purposes (Samorodnitzky-Naveh et al., 2007). While protecting the health, function of teeth and soft tissues in restorations made with conservative approaches in aesthetic dentistry, it is aimed to create a new smile with the most natural effect (Gürel, 2003; Iliev, 2016). The results of medical and dental anamnesis, clinical examination, photographs, and study models reveal a suitable diagnosis and treatment plan for aesthetic dentistry, but these are not enough to analyze the patient's smile. In addition, at the start of treatment, it is necessary to determine the relationship between the face, lips, teeth, and gingiva while accessing their function for predictable results with the final product (Coachman et al., 2017; Goldstein et al., 2018). For this purpose, Digital Smile Design software is a useful tool to show the possibilities of increasing the smile of the patient by creating an esthetic treatment scheme (McLaren et al., 2013). This software provides excellent communication between the dentist and the patient, while providing the dentist with an ideal means of communication with the dental technician by choosing the right treatment through algorithms. Dental process planning keeps a digital pathway so the patient can observe the outcomes before the process begins. These processes provide correct layout and guarantee aesthetic, functional and predictable results. (Moss et al., 2005; Ahrberg et al., 2016). At the same time, digital systems enable the dentist to follow-up and evaluate the patient during the treatment period (Mehl et al., 2013).

The aim of this study is to enlighten dentists about digital smile design parameters and current digital smile design software.

2. What is the smile design?

The smile design is the combination of aesthetic principles that make facial aesthetics compatible with the dentogingival structures (Davis, 2007). Or, more simply, it can often be described as the aesthetic treatment of anterior teeth in the visible aesthetic region (Zimmermann and Mehl, 2015). These aesthetic concepts were created with information gathered from cases, diagnostic moulds, photographic records, scientific dimensions, and fundamental aesthetic beauty principles (Davis, 2007).

The digital smile design starts with properly captured photos. It allows for a comprehensive workflow that simulates the patient's treatment process. Facial application is generally completed by applying guidelines which standardized parameters are improved for the front and profile look of the face. The process of designing a smile relates to various anatomic areas concerned in the process such as teeth, gingiva, mucous membranes, lips and skin based on symmetry, shape and golden ratios (Cervino et al., 2019).

3. Aesthetic concepts

The basic concepts for aesthetic analysis have been reported to be facial, dentogingival and dental aesthetics (Magne and Belser, 2010; McLaren and Culp, 2013). The American

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Academy of Cosmetic Dentistry mentioned the artistic parameters of the smile design in order to reproduce nature aesthetically (Blitz et al., 2001). Smile aesthetics is about color, shape, texture, tooth alignment, gingival contour, and their relationship with the face (Levin, 1978; Morley and Eubank, 2001; Frese et al., 2012). To plan a proper aesthetic rehabilitation, it is necessary to meet the expectations of the patients at the end of the treatment considering all these parameters (Meereis et al., 2016).

3.1. Facial features

Facial aesthetics are supported standardized aesthetic rules that include correct alignment, proportion and dimensions of the face (Davis, 2007). Facial examination is accomplished using guidelines in which standardized features are improved for the anterior and profile look of the face. Horizontal guidelines applied to the anterior examination comprises of interpupillary and intercomissural lines (Chiche and Pinault, 2004; Cohen, 2007). Vertical guidelines comprise of the facial, dental and mandibular midlines, which are very significant in defining the amount of symmetry of the face (Naini, 2011) (Fig. 1). The more symmetry between the right and left sides of the face is seen as a face closer to perfection. The dentist should visualize and record the vertical and horizontal lines to assess the existing symmetry on the patient's face. In the final assessment, it was stated that the relationship of the patient's face and teeth will be determined with this record (Calamia and Wolf, 2015).

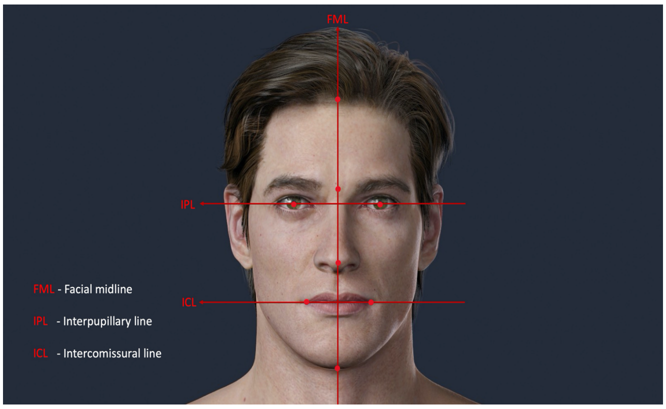

Fig. 1. Anatomical lines (vertical and horizontal guide lines) related to face using in digital smile design

Another important factor in facial aesthetics is lip dynamics. The upper and lower lips are the frame of the smile, which include the teeth and gingiva. Soft tissue markers of this frame are lip width, intercommissure width, interlabial space, smile index (width/height) and gingiva (Ackerman and Ackerman, 2002). The condition of the lips at rest should be analyzed in terms of lip structure during the lower and upper lip contact and smile, which determines to what extent tooth and gingiva appear. It has been reported that lip assessment can also be useful to reveal tooth and tissue asymmetries or defects (Blitz et al., 2001).

The lip line is an important determinant of the amount of visible incisal edge screen (Tian et al., 1984). In the absence of dental abrasion in the resting position, it has been reported that the visible incisal edge of the lips and maxillary central incisors should be 2 to 4 mm, and this distance may differ greatly depending on the age and gender of the patient (Vig and Brundo, 1978). In addition, for a nice smile, the smile line described as a fictional line figured throughout the incisal edges of the upper jaw front teeth is also an important factor. In optimal dental placement, this line should pursue the curvature of the lower lip (Ahmad, 1998).

3.2. Dentogingival features

Dentogingival features comprise of gingiva health and morphology like gingiva shape and contour, free gingival position, the position of the gingival zenith, color and pigmentation of the gingiva, position of the papilla, gingival line, buccal corridor dimensions, inflammation status, interdental papilla status and black triangle formation (Prato et al., 2004; Magne and Belser, 2010; Camare, 2010; Pawar et al., 2011; Nascimento et al., 2012; Priya et al., 2013; Patel and Chapple, 2015) (Fig. 2). A dentist should pay attention to these parameters while designing a smile. Designing the teeth within the limits of the gingival architecture significantly affects the aesthetics of the smile. Irregular papillary position on the anterior teeth or inflamed gingiva can have a dramatic effect on aesthetics. While some details may seem negligible, even a small black triangle can disrupt all efforts to create a beautiful smile (Batra et al., 2018).

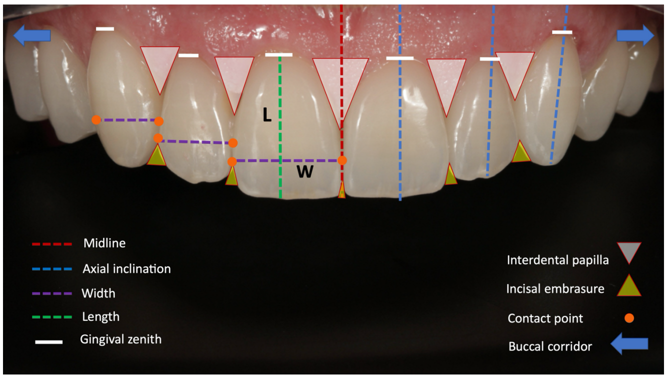

Fig. 2. Dental and gingival landmarks using in digital smile design

3.3. Dental features

The position, form, size and color of the maxillary anterior teeth are very important in terms of the aesthetic results of the smile design (Feraru et al., 2016). Some anterior teeth are in flatter form, while others are in a more convex form. Or some teeth have a rectangular look, while others have a more oval look. Different features such as these are indicative of the smile specificity of the patient (Dawson, 1974). It is considered by some researchers that the width of maxillary central incisors should be between 75-86% in length (Dickerson, 1996; Magne and Belser, 2003; Chu, 2007). The length of the teeth has also been reported to affect aesthetics. It is stated that the length of maxillary central incisors is between 10-22 mm on average (Magne et al., 2003). The midline identifies a vertical line shaped by the contact of the maxillary central incisors. It is asserted that the midline should be orthogonal to the incisal plane and concurrent or overlapping the midline of the face

(Miller et al., 1979). When viewed from the front, the axial inclination of the anterior teeth tends to incline towards the midline, making it more prominent from the central incisors to the canine teeth. It is very important in terms of appearance that the maxillary anterior teeth are proportional to each other. Many dentists accept and apply the Golden Ratio principles stated by Lombardi and then improved by Levin (Rufenacht Claude, 1990). With the ideal arrangement of anterior six teeth of these ideal sizes, an open space is formed between the contact points and the proximal surfaces of the incisal edges. This area is expressed as incisal embrasure. These embrasures end at the point where they touch the adjacent teeth. Incisal embrasures should show gradual improvement from the central tooth to the posterior (Wheeler, 1965) (Fig. 2).

In view of tooth color, there are four main features (value, hue, chroma and translucency) and features like structure and brilliance that could reform the impression of dental form and value (Culp et al., 2013). Color selection in smile design should be customized according to the satisfaction of each patient. It has been mentioned that informing the patient about the general rules for the natural appearance of the teeth and the color selection can also be favourable to meet the patient's hope in a realistic way (Blitz et al., 2001).

4. Esthetic rehabilitation

One of the most remarkable innovations in dentistry is the emergence of Computer Aided Design and Computer Aided Manufacturing (CAD/CAM) technology. This technology enables dentists to replicate from an anatomical and functional perspective and achieve remarkable results (Moss et al., 2005; Ahrberg et al., 2016). Digital dentistry includes high- and low-resolution data, 3D photos and various programs that allow dentists to collect data and create digital restorations and digital patients using various data (Ringer, 2007; Beuer et al., 2011). Digital Smile Design is one of these programs. Providing an effective communication between the patient-dentist-dental technician, the program is an excellent tool for correct detection of problems, visualization of possible solutions, and thus balancing expectations and increasing mutual trust. With the help of the photo protocols taken with certain parameters on the face, the dentist can identify and emphasize inconsistencies in face, dentogingival and dental morphology, discuss treatment options with magnified images on the monitor, and find the best solution (Fig. 3). Thus, by determining which material to use with the appropriate treatment option and communicating to the dental technician, both the treatment cost is reduced and time saving is achieved (Coachman et al., 2012; www.dentalphotomaster.com, 2020). In addition, it is possible to make comparisons between drawings and reference lines and before and after images by evaluating the results obtained at each stage of treatment (Goodlin, 2011; Coachman and Calamita, 2012; McLaren et al., 2013; Lin et al., 2015) (Fig. 4). In recent years, as technology advances, many software programs have been developed to be used in digital smile design for aesthetic rehabilitation. These software programs provide a stronger diagnostic and therapeutic predictability in the analysis of features that can be overlooked regarding the patient's face and teeth in clinical evaluation (Coachman and Calamita, 2012).

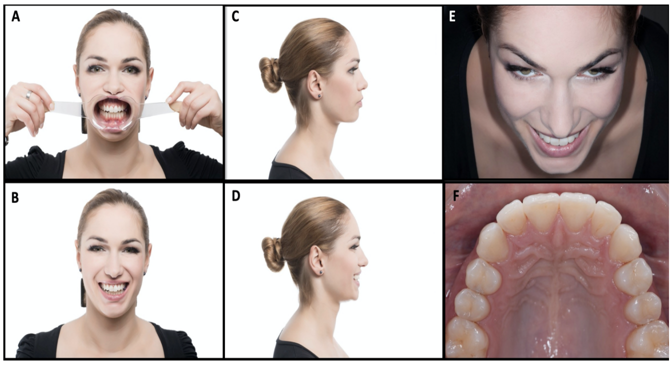

Fig. 3. Photo protocol for digital smile design. A: Front view with teeth retracted. B: Front view with full-smile. C: Profile with lips and teeth in contact. D: Profile with full-smile. E: 12 o'clock photo. F: Occlusal view of the upper arch. (www.dentalphotomaster.com, 2020)

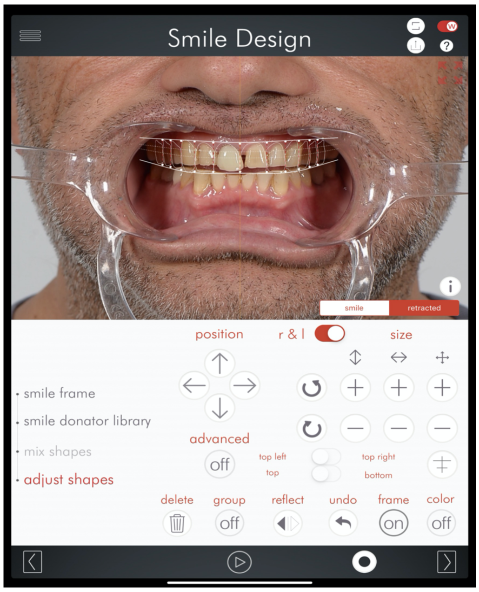

Fig. 4. It is possible to make comparisons between drawings and reference lines with softwares

5. Digital smile design software

5.1. Coachman (DSDApp LLC)

The DSD application was advanced by Coachman, who formerly announced research on using Keynote for digital smile design. Three photo views are required. Photos with full face and only teeth are taken, the first at maximum smile, the second at rest. Thirdly, a retracted full maxillary arch photograph is taken. In addition, at the same time, the video containing all feasible tooth and smile situations, including 45 degrees and profile views, are taken. Then the recorded photos and videos are added to the slide presentation. Smile designs can be realized in presentation software such as Keynote or Microsoft PowerPoint. This advanced visualization makes it easy to choose the ideal restorative technique (Coachman and Calamita, 2012) (Fig. 5-A).

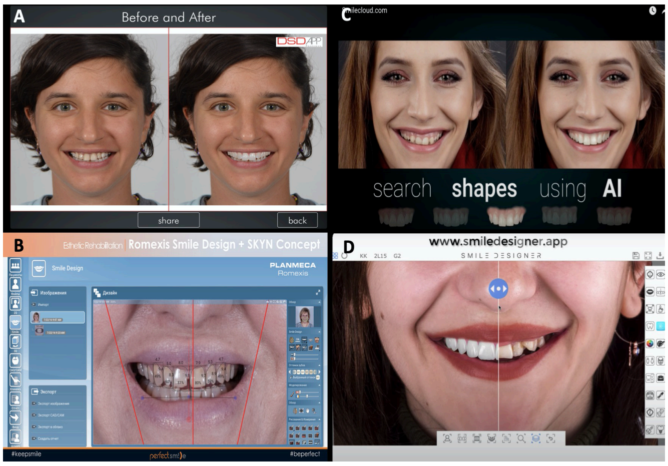

Fig. 5. Digital smile design softwares. A: Coachman (DSDApp LLC). B: Planmeca Romexis Smile Design (PRSD). C: Smilecloud, ADN3D Biotech. D: Smile Designer App

5.2. Planmeca romexis smile design (PRSD)

Planmeca Romexis Smile Design software, which was released in 2015 and gives the opportunity to make smile design in a very short time, does not need any extra supportive program to run on Windows and MacOS. First of all, when the patient smiles naturally, full face photographs are taken from the anterior region. The software then creates a tooth image with automatically determined W/L ratios. It is stated in the program that these tooth images can be edited for a maximum of 14 teeth and five different character types. In the software containing the VITA Classical and VITA 3D-Master tooth shades (Vita) in its library, the colors of the existing teeth can be defined and cooperated with virtual diagnostic wax-up thanks to a Color Picker tool (Zimmermann and Mehl, 2015) (Fig. 5-B).

5.3. Smilecloud, ADN3D biotech

Smile Cloud, a new cloud-based technology platform, gives users the opportunity to store patients' medical data, personal data, photos, videos, intraoral scanners (STL) or cone beam computed tomography scanners (CBCT), and radiographs. After the necessary loading is done, the artificial intelligence finds the proper shape of the teeth and aligns. The dentist can change this design if she/he wishes. It can also be used for the STL file for mock-up model, preparation and surgical guidance (Chen et al., 2020) (Fig. 5-C).

5.4. Smile designer app

Smile Design App, the online digital smile design software, uses the "Smile Design Algorithm" method coded quickly and easily. In this "Smile Design Algorithm" system, not only the face and teeth feature of the patient, but also information such as "which profession the patient has" or "character characteristics of the patient" are also recorded. It has been reported that the smile design for all CAD/CAM systems of this software can export PNG image output, the pre-designed STL outputs of tooth models can be printed with 3D printers (www.smiledesigner.app, 2020) (Fig. 5-D).

5.5. Smile designer pro

This digital smile design program, specially designed for use in the field of dentistry, needs additional photos as well as a front-face smile photo. The software, which has limited features in terms of front and profile aesthetic parameters, has been reported to have five ready-made templates for determining tooth forms and the software is similar to the Photoshop program in terms of design and interface (Zimmermann and Mehl, 2015; Omar and Duarte, 2018) (Fig. 6-A).

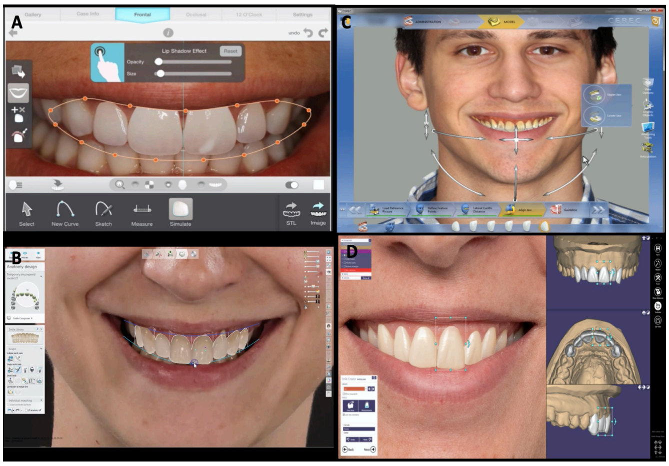

Fig. 6. Digital smile design softwares. A: Smile Designer Pro. B: 3Shape Smile Design (PRSD). C: Cerec SW. D: Exocad Smile Creator

5.6. 3Shape smile design

3Shape Smile Design uses the principles of Digital Smile Design (DSD) and a smile design is made directly over the 2-dimensional picture taken from the patient. The software allows the patient, dentist and dental technician to evaluate directly from the same photo, while technicians then transmit patient-approved smile designs to the 3Shape Dental System software to complete the procedures. In the system using the Real View engine, the 2D image is combined with the 3D digital image from the scanner. Before the completion of the restoration, the mock-up model can be produced upon the request of the dentist (www.3shape.com, 2020) (Fig. 6-B).

5.7. Cerec SW

It has been reported that Cerec SW software can control many steps and algorithms with artificial intelligence. Full face image is required for the software, which provides marginal compatibility of multiple preparations and clearer models. After uploading the file to the software, it was stated that 16 important points should be specified in the image. Then, after making various calibrations by the software using these points, the 2D image is converted to 3D. The Cerec Smile Design tool is located on the toolbar and can be activated during the CAD design process (Zimmermann and Mehl, 2015; Skramstad, 2020) (Fig. 6-C).

5.8. Exocad smile creator

With the Smile Creator integrated into the Chairside CAD platform, the photos taken using existing patient photos or webcams are automatically converted into 3D objects and then synchronized with 3D scans of the teeth. With the guided workflow and extensive library, it is stated that a smile can be created using 2D shapes and then it can be converted into 3D images (www.exocad.com, 2020) (Fig. 6-D).

6. Conclusion

Digital smile design is an instrument that can help the dentist from the first session to the last, provide an understanding of aesthetic problems, and produce reliable and predictable results for the trio of patient-dentist-dental technician. Using the digital software technologies, the dentist can evaluate the patient's anterior tooth region and include the smile analysis in routine treatment planning.

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Virtual articulators, virtual occlusal records and virtual patients in dentistry

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Abstract

Digital technology is broadly used in almost every part of medicine. As tools of digital technology, augmented reality and virtual reality have been adopted in all disciplines of dentistry and dental education. In particular, virtual articulators have allowed for a full analysis of occlusion with dental models that can simulate all mandibular movements in static and dynamic positions. When combined with additional software, virtual articulators can also enhance education and practice, allow for quicker and more precise individualized diagnoses and enable discussions of dental treatment planning options with patients during their first appointment. This article reviews the requirements for virtual articulators and occlusal recordings and assesses their advantages and disadvantages in various aspects.

Keywords: augmented reality and virtual reality, virtual articulator, virtual dental education, virtual occlusal record, virtual patient

1. Introduction

Over the last few decades, newly developed technologies have revolutionized the world of dentistry and paved the way for exciting developments. For example, virtual reality's applications in dentistry are still being developed but have already resulted in many advances (Patzelt et al., 2014). Virtual reality is a simulation of actual reality that generates an artificial place to replace the real world. Technologies and equipment that are created in virtual environments but have real-world applications are called 'virtual reality technologies and equipment'. The applications of virtual reality in clinical and laboratory procedures have had an impressive influence on research, development and industrial manufacturing and have provided better education and training to dental students by simulating real-word situations through a combination of virtual articulators, computer-aided design, and computer-aided manufacturing (CAD/CAM) technologies, digital face bows, visualizations and virtual dental patients (Bisler et al., 2002; Bhambhani et al., 2013).

'Single visit dentistry' is the most important concept in current practice for patients and dentists. Thanks to newly developed CAD/CAM technologies, a digital impression can be made and a restoration designed in a computer in a few minutes, then milled from a block in an hour. However, with the restricted accuracy of the interocclusal relation in a mechanical articulator, these restorations are merely static designs that have to be adjusted in the mouth or in the articulator during the functional movements of the mandible, and even semi-adjustable mechanical articulators cannot redesign the occlusal surface of a restoration accurately and precisely while mandibular motions are occurring in real time. These problems can be resolved by using a virtual articulator instead of a mechanical articulator (Solaberrieta et al., 2009).

2. Selection of articulator

An articulator is an important factor in patient outcomes that requires the dentist's full skill and care. In this sense, which type is selected has a direct impact on the efficiency and success of removable and fixed prostheses, as well as other dental practices. Most articulators are used to demonstrate only the intercuspation relation in a static situation, like a hinge. However, the mandible does not work like a simple hinge. Even its rotational movement takes place in three planes: sagittal, frontal and horizontal. Parameters such as condylar angle, Bennett angle and immediate side shift should be adjusted as they would be with a mechanical articulator. Under these adjustments, the occlusal surface design of any prosthesis in the mouth must allow for free space between the opposite tooth and prosthesis in order to avoid collisions. It is crucial to control the occlusal interferences and premature contacts, since these issues may result in serious pathologies. Using fully adjustable articulators can prevent this problem since they can simulate all mandibular motions with a high sensitivity. However, rehabilitating teeth using this type of articulator not only costs time, but also requires extra skill on the part of both the dentist and dental technician (Hobo et al., 1976; Pandita et

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al., 2016).

2.1. Mechanical dental articulators

The first mechanical articulator was described in 1756. Ever since, hundreds of articulators have been contracted and used (Mitchell and Wilkie, 1978). Mechanical articulators simulate the movement of the mandible and the temporomandibular joints. They are the most important devices for both dentists and dental technicians, because they are commonly used in the production of dental prostheses, as well as in the diagnosis and analysis of the occlusal relationship (Fig. 1).

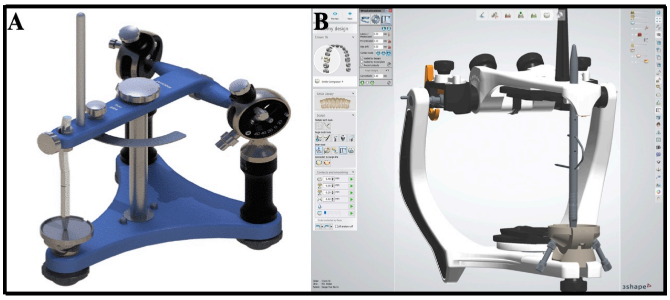

Fig. 1. a: Mechanical dental articulator, b: Virtual articulator

However, they have many restrictions. For example, the dynamic interrelation of the jaws cannot be demonstrated by a mechanical articulator during the chewing process. In addition, time-dependent muscle-guided movement patterns, the resilience of the soft tissue and the real border structure of the mechanical joint cannot be recorded sensitively during chewing (Mitchell and Wilkie, 1978; Solaberrieta et al., 2009). However, with the time-consuming measurements and more complex tool as the axiograph, individual occlusal parameters like protrusive and lateral movements can be recorded (Solaberrieta et al., 2018). Furthermore, comparatively location of occlusal plane can be transferred by using face bow. Mechanical articulators also cause numerous problems during dental technical procedures because of their dental material quality leading to deformations of the plaster and bite registration materials. These problems restrict repositioning the casts into the right bite position and tooth mobility cannot be transferred by a cast. Because of these restrictions, a real dynamic occlusal relationship cannot be established with a mechanical articulator (Gugwad et al., 2011; Maestre-Ferrín et al., 2012; Shadakshari et al., 2012; Singh et al., 2014; Koralakunte and Aljanakh, 2014; Luthra et al., 2015).

2.2. Virtual dental articulators

Virtual dental articulators use a computer program called a 'software articulator' (Fig. 1). Thanks to their visualization and simulation of all mandibular movements, they have led to more and more virtual reality applications in dentistry, particularly in regard to the analysis of complex dynamic and static interocclusal relations against each other (Bisler et al., 2002). Combined with CAD/CAM technology, virtual models are obtained and utilized for both the diagnosis and treatment planning of prosthetic rehabilitation, ranging from a single crown to complex cases involving full mouth rehabilitation, and clarify the process from the initial step to the final result of the treatment. When these factors are taken into consideration, this system offers great advantages not only for prosthetics, but also for orthodontics and dental implant surgery because of its precise measurements. For example, it allows a dentist to replace fragments of jaw bones and fix them into the correct position, realign teeth, create a smile design using artificial optimized teeth, detect and prevent occlusal collisions and analyze the morphology of a patient's teeth (bruxism) by means of dynamic monitoring in three dimensions (3D) of the mandible, maxilla or both (Ryakhovsky and Ryakhovsky, 2020). Using this technology, a dentist can also monitor dynamic movements and make specific observations about areas of concern, such as the motion of the temporomandibular joint (Maestre-Ferrín et al., 2012). Virtual articulators can also be used in education to teach students about the function of the articulators, the different movements of the lower jaw, the intermaxillary relations and their influence on the occlusal surface (Sabalic and Schoener, 2017).

2.3. Evaluation and classification of virtual articulators

Two main types of virtual articulators exist: 'mathematically simulated articulators' and 'completely adjustable articulators'

2.4. Mathematically simulated articulators

This type of articulator, which was first designed by Szentpetery, depended on a mathematical simulation of articulator movements (Szentpétery, 1997). This device enables a dentist to reproduce the movement of a mechanical articulator, making it a fully adjustable 3D virtual articulator (Luthra et al., 2015). Furthermore, mathematical simulation supplies measures that are not obtainable with some mechanical dental articulators, such as condyle angle, Bennett angle, and movements of retrusion, laterotrusion or protrusion in the setting. With these measures, the articulator automatically simulates the movement of the mandible, like a mechanical dental articulator would (Mitchell and Wilkie, 1978; Solaberrieta et al., 2009). These properties make the mathematically simulated articulator far more versatile than a mechanical dental articulator. However, because of the mathematical approach, an average value is used like in the mechanical dental articulator. Consequently, the individual movements for each patient cannot be tracked easily. Examples of mathematically similar articulators include the Stratos 200 (Ivoclar Vivadent; Amherst, NY) and Szentpetery's virtual articulators (Fig. 2). (Gugwad et al., 2011; Koralakunte and Aljanakh, 2014; Bhayana et al., 2015).

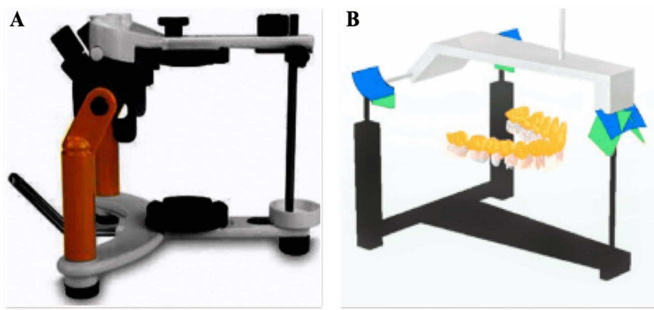

Fig. 2. a: Stratos 200, b: Szentpetery's virtual articulators

2.5. Completely adjustable articulators

These articulators were first designed by Gaertner and Kordass and can record and reproduce the precise movements of the lower jaw using an electronic jaw registration system called the 'Jaw Motion Analyser' (JMA) (Fig. 4). This system consists of a basic unit, lower jaw sensor, head bow, bite fork and sensor pen (Gärtner and Kordass, 2003). Its components transmitter and receiver are mounted in the correct position by means of the sensor. The head bow has eight ultrasonic microphones transmitters that make continuously pulse and calculates the pulse between the transmitter and receiver microphone via the triangulation method to determine the location of the patient's mandible (Koralakunte and Aljanakh, 2014). The working procedure is as follows. First, the software should be installed, and the device should be connected to the computer. Next, the clinician should fix the bite fork to the mandible, then place the head bow device on the patient's head and the face supporter on the patient's nose. The patient's TMJ and infraorbital notch should be pointed by a sensor pen following the manufacturer's instructions. Finally, the mandible sensor should be connected to the bite fork. The device will then track the movement of the mandible identifying issues such as retrusion, protrusion and laterotrusion. These movements will then be converted to numbers that can be used to program a fully adjustable articulator, such as KaVo Protarevo 7 (KaVo Dental GmbH), SAM 2 (SAM Prazisionstechnik GmbH), Artex CR (Amann Girrbach AG) or Stratos 300 (Ivoclar Vivadent; Amherst, NY) (Fig. 3).

Fig. 3. a: KaVo Protarevo 7, b: SAM 2, c: Artex CR, d: Stratos 300

In addition, certain movements of the mandible can be exported to a CAD system through XML-files. Mandibular movements along the dental arch can then be viewed by the software, and the same motion can be monitored from different planes by three computer screens. Thanks to the CAD system, this software can visualize and calculate the kinematic and static occlusal collisions and determine the necessary corrections when redesigning the occlusion. Combined with 'Dent-CAM' (Comp. KaVo, DLeutkirch), the software for virtual articulators, which was developed at Greifswald University (Fig. 4), displays the mandibular movement and slice window with three basic screens: the interpretation screen, occlusion screen and section screen. All of the screens show the same motion pattern in different views to highlight various aspects of the motion and allow for analysis:

a. Rendering screen: Premature contacts and occlusal collisions can be analyzed in this screen during the mandibular motion. For instance, the surface of the teeth and interrelation of the teeth can be analyzed during mastication using this screen.

b. Occlusion screen: Occlusal contacts between the maxilla and mandibular teeth can be watched as a function of time.

c. Section screen: Various frontal aspects can be watched along the dental arches. A series of frontal aspects are demonstrated throughout the dental arch (Kordaß et al., 2002). In addition, the interrelationship between the upper and lower teeth, shape of teeth and height of the cusp can be used to examine the intercuspidation and the height and functional angles of the cuspids.

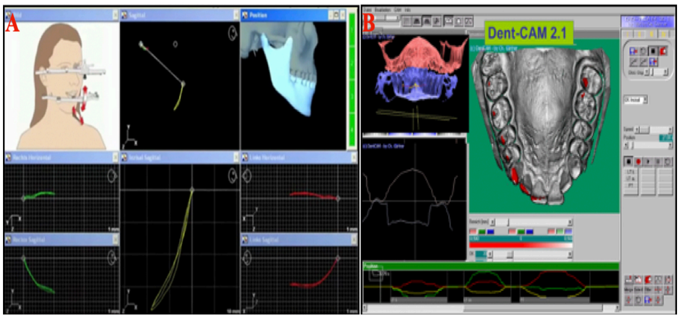

Fig. 4. A: Jaw motion analyzer, B: Dent-CAM

With the addition of a module to this software, the condylar trajectories can also be analyzed in the horizontal and sagittal planes within a virtual setup. Thanks to this module, the interrelationship between the incisal guidance and the condylar guidance, the impacts of TMJ mobility on the surface of the teeth and the occlusal collisions in both static and kinematic situations can also be analyzed (Bisler et al., 2002; Kordaß et al., 2002; Park, 2017). However, this system also has drawbacks. First, it requires the use of special devices, such as a mandibular motion-tracking system. Second, it lacks a universal digital format to save the movement of the lower jaw. Thus, this system cannot be used with some virtual articulator software package (Park, 2017).

2.6. Modjaw

This system uses optical scanning to record all mandible movement without information from a CBCT. By merely capturing jaw movements, kinematics of patient is modelled. Modjaw has been developing itself, including dynamic visuals of model in 3D and 4D automatic calculation of occlusion parameters such as Spee curve, Bennett Angles, condylar slopes etc., creating dynamic map of test contact (Solaberrieta et al., 2018).

2.7. Freecorder BlueFox

Freecorder BlueFox is an optical measuring method. Optoelectronic registration device is utilized to register all jaw movement and the individual mandible position. The ultralight carbon reference bow is placed on the ears and it is fitted to the nose's bridge. Other light modular arch is fitted to the mandible to capture its movement. Thanks to special cameras, high resolutions are obtained by capturing 100 times per second. Simple control by computer monitor or touchscreen monitor. The movement information and position information can be integrated in XML that enables date export and import (Dai et al., 2016).

2.8. ARCUS digma

With ARCUS digma, the jaw movements can be simply and quickly detected by using ultrasound transmission. Four microphones adopted a bow is fixed to head and a support with three pingers is set on the jaw. This system offers mandibular movement analysis, 3D comparison of arbitrary occlusal positions temporomandibular joint diagnosis and also analysis of muscle activity (EMG) (Lippold et al., 2008; Sójka et al., 2017).

2.9. Planmeca 4D jaw motion

Planmeca 4D jaw motion system is CBCT integrated solution for recording, tracking, visualizing, and analyzing jaw movements in 3D. It offers visualization creating a fourth dimension in diagnostics. Integrated Planmeca ProFace camera are used to track mandible movements in relation to the maxilla. It records the movement and position of eight spheres. Half of them is integrated to a glasses and another to a bow. Movement of skull is defined by glasses position. The bow is fitted to lower arch detecting relative distances. Combined with its X-ray system, mandibular movement can be copied by the software (Solaberrieta et al., 2018) (Fig. 5).

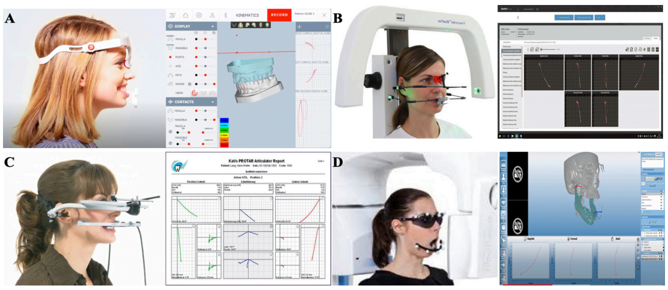

Fig. 5. A: Modjaw, B: Freecorder BlueFox, C: Arcus digma, D: Planmeca 4D jaw motion

There are several jaw movement tracing systems. Each of them has been improving their function, software and integration with CAD software. Tracking plates, brackets attached to teeth or modular arches are used to indirectly record the movement of mandible. Denture and dental cast ought to be scanned twice to reproduce mandibular movements, initial separately and second, with the fixed attached elements. The former one captures the teeth surface and the latter makes the relative interval from the references to the teeth. Hence, after getting the references, the registered movements and the relative distance, the mandibular arch can be reproduced. Initial positions of the mandible and skull need to be fixed and measured even as recording merely relative positions. Even this measurement could be done at any time of motion capture. Each system uses special software package which enables the processing the data. However, in some instances initial measurement can be taken to use it as reference. Registration of mandibular movement for dental diagnosis, planning and treatment (Solaberrieta et al., 2018).

2.10. Data registration for virtual articulators

Intraoral scanners (IOS), which are devices that take a digital impression of a patient's teeth, represent an important advancement in virtual technology within dentistry. Two different systems are available. The first one, a photographic technology scanner system, records individual images of an object. The other one, a video technology scanner system, works similarly to a video camera recording at high speed. During the first stage of using an IOS, such as the Laser Scan 3D (Willytec, Munich, Germany), an image of the occlusal part of the teeth, of the whole dental arches, and of the interocclusal relations are taken. After scanning, the collected information is converted to digital data and sent to the electronic processing system. Digital data are compiled by the software program, then the image is visualized on the computer screen where it can be manipulated (Fig. 6). (Gärtner and Kordass, 2003; Abad-Coronel et al, 2019).

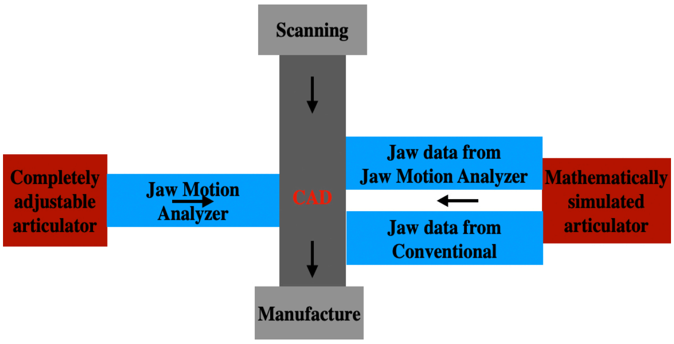

Fig. 6. Schematic diagram of integration of data

2.11. Virtual occlusal record

Virtual articulators are designed to mimic the function of mechanical articulators and require a patient's information to be inputted into dental digital design software. Virtual environments allow one to examine static occlusal and proximal relationships. Therefore, studies have analyzed clinical achievements using static digital articulation. Some studies have compared virtual and mechanical articulators at the maximum intercuspation position using contact point patterns.However, specific patterns of mandibular movement, such as protrusion, laterotrusion and retrusion were not set in depth and the researchers did not analyze the effect of alterations to these setting parameters, consequently leading them to the conclusion that there is no significant difference between virtual and mechanical articulators (Gärtner and Kordass, 2003; Yee et al., 2018a, 2018b) Others used 2D and 3D software to superpose and evaluate distortions in the data from virtual models, but only at the maximum intercuspation in a static position. Thus, within these studies, both systems are comparable and result in acceptable accuracy (Wriedt et al., 2013; Solaberrieta et al., 2015; Arslan et al., 2017).

It is widely accepted that there is no significant difference between virtual and mechanical articulators in a static position, but this assumption cannot reflect reality. For example; the mandible is a mobile bone and dislocates inferiorly, anteriorly and posteriorly, and virtual articulators have far more advantages in anticipating and dealing with these problems. Virtual articulators have special devices, such as JMA, for recording the specific movements of the lower jaws of patients; in addition, these movements can be recorded in an animation (Kusnoto and Evans, 2002; Quimby et al., 2004; Fleming et al., 2011; Cuperus et al., 2012; Sweeney et al., 2015). Accuracy and precision are important criteria for these systems. While accuracy is defined as how close the measurements are to the accurate value of the original sample, precision refers to the degree of reproducibility or the agreement between repeated measurements (Ziegler, 2009; Ender and Mehl, 2013; Güth et al., 2013; Atieh et al., 2017).

The dynamic motion of the mandible is affected by many specific factors for each patient. Therefore, user-defined settings, such as sagittal condylar inclination (SCI), immediate lateral translation and lateral condylar inclination, should be transferred from a mechanical articulator to a virtual articulator, depending on the classification and type of the virtual articulator (Fig. 7) (Szentpétery, 1997; Gärtner and Kordass, 2003).

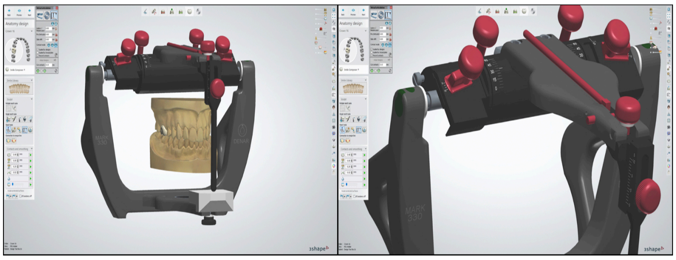

Fig. 7. Denar Mark 330 articulator

This process is important for increasing the accuracy of the diagnosis and treatment planning (Solaberrieta et al., 2015). Regarding the accuracy and the precision, many studies have compared the virtual occlusal record to the mechanical one, and while there is no significant difference in static relation, there is also no sufficient information on the dynamic relation (Hsu et al., 2019).

2.12. Advantages and disadvantages of virtual articulators

Advantages:

- Give rise to better communication between the dentist, dental technician and patient
- Work with CAD/CAM systems to design the occlusal surface
- Examine not only the static but also the dynamic occlusion
- Analyze the gnathic and joint conditions
- Eliminate the problems caused by manufacturing and can visualize certain regions in 3D
- Simplify the procedures for the dentist and technician
- Are more time-efficient
- Simulate the real patient, helping to modify the restoration and educate the patient

Disadvantages:

- Lead to high purchasing and managing costs, because virtual articulators require supplemental technology, such as digital sensors, digital scanners, software and multiple articulator models that can mimic mechanical articulators based on the patient requirements
- Require technical information, such as date input, the recording scanner's data and motion parameters, and knowledge of mechanical articulators, CAD/CAM technology and software (Koralakunte and Aljanakh, 2014; Agnini et al., 2015).

2.13. Virtual patients in dentistry

Digital technologies have had a strong impact on almost every part of life, including dental medicine. Various software packages have directed clinical practices, education of dental students and laboratory techniques to virtual-based processes (Eaton et al., 2008). These softwares are of great importance in dentistry and are used in almost every department, including diagnosis, treatment simulation, training and all steps of patient follow-up (Luciano et al., 2009; Curnier, 2010; Dutã et al., 2011; Nkenke et al., 2012; Schoenbaum, 2012).

In general, diagnostic methods utilising virtual patients include cone beam computed tomography (CBCT), working casts, face scans (FS) and photography; recently, treatment concepts based on digital workflows with intraoral scanning (IOS), the rapid manufacturing of dental prostheses and computer-assisted implant surgery have also been adopted (Fig. 8) (Patel, 2010). In light of these developments, virtual dental patients (VDPs) that replicate the superficial surface of the skin combined with the underlying bony structures of the skull and teeth including the oral soft tissue layers are needed (Lee et al., 2012; Lin et al., 2013).

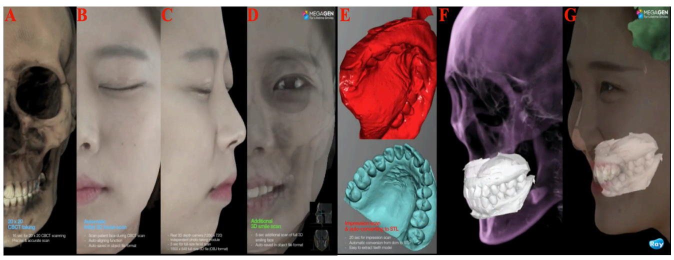

Fig. 8. A: CBCT, B-C: Frontal and lateral FS, D: Superimposing CBCT onto FS, E: Impression scan, F: Superimposing IOS onto CBCT, G: Superimposition of IOS + CBCT + FS

Virtual patients have many advantages:

- Make it possible to present the entire treatment plan in 3D to a patient

- Help with shaping the patient's expectations
- Allow for the creation of several alternative treatment plans
- Non-invasively simulate the progress step-by-step
- Support the cost-effectiveness of treatment by decreasing the number of patient visits, enhancing the doctor's productivity and the patient's quality of life
- Offer preoperative assessment and allow for a wide range of maxillofacial surgeries due to their high-precision anatomical documentation
- Streamline interdisciplinary communication between the dentist and dental technician
- Enhance student learning of the static and dynamic maxillofacial relationships (Yu and Brewster, 2002; Eaton et al., 2008; Ghanai et al., 2010; Kau, 2011; Orentlicher and Abboud, 2011; Sabalic and Schoener, 2017; https://www.r2gate.com, 2020).

Creating VDPs under static conditions requires digital data from various tissues to superimpose the 3D media gathered from IOS, CBCT, FS and the CAD/CAM systems. However, it is important to note that clinicians should combine different formats and files. In addition, these dataset superimposition techniques are not standardized; they are still experimental (Joda et al., 2018).

3. Conclusion

Developments in digital dental technology, particularly in virtual reality, have resulted in great advances in accurate and precise static and dynamic simulations in all disciplines of dentistry and in dental education. Thanks to this software, functional occlusion can be examined in different aspects, so that optimized restorations designed to avoid tooth surface collision can be manufactured. In addition, the simulations that are now possible allow students to transition from theoretical learning models to real patient situations. In the future, these systems should be enhanced with 4D technology in dynamic simulations. For these reasons, virtual reality has revolutionized dentistry and will continue to enhance dental practices for the foreseeable future.

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Review Article

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Direct digitalization devices in today's dental practice: Intra oral scanners

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Abstract

Rapidly developing technologies and new changes in modern dentistry have led to more effective solutions to be used in our clinical practice. The digital workflow includes some steps, such as data acquisition, digitalization, designing, and subsequently manufacturing by using digital devices. In this process, acquiring the images from patients' mouth, which is named computer-aided impression (CAI), is the first step of the digital workflow and named as digitalization. The need to skip many time-consuming intermediate steps and reduce the possibility of fabrication errors has made the digital workflow a popular choice for dentists and dental technicians. The popularity of intraoral scanners has increased rapidly since the 1980s. With the development of camera systems and software engineering, many companies have presented many different IOS devices, which are based on different software systems. This situation causes dentists to get confused due to the formation of a large data cluster. IOS devices are used to capture the digital data and they are an effective alternative to conventional impressions in many ways, such as increased patient comfort, time efficiency, hygiene, predictability, and precise results. Clinicians should have enough technical information about the IOS they use to obtain optimal results in fabricated restorations. The aim of this review is to evaluate the scanning technologies of intraoral scanners, their advantages, and disadvantages in clinical practice, scanning strategies, accuracy of scanning processes, and software protocols.

Keywords: CAD-CAM, digital dentistry, digital workflow, intraoral scanners

1. Introduction

The main goal of the dentistry is to provide an optimal treatment modality to patients. The modern dentistry still looks for new opportunities regarding with new challenges. The conventional workflow in restorative dentistry generally involves an impression process as the first step to obtain the data, and a model fabrication process as the subsequent step. Although this workflow has some disadvantages, such as dimensional stability and accuracy problems, conventional workflow is still used in routine dental practice. Nevertheless, rapidly developing technologies and new changes in modern dentistry have led to more effective solutions to be used in our clinical practice (Moörmann, 2006; Miyazaki et al., 2009; Persson et al., 2009; Chiu et al., 2020). The workflow, which includes the data acquisition, digitalization, designing, and subsequently manufacturing by using digital fabrication devices is called complete digital workflow, and this workflow is about to be used in routine clinical practice. Complete digital workflow is also defined as computer-aided design and computer-aided manufacturing (CAD-CAM) process, and this technology has provided a highly effective, predictable, and accurate workflow for our modern dentistry since it was introduced in 1980's. (Moörmann, 2006; Miyazaki et al., 2009; Persson et al., 2009; Chiu et al., 2020).

In this process, acquiring the images from restoration site, which is named computer-aided impression (CAI), is the first step for the digital workflow and named as digitalization. Intraoral scanner (IOS) devices used to capture the digital data, and they are an effective alternative to conventional impressions in terms of many ways, such as increased patient comfort, time efficiency, hygiene, predictable and precise results. Other advantages of intraoral scanners include real-time visualization, and objective and simple communication between patients and technicians. The use of IOSs to acquire digital images of restoration area has become a common modality for fixed prosthodontic treatments (Giachetti et al., 2020).

In the available literature, there are many studies comparing digital impression methods with conventional impression techniques as an alternative workflow. Since the digital impression systems offer improved reliability and reproducibility, their acceptance and popularity have increased (Punj et al., 2017; Chiu et al., 2020). With the rapid development of this technology, the number of dentists, who use digital technology in their routine clinical practice, has increased.

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The IOS devices mainly consist of three components: portable digital camera (hardware), computer, and software. The main goal is to obtain the surface properties of related area as 3D and precisely. Subsequently, the obtained data are transferred to a design software and the design process of the restoration begins. Although these devices generally use standard tessellation language (.stl) file format to transfer the data to the design softwares, some other file formats have been developed to obtain color and texture of dental tissues, such as polygon file format (.ply). These file formats are also used in other fields of industry.

The basic philosophy of the IOSs is transferring the surfaces into a point cloud. Subsequently, this point cloud is transferred into triangles connected to each other by the help of software (Richert et al., 2017). Each triangle can be defined as three points on surface. Regardless of camera type, all IOS systems require a light projection, which is recorded as images or capturing videos and compiled by specific software after recognition of POI (Points of interest). To detect these points, first two coordinates (x and y) of each point are calculated, and the final coordinate is calculated according to distance from the camera to the object (Ireland et al., 2008; Geng, 2011; Richert et al., 2017).

2. Scanning technologies of intraoral scanners

The technologies, which are used to capture the digital images of restoration areas, can be divided into five main categories:

Light Projection and capture

Passive and active techniques can be used. The active and passive classification mainly depends on the light, which is used by the IOS to detect surface properties. If the camera uses a light source, it is called as active, whereas if the IOS use only ambient lightening, it is called as passive (Fig. 1). White, red, or blue lights can be used. In active technologies, a luminous point of light is reflected onto the object and the distance is calculated by triangulation process (Taneva et al., 2015; Richert et al., 2017).

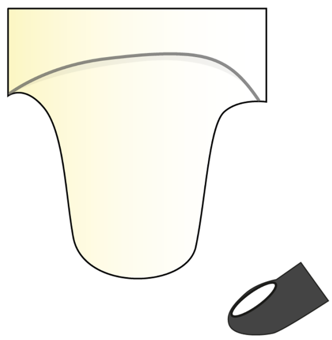

Fig. 1. Scanning tip that using light for image capturing

Triangulation

This philosophy mainly depends on the calculation of a point, which is a part of triangle that can be calculated when the other two points and angles are known. These two points can be detected by a double camera system, or a single camera system that uses a prism or other technologies (Fig. 2).

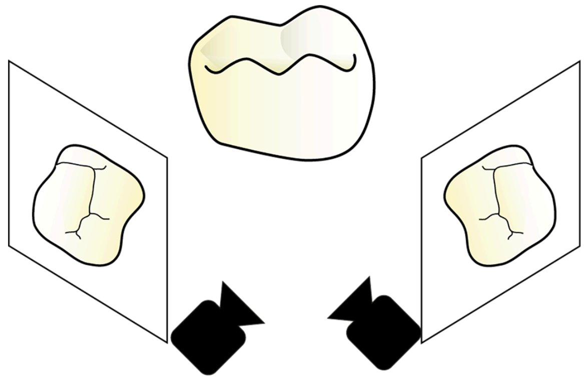

Fig. 2. Determining the distance of the object by using triangulation technique

Confocal technologies

Confocal technology works with the acquisition of focused and defocused images from selected teeth surfaces (Fig. 3). A successful digital impression and acquisition can be obtained by taken images with different focuses and aperture values from different angles of scanned region. This technology requires larger optics (Giménez et al., 2015; Richert et al., 2017).

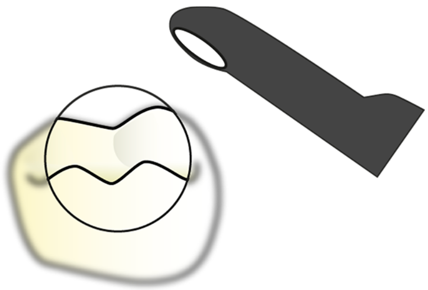

Fig. 3. Distance to the object is determined by the focal distance

AWS (Active Wave Front Sampling)

AWS is a surface imaging technique that requires a camera and an off-axis diaphragm module (Fig. 4). The module moves in a circular path around the optical axis and produces a POI rotation. The information of distance and depth are then derived from the model produced by each point and calculated (Logozzo et al., 2014; Richert et al., 2017).

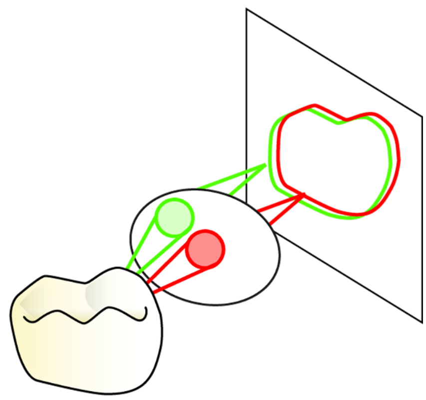

Fig. 4. AWS requires a circular path around the optical axis and produces a rotation of interest points

Stereophotogrammetry

This system can be described as a technology with high level of accuracy, which allows to determine the spatial positions of different objects. The accuracy is ensured by recording multiple photographs from different angles and constant distance. This technology was frequently used in engineering and fabrication process, architecture, and topography mapping. It has been used in dentistry since 1990s. Stereophotogrammetry may be particularly important for implant-supported restorations because frameworks, which have an error of only 10-µm, can be fabricated by using the obtained spatial positions of the implants. Moreover, the passive fit of the restoration can be achieved more accurately (Fig. 5).

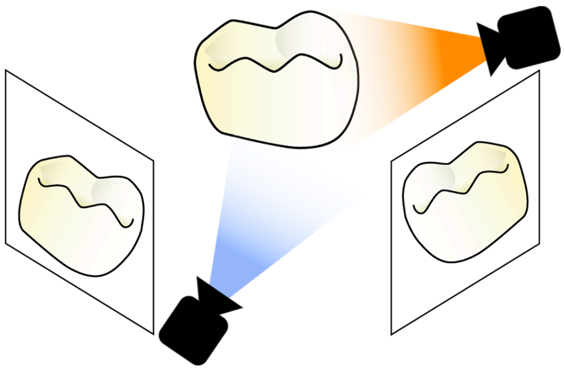

Fig. 5. Stereophotogrammetry is a technology that generates files by algorithm analyzing numerous pictures

One of the most important advantages of this technology is improved patient comfort. Another important advantage is that the operator does not need to take an impression both by conventional and digital. Nevertheless, one disadvantage of this system is that this technology is restricted to large implant cases, as it is not possible to obtain digital data for a single implant case. Also, this technology cannot be used in digitalization of tooth-borne restorations or soft tissues. To acquire the data of soft tissues in implant cases, an additional conventional or digital impression is taken and combined the data acquired by stereophotogrammetry system (Tamimi and Hirayama, 2019).

3. IOS usage in dental clinics

What are the advantages and disadvantages?

Recent studies have indicated that digital impression techniques are much faster and comfortable for both patients and clinicians (Patzelt et al., 2014a; Gjelvold et al., 2016; Richert et al., 2017). In conventional impressions, some problems may occur, such as gag reflex, and some patients cannot tolerate this situation. In these cases, replacing the conventional impressions with digital ones is a considerably important advantage. However, many studies reported that digital impressions are more time efficient when compared with conventional impressions due to absence of long working times. Although most of the research reported that full arch scan duration with an IOS device is indicated under 3 min. (Grünheid et al., 2014; Goracci et al., 2016; Mangano et al., 2017) according to learning curve and experience of clinician, this duration can be up to 3-5 min after completing the scanning process. It is possible to send the .stl file of working digital model via by e-mail to the dental laboratory, and hence save money and time.

Another advantage is simplified procedure in complex cases, such as implant-supported restorations and cases with undercuts. The digital impression is simpler and more comparable when compared with the conventional impression in such cases (Lee and Gallucci, 2013; Joda and Braegger, 2015; Mangano et al., 2017). Moreover, if the clinician is not satisfied with the result, renewal of the impression is easier and more economical in the digital workflow. The communication is another important issue. The digital technology ensures that the clinicians make this communication more objectively and with real time. In fact, lab technicians can check the impression immediately after the scanning procedure and clinicians can discuss on every issue. Also, digital impressions are a powerful tool for marketing and communication in terms of patient communication.

Consequently, the advantages can be classified as follows: less patient discomfort, time efficient, simplified clinical procedures, absence of plaster casts, better and objective communication with dental technicians, better communication with patients. Nevertheless, IOS technologies have some disadvantages, such as detecting the deep marginal lines above the soft tissues, the need for to reach learning curve, and managing cost (Ting-Shu and Jian, 2015; Zimmermann et al., 2015; Mangano et al., 2017).

Which technology?

Lee and Gallucci have reported that confocal technology is better for short, prepared teeth, and implant restorations that are scanned by unexperienced clinicians (Lee and Gallucci, 2013). On the other hand, even if some studies have indicated that confocal and AWS technologies have been frequently preferred for digital impressions, this does not indicate that which technology is better because the accuracy mostly depends on the software and employed technology (Richert et al., 2017). A whole series of elements (necessity of opacization with powder, scanning speed, tip size, ability to detect in-colour impressions) differentiate IOSs in terms of their clinical use and accuracy (Mangano et al., 2017).

Learning curve

Previous related studies exhibited that the clinicians using IOSs would need time and education to develop their skills and complete the digital impression rapidly with high accuracy (Ender and Mehl, 2015; Lim et al., 2018). The scanning time differs from 4 to 15 minutes and this is also related with the software technology employed and scanning strategy (Richert et al., 2017). In the literature, there are many studies, which evaluated the effects of repeated practice and learning curve when a new technology or technique introduced. The developing skill on a new device also increases the treatment

Table 1. Overview of intraoral scanners systems available on the market (Zimmerman et al., 2015)

	3M Espe True Definition	3Shape Trios 3	Align Technology Itero Element	Carestream CS3500	Dental Wings Dwio	Gc Aadva	Kavo Lythos	Planmeca Plan Scan	Sirona Cerec Omnicam	Medit i500
Powder	Yes	Yes	No	No	No	No	No	No	No	No
Color	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Scanner Size (LxWxH)	254x16x14 mm	No details given	No details given	245x62x37 mm	No details given	160x260x160 mm	No details given	No details given	228 x 16 x 16 mm	19x15.2 mm (W x H)
Data Capture Mode	Video Squence	Video Sequence	Video Sequence	İndividual images	Video Sequence	Video Sequence	Video Sequence	Video Sequence	Video Sequence	Video Sequence
Data Capture Principle	Wave front Sampling	Confocal laser technology	Confocal microscopy	Triangulation	Multiscan imaging	Confocal microscopy	Triangulation	Triangulation	Triangulation	Triangulation
Chairside	Established	Established	Not everywhere	Established	Not established	Not established	Established	Established	Established	Not established
Labside	Established	Established	Established	Established	Established	Established	Established	Established	Established	Not established
Implantology	Established	Established	Established	Not established	Partly established	Not established	Not established	Not established	Established	Established
Orthdontics	Established	Established	Established	Partly established	Partly established	Not established	Not established	Not established	Established	Partly established

quality and decreases the treatment time. As parallel with these statements, Lim et al. (2018) reported that repeated experience, clinical experience, and the scanned region all affected the trueness of the scanned images in the single-image-based systems.

Scanning strategies (scanning path)

Scan path or strategies can be defined as specific movements of IOS during the scanning procedure to increase the accuracy of digital impressions. Both invitro and *in vivo* studies exhibited that the accuracy of digital impressions is affected by the scanning strategies (Zimmermann et al., 2015; Müller et al., 2016).

The scanned object should be placed in the middle of an acquisition area to identify the most appropriate sphere around the object. Practitioners must also control the fluid movement, and the camera should be hold between 5 and 30 mm of the scanned surface depending on the focal distance of scanner (Logozzo et al., 2014; Richert et al., 2017). This handling procedure is not quite easy, especially during the transition between anterior and posterior sites. Different strategies were presented according to different technologies of IOS devices. The most used and advised strategy is linear movement of the camera over all the occlusal surfaces followed by scanning of buccal and palatal surfaces. Another strategy consists of making an “S” movement on vestibular, occlusal, and lingual surfaces.

The linear movement strategy limits the 3D distortion by finishing the capture at the initial position. However, this strategy has one limitation; this type of movement may cause imprecise scans especially on interproximal areas (Müller et al., 2016; Richert et al., 2017). The most difficult areas of scanning are interproximal areas, high curvatures of central incisive and axis around canines, and steep downward slopes, such as lingual area of mandibular incisors. The clinicians must adapt their own clinical protocols in these areas to overcome the imprecise scanning problems. In this situation, the IOS tracking, and software of the technology become more important.

Scanning flow and software

During the intraoral scanning, some problems may occur, such as tracking lost or stopped capturing. This situation is an unexpected result for the clinicians, and it may be uncomfortable for both clinicians and patients. The movement can be visualized too slow, too fast, or too jerky. In these types of situations, the followed scanning strategy should be start from the beginning. First, the clinician should scan easy areas, such as occlusal surfaces of posterior teeth, so the IOS can continue to capture again and go on scanning process. Currently, manufacturers develop different strategies and software algorithms to continue scanning when tracking is lost, and these algorithms are mainly based on recognizing the saved geometry of the object (Richert et al., 2017). For this reason, clinicians have to give enough information for stitching the first and last scan data. The second scan allows matching the previous POI, and software complete the missing part of scanned area (Mao et al., 2014).

Accuracy of digital impressions

In the literature, the accuracy of digital impression is determined by two measurements, one is trueness and the other one is precision. Trueness refers to the closeness of consistency between the arithmetic mean of a large number of test results and the true or accepted reference value (Richert et al., 2017). Precision refers to the closeness of consistency between test results. The method of measurement contributes to the variability of trueness and precision reported for the IOS, as this depends on aspects, such as the operator, equipment and calibration, the time elapsed between measurements, and the environment (temperature, humidity, etc.). Precision describes how repeated measures are close to each other. Therefore, a scanner with high precision correlates to a more repeatable and consistent scan (Renne et al., 2017). Trueness describes how far the measurement deviates from the measured objects (Ender and Mehl, 2013; Renne et al., 2017). Therefore, a scanner with high trueness indicates that it can deliver close results to the actual dimensions of the scanned object. Ultimately, the accuracy can be defined as the summary of trueness and precision. Ideally, an IOS device should have high trueness values, and the virtual model, which is acquired from the digital impression should match up with the scanned area.

Currently, the scientific literature considers that the accuracy of optical impression systems is considerable in case of single tooth restorations and partial fixed dentures up to 4-5 units. Today, it can be reported that the trueness of optical impressions in case of short span areas are comparable with the conventional impression techniques (Mangano et al., 2017). However, optical impressions cannot show the same accuracy values in complete edentulous or long span areas (more than 5 units) in both tooth-borne and implant supported restorations (Mangano et al., 2017). In complete edentulous patients, the optical impression acquired by using confocal, AWS, and triangulation languages, the success of digital impressions is less accurate in terms of deformation of acquired images when compared with conventional impressions. Most of the related literature reported positive results in single implant-supported restorations. However, the accuracy of digital impressions can decrease when the inter-implant distance increased. Also, the accuracy of digital impressions can be affected by the learning curve, as well (Logozzo et al., 2014; Richert et al., 2017).

Ender and Mehl (2013) found that conventional impressions were significantly more accurate than digital impressions in complete arch treatments. Furthermore, Flügge et al. (2018) found that the precision of intraoral scanners decreased as the distance between the scan bodies increased. However, the latest generation scanners may show minimal deviation values in complete arch impressions (Mangano et al., 2017).

Powdering

Dental tissues have many reflective surfaces, and this may cause some misfit in POI matching via by software. To eliminate this problem, the clinicians can alter the light diffusion by changing the orientation of the camera (Da Costa et al., 2010; Burgner et al., 2013; Joda and Brägger, 2016). Another solution to overcome this problem is the use of polarized filters within the camera systems. For other systems without polarized filter, the use of a titanium oxide powder, which has a thickness of 20-40 µm, may be required. However, with the recent developing technology, most of the IOSs can overcome this problem and do not need to use a powder. Although, some researchers reported that powder based digital impressions showed very accurate results (Patzelt et al., 2014b; Richert et al., 2017), powder use may cause some comfort problems for patients and additional scanning time. Moreover, if the powder is contaminated with saliva during the scanning process, this require removing the powder from the teeth surface and re-scanning process. As a consequence, powder use is not comfortable during digital impressions and no clear difference can be found in the articles concerning the effect of powdering on scanning area.

Artificial Intelligence (AI) in IOS

It is commonly defined as “the ability of a system to interpret external data, learn from them, and use those learnings to achieve objectives and goals through flexible adaptation” (Lerner et al., 2020). IOS devices are frequently used in digital implantology, and one option is to use this technology in fabrication of customized abutments. Currently, these customized abutments can be designed in the CAD software and subsequently fabricated by subtractive (Milling) or additive manufacturing technologies (Direct Metal Laser Melting or Direct Metal Laser Sintering). In this workflow, dentists should acquire the true image of the scan body, which is screwed to the implant fixture, by the help of IOS devices; and subsequently, technician should carefully replace the .stl file of the scan body from the digital implant library files after importing the data to the CAD software (Lerner et al. 2020). With the help of AI technology, clinicians can mesh .stl file and digital library file during the scanning process by the help of data, which are previously imported to related software. This protocol allows the technicians to skip a lot of steps during the 3D design process. Also, this workflow can present a lot of guided points for complete arch scanning and may increase the accuracy of complete-arch digital implant impressions.

Which optical impression optical system

Although there are a lot of scientific studies, which focused on the accuracy of different optical systems, these research exhibit in vitro study results because it is impossible to measure the trueness values in in vivo studies. Some of these studies focused on dentate models and some of them evaluated the implant- supported restorations with different experimental designs. According to these studies, different devices with different technologies showed statistically different results. It is very difficult to compare the test results, as the scanners have different technologies and different scanning strategies (Park, 2016; Güth et al., 2017; Mangano et al., 2017). Scanning speed and scanning flow is a very important factor on selection criteria. The devices showed different scanning speeds, and the latest generation IOS devices showed faster results than the old version of IOS devices. Nevertheless, the literature cannot show which device is more efficient in terms of scanning speed (Mangano et al., 2017). The size of a tip also plays a major role as a selection criterion. Especially in case of second and third molars, the size of scanners tip becomes more important. A scanner with a tip of limited size would be preferable for patient comfort; however, bigger size tips may be useful for in posterior areas to acquire more data for per second. The detection of caries and acquiring 3D color models of dental arches are also new technologies, which are presented with the latest versions of IOS devices. The information on color become more meaningful especially in communication with patients. Also, some IOS devices can be used in shade determination; however, there isn’t enough scientific literature, which compares the accuracy.

Purchasing and cost

Depending on the model, generation, and technology, the cost IOSs may differs between 15,000.00 and 35,000.00 euros. For ten years, companies have released a lot of technologies and features with the new generation models (Ting-Shu and Jian, 2015; Zimmermann et al., 2015; Imburgia et al., 2017). This growth in the supply is accompanied by the reduction in the purchase costs. Some companies have different policies, and they can request some managing cost and fee associated with software upgrades. It is important to inform the clinicians well about the additional managing cost (Mangano et al., 2017).

3. Conclusion

The future of dentistry is all about digital innovations and related technologies, and they will unquestionably develop the clinical practice with no doubt on this issue. Clinicians need to learn the new technologies and new workflows and also need to enhance their learning curve. An important step to enter this digital world is the use of IOS devices routinely and establishing private digital workflows. However, this rapid developing of technology makes the dentists have faced a new development and workflow every day. The main problem and the main question is not which one is better; the true question is when dentists will use the digital technology in every phase of their treatment workflow.

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Direct digitalization devices in today's dental practice: Lab scanners an update and review

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Abstract

Every day, modern dentistry faces with new technologies, which have begun to be used in daily clinical practice, and computer-aided design and computer-aided manufacturing has brought new technologies and opportunities to all fields of dentistry. The first step is acquiring the true data, which belongs to the patients, digitalization of intraoral structures. By acquiring these data, the restorations can be designed and fabricated by using digital workflow. Dentists have two main options for capturing the data from the related surfaces; one is the direct digitalization and the other one is the indirect digitalization process. In the indirect process, extraoral scanners, which are called lab scanners or cast scanners, are used. Every system has different advantages and disadvantages, and the clinicians or dental technicians should know the technology and different features of these devices to choose the optimal device for their workflow.

Keywords: digital, digital dentistry, digital workflow, extraoral scanners

1. Introduction

Computer-aided design and computer-aided manufacturing has brought new technologies and opportunities to all fields of dentistry, which includes digitalization of intraoral structures, and design and manufacturing stages (Strub et al., 2006; De Villaumbrosia et al., 2016). This technology started with Dr. Werner Mörmann at the 1980's, and it has been developed every day since its introduction (De Villaumbrosia et al., 2016). The digital workflow can be described as a workflow, in which each phase of the treatment procedure is conducted by digital devices. By this workflow, more precise, more predictable, and more accurate results can be obtained. Moreover, the use of prefabricated materials provides a standardization in manufacturing, and most of the fabrication errors can be eliminated (Prasad and Abdullah Al-Kheraif, 2013).

This digital process includes three main steps; data acquisition (digitalization of intraoral anatomy) (Fig. 1), design process, and finally manufacturing. The first and the most important step of this workflow may be the digitalization of intraoral anatomy because if a clinician cannot obtain the true data, the final result will not be precise (Chan et al., 2011).

Currently, clinicians have two main choices for the digitalization of anatomical structures: (1) direct digitalization with intraoral scanners, (2) and indirect digitalization with cast scanners. Intraoral scanners have many advantages, such as direct digitalization from patients mouth and no need of plaster cast, and chairside workflow completed in the clinics. Nevertheless, dental laboratories may obtain the data by using lab or cast scanners. Both type of scanners obtains a digital model of patients mouth by acquiring images, and subsequently processes a triangulation by the help of CAD software (Miyazaki et al., 2009; Chan et al., 2011). At the end of the process, the obtained files are used to fabricate restorations via different manufacturing alternatives, such as three-dimensional (3D) scanners or milling machines by using polymethyl methacrylate, resins, alloys or different ceramic materials (Ebert et al., 2009; Kachalia and Geissberger, 2010; Fielding et al., 2012; De Villaumbrosia et al., 2016).

Cast scanners can be classified as follows: contact and non-contact scanners. In terms of used technology, cast or extraoral scanners mainly use three different technologies. These are visible structured light, laser or contact type scanning (Lee et al., 2017). In contact scanners, a digital cast is created by directly touching to the cast with a probe, and computing the x, y, z coordinates for each location, which are read by the probe. Even if this approach is highly accurate, it has also some drawbacks: (1) it takes a long period of time, (2) and it is possible to damage to cast model during the scanning (May et al., 1998; Persson et al., 2006; Lee et al., 2017).

The laser scanners and optical scanners are classified under the non-contact category. Although the laser scanners are precise, they are not as fast as the optical scanners. Additionally, the laser scanners have a different drawback, which is called "speckle" (Persson et al., 2006; Jeon et al.,

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2013; Lee et al., 2017). The optical scanners capture images by using both white and blue light. The main difference between white and blue light is ambient light amount, and this may cause a misfit when it is too much (Jeon et al., 2015). Intraoral scanners can be affected by several complex environmental factors, such as humidity, saliva, movement of the patient. Even if there are more or less factors, which affects the accuracy of digital impressions when compared with conventional ones, the technology directly affects the accuracy (Jeon et al., 2015; Lee et al., 2017).

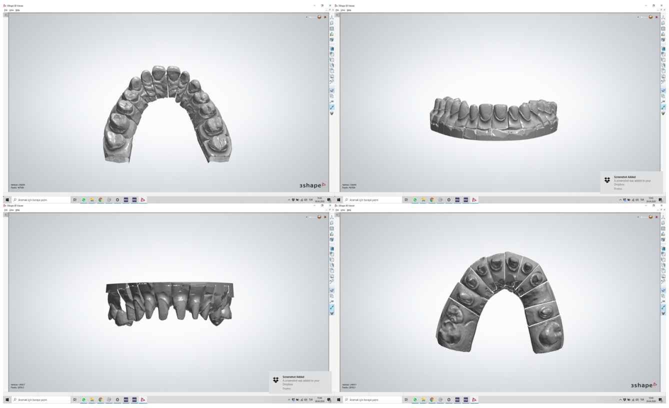

Fig. 1. An example of scanned plaster cast from different views, which are captured by an extraoral scanner

2. What is the technology of the cast scanners?

Approximately all 3D scanners work on the same principle. They have one light source, one or more cameras, and a motion system that supports several axes to position the scanned objects towards the light source and cameras. Structured light generates well-designed lines on the surface of the model, and cameras subsequently can detect the images of these lines. Based on the known angle and distance between the cameras and light source, 3D positions can be calculated where the structured light, which reflects from the surface of scanned object. This is based on trigonometric calculations and named as triangulation.

In most of scanner systems, only one camera works; however, two cameras increase the scanning speed and accuracy. Each projected line causes a 3D contour line. Laser scanners generate multiple lines by moving the scanning head along a precise axis. In contrary, white light scanners do not have a movable scanning head. By moving the object, several projections can be detected from different angles. Although these two different types of scanners have different technologies, it is difficult to say which one is better.

Some 3D scanners support a high-quality mechanical motion system, in where all 3D views can be directly transformed into a common coordinate system and then simply appended to each other. Other 3D scanners with less accurate mechanics do not rely on the quality of motion system, instead, they virtually align the 3D views by detecting similar 3D structures in overlapping regions of at least one pair of views. Software alignment thus works best for objects with pronounced structures, e.g., molars (Shembesh et al., 2017).

Triangulation process needs some sharply projected light patterns. This can be obtained by both laser and white or structured light scanners. Laser scanners can achieve minimal light projections of the scanned surface; however, if they are not controlled carefully, this may cause speckle that can be defined as slight randomness in light intensity. However, white light scanners may cause blur effect due to different color components of white light (Shembesh et al., 2017). As a result, the accuracy of devices is directly related to the resolution of the cameras, which cast scanners have. Today, most of the developing scanners have five megapixels or above cameras (Table 1).

In the final step, the point cloud, which is obtained from every aspect of objects, is converted into a 3D surface of fine triangles. This step can be achieved by software algorithms and smart surface generation algorithms. By using smart algorithms, the number of triangles can be significantly reduced without any problem in accuracy. So, why reducing the triangles number is necessary? The answer is about the CAD design software. Processing the 3D image takes much more time unless the triangles are reduced (Shembesh et al., 2017).

3. Which type of cast scanner?

A 3D scanner is a technological device capable of capturing and processing images or video files from the surface of a restoration cite for fabricating a digital copy. Cast scanners are either tactile or optical. Tactile scanners are known as contact scanners, and these kinds of scanners acquire the data and capture the surface details by contacting via the help of detection unit.

Optical scanners, also known as noncontact scanners, capture the images using laser or structured light. Contact scanners are more precise, but they work slowly during digitization process. This type of scanners are the first introduced scanners on the market, and they are the most accurate ones. Nevertheless, they are slow because they need to contact every point of the entire scanned surface by a moving probe. Nowadays, they are rarely used in the laboratories. Contact scanners employ a probe made of a very resistant material, such as ruby. These types of scanners are not affected from the optical characteristic of surfaces, but they can be affected from the surface characteristics of materials.

Non-contact scanners use structured light or laser for detecting the surface properties and capture the scanned surface digitally. This type of scanners is extremely fast when compared with contact type of scanner, and they do not create distortions on the scanned surface. However, light can be affected from the surface properties, and may show reflective behavior, and this can change the light reflection characteristics, which is directly related with accuracy. Non-contact type scanners capture the entire surfaces to collect much more data at the same time; and therefore, they can be more precise (Tamimi and Hirayama, 2019).

Table 1. Currently available extraoral scanners with information of their technology, manufacturer and accuracy

Technology	Scanner	Manufacturer	Accuracy
Structure Light	AutoScan-DS300	Shining (Hangzhou, China)	10 µm
	Cara Scan	Kulzer (Hanau, Germany)	15 µm
	Cendres+Metaux	Cendres Metaux (Biel, Switzerland)	5 µm
	Ceramill Map 400	Amann Girbach (Koblach/Austria)	6 µm
	D2000	3shape (Copenaghen, Denmark)	8 µm
	Dental Scanner MDS 550	Maestro (Pisa, Italy)	10 µm
	Deluxe 3D Optical Scanner	Open technologies (Rezzato, Italy)	5 µm
	inEos X5	Dentsply/Sirona (Bensheim, Germany)	7 µm
	Identica T500	Media (Incheon, South Korea)	2.1 µm
	IScan L1	Imetric (Courgenay, Switzerland)	7 µm
	Kavo LS3 Scanner	Kavo (Biberach, Germany)	<15 µm, depending on the type of case
	S900 Arti	Zirkonzahn (Gais, Italy)	10 µm
	Vinyl	Smart Optics (Bochum, Germany)	6 µm
	Evolution Plus	Zfx (Munich, Germany)	9 µm
Laser	7 series	Dental Wings (Montreal, Canada)	15 µm
	ConoScan 4000	Optimet (Jerusalem, Israel)	10 µm
	Cyno Prod i3.5	Numeq Inc (Quebec, Canada)	30 µm
	OpenScan 100	LaserDenta (Berghain, Germany)	20 µm
	Orapix 3D scanner	Orapix (Seoul, South Korea)	20 µm
	ShapeGrabber	ShapeGrabber (Ottawa, Canada)	40 µm
	Zeno Scan S100	Wieland (Pforzheim, Germany)	50 µm
Contact	Procera Forte	Renishaw (Gloucestershire, UK)	1–2 µm
	Renishaw Incise	Renishaw (Gloucestershire, UK)	1–2 µm

4. Accuracy

Of course, every step of dental fabrication process has potential source of errors. So, every step is very important for avoiding inaccuracies, and accuracy is an important criterion for restorative dentistry. In the conventional workflow, accuracy can be affected by a lot of factors, such as humidity, isolation of the impression area, type of impression material, dimensional stability of the impression materials, dimensional stability of the cast material, and etc. Digital technology eliminates most of these factors, but the key question is: are the digital impressions comparable with conventions impressions? Unfortunately, there is no common standard for measuring or validating the accuracy of dental scanners as in vivo. Almost all researches are performed in vitro and also comparing the results is not very easy due to lack of standardization of the methodologies (Tomita et al., 2007).

Another important question is that may we have to ask is can the difference in technology of cast scanners affect the accuracy of digital impressions De Villaumbrosia et al. (2016) reported that the mean accuracy values, which were obtained by six different extraoral scanners, were higher than those of declared by manufacturers. There is no doubt that the accuracy is affected by how well the scanner is manufactured. In mechanical movement systems with have high accuracy, the different captured images are stitched. Nevertheless, software alignment in less accurate systems mainly depends on the matching of the surface structures in overlapping areas. This is potentially prone to inaccuracies especially in small, smooth, and less defined areas. De Villaumbrosia et al. (2016) also found that each scanner had a less discrepancy on the axial surface than margin and occlusal groove areas. In other words, the researches revealed that extraoral scanners are much more accurate on smooth surfaces than sharp angled areas (Rudolph et al., 2007; De Villaumbrosia et al., 2016).

When the related literature evaluated, the accuracy and trueness values of cast scanners are less than intraoral scanners. Vlaar and Van Der Zell (2006) reported a discrepancy between 7.7 to 13.9 µm. Persson et al. (2006) showed that the trueness of a contact scanner was within 10 µm. Delong et al. (2003) found that the average values changed between 18 to 30 µm for a cast scanner, which used structured light (De Villaumbrosia et al., 2016). Another factor is the resolution for evaluating and determining the trueness of different cast scanners. De Villaumbrosia et al. (2016) reported that the correlation between the resolution and other variables are irregular. The higher resolution may provide much less misfit in sharp edges and complex surfaces, and this statement also was reported in different studies (Arnetzl and Pongratz, 2005; Al-Fadda et al., 2007; Quaas et al., 2007; Del Corso et al., 2009). This may be because the scanner records some points which is called "point of interest" (POI) on the scanned surface. Noncontinuous reading at sharp and complex surfaces scanners tend to measure the edges. In the high-resolution scanners, this would be finer when compared with low-resolution scanners, because the scanner software fills the gaps among POI on the sharp edges. However, it would be beneficial to explain that the higher resolution mainly does not imply a higher accuracy (trueness and precision) but only the capability of recording in detail (Persson et al., 2008; De Villaumbrosia et al., 2016).

It was reported in a study that the contact scanner which had the highest resolution (216.4 points/mm^2) showed the lowest discrepancy values (Joós-Kovács et al., 2019). In contrary, the laser-based scanners had the best results regarding the precision and trueness. On the other hand, studies show that there is no correlation between the triangulation numbers and accuracy, and the quality of points that captured by the scanner and point cloud generated by the algorithm are more important (Joós-Kovács et al., 2019). As a consequence, technology may directly affect the accuracy of scanners.

5. Scan speed and productivity?

Scan speed is a very important factor on the overall success, especially in laboratory workflow. As for accuracy, it is difficult the say which scanner is faster due to standardization problems. Although, there is no common and standard reference, some comparisons showed that scanning times can be vary from 30s to several minutes for the same basic die. However, there is no doubt that the scanning time is not a meaningful factor on the overall productivity.

The more important point in productivity is the high degree automation of hardware because this will prevent or correct many human source errors. For example, the adjustment of manually controlled camera brightness can result in over-exposed images, in which projected lines of light can no longer be detected. Some hardware features can save working time by using die feeder or multi die plate. Good fixture reduces the number of failures, which is an annoying source of wasted time. As a result, even if the speed is very essential and important on the productivity, this is not a factor that can be evaluated alone to assess the productivity.

6. Conclusion

Today many laboratories use extra oral scanners and these devices take place of conventional workflow. Several 3D scanners are presented every day. Due to lack of common standards, the increased choices can be confusing. During evaluating and comparing the devices, commonly accuracy, scan and workflow time, different useful features of devices, and supported indications should be considered. Even if cast scanners are not necessary for routine clinical use, they are indispensable to increase the fabrication quality and effectiveness.

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Accuracy and efficiency of digital implant planning and guided implant surgery: An update and review

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Abstract
Advances in digital technology present seamless 3D integrated workflow options to eliminate surgical and prosthetic complications in dental implant treatment. Virtual implant planning with guided implant surgery is claimed to provide predictable results. State of art technology is capable to transfer virtual implant planning from software to clinical application. However, clinicians have to be aware of the potential deviation factors and risks of the different types of guided implant surgery systems to reduce the complications. This review aims to evaluate the efficiency and accuracy of different computer-assisted dental implant surgical techniques and to discuss their potential error sources.

Keywords: accuracy, computer-assisted dental implant surgery, digital implant planning, guided dental implant surgery

1. Introduction

The latest improvements in technology have implemented digital workflow options into implant treatments and restated implantology. The term "digital implantology'' refers to a glance that covers digitally supported treatment stages. These stages include digital implant planning and guided surgery as well as the digital impression of implant position and production of the final restoration. This review aims to discuss the advantages, disadvantages, and possible limits of dynamic and static navigation techniques in dental implant surgery.

Ideal 3D positioning of an implant has a critical role in the long-term stability of peri-implant tissues. Not only for biological concepts but also for the biomechanical principles that must be considered while deciding the location of an implant in apico-coronal, mesio-distal, and oro-facial directions. Non-ideal implant position may cause damage to anatomical structures as well as aesthetic and biomechanical complications (Buser et al., 2004; Pjetursson et al., 2007; Misch et al., 2008; Sadid-Zadeh et al., 2015).

Prosthetic and surgical principles for predictable implant treatment outcomes are well defined in the literature. Ideally, a dental implant must be circumferentially surrounded by healthy bone or bony like substance. Critical anatomical structures like inferior alveolar nerve in the mandible must not be damaged during osteotomy. The implant should provide esthetic and biomechanical requirements of future implant-supported prosthesis after osseointegration (Brief et al., 2005).

In most cases, the ideal 3D position of a dental implant might be challenging because of reduced bone and soft tissue volume. Nowadays computer-assisted navigation techniques have become favorable to overcome this challenge and optimize implant positioning. The latest CBCT technology has provided the possibility to analyze the 3D anatomy of the implant sites with a reduced radiation dose. Additionally, digital implant planning softwares have been developed to simulate 3D virtual implant planning. The planning software should be able to import and export. DICOM and .STL files and merge them to perform a prosthetically driven implant placement. This integrated approach helps to minimize the risk factors to avoid biological and biomechanical complications (Bou et al., 2000; Dula et al., 2001; Kopp et al., 2003; Lund et al., 2009; Greenberg et al., 2015; Panchal et al., 2019).

The very first digital implant planning software has been presented in the early '90s. In 1991, Image-Master-101 software placed some graphic images of implants on cross-sectional images. In 1993, the first version of Simplant was introduced providing 3D planning tools. Today there are many different planning software on the market, some of which are working as closed systems. The others are capable to support various implant brands. Selecting implant diameter, platform diameter, abutment height, abutment angle, performing multiple measurements on CBCT, aligning implants are some of the capabilities of these softwares (Panchal et al., 2019) (Fig.1).

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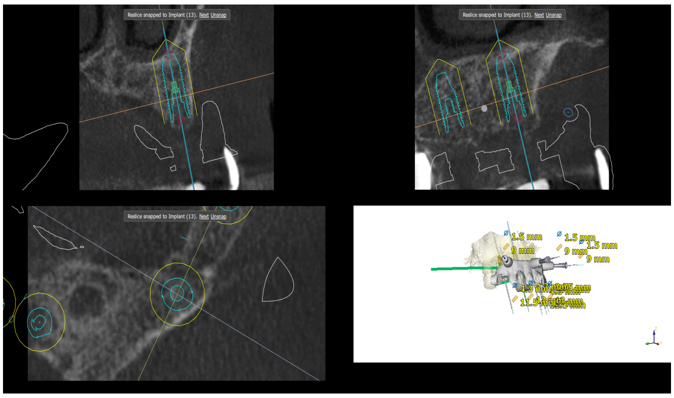

Fig. 1. Virtual implant planning (DTX Studio Implant, Nobel Biocare)

The next step after virtual implant planning is to transfer the 3D positions of implants to the surgical site. Two different techniques were defined for this purpose to make an accurate transfer of the virtual plan to the surgical area (D'haese et al., 2000; Vercruyssen et al., 2014a; Vercruyssen et al., 2015; Gallardo et al., 2017; Jung et al., 2009).

1. Dynamic Navigation
2. Static Guided Surgery

2. Dynamic navigation

This technique was first introduced for neurosurgery in 1992. In dentistry, it was first used in 2000 in the USA (Dyer et al., 1995; D'haese et al., 2000; Panchal et al., 2019). The system uses optical motion tracking technology that allows real-time guidance during surgery. Light is projected from a special source above the patient. The light is reflected off tracking arrays that are fixed to patient, surgical handpiece and drills. The software recognizes the reference markers and tracking arrays. Then it calculates the position of the jaw so a virtual reality simulation is created on screen (Fig. 2). The patient should be scanned with a special reference marker system rigidly fixed to the teeth (for a dentulous patient) or jaw (for edentulous). After virtual planning on CBCT, calibration, and registration of the system are performed. Surgery can be performed with or without a flap. There are different workflows for dentulous and edentulous patients. An edentulous patient requires screws to be placed in the bone to perform the registration in CBCT. For dentulous patients, a single-use fiducial clip is placed on teeth. Both osteotomy and implant placement are performed freehand with dynamic navigation. The freehand approach provides the operator with the freedom to be able to change the position of the implant during surgery.

Dynamic navigation ensures good visibility to the operation site and irrigation of the drilling area is predictable. There is no need for a special drill kit, reference markers can be fixed to every drill set. This technology allows guidance even when the mouth opening is limited (Stefanelli et al., 2019; Guzmán et al., 2019; Lopes et al., 2020).

Limited in vivo studies in the literature are available. Some in vitro studies show that there is a specific learning curve for this system and personal training on models is essential before performing clinical cases. Because the operator has to look at the computer screen instead of the surgical site during surgery, coordination of the operator is crucial (Block et al., 2017; Lopes et al., 2020). Sun et al. (2018) showed that gaining experience with the system reduces the operation time. Although clinician has been experienced, there is a certain level of error which is caused by the system. Stefanelli et al. (2019) found similar results in a clinical study with 231 implants.

Dynamic navigation is reliable and efficient for both experienced and novice operators. The difference between the two groups doesn't have statistically different accuracy. The only difference reported with the experienced group is the reduction of operative time but this is not at a level of changing clinical results. However, all these results are reported from in vitro studies (Jorba-García et al., 2019; Pellegrino et al., 2020). In clinical scenarios, accuracy might change as operator experience may influence the result. Deviations in dynamic navigation technology are reported in both in vivo and in vitro studies.

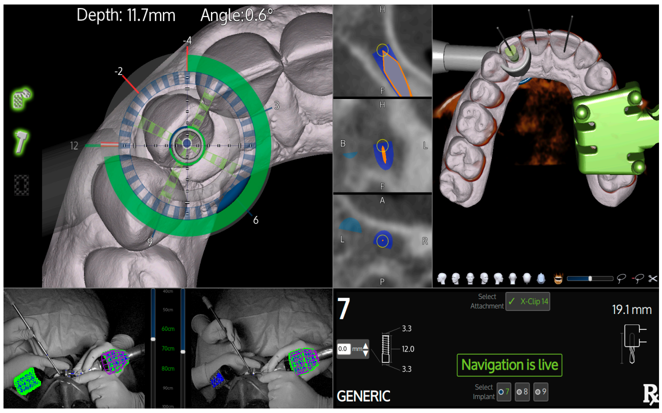

Fig. 2. Dynamic navigation operation screen (X-Guide, XNav Technologies)

The measurement for accuracy in static or dynamic navigation systems is usually performed by superimposing the preoperative planning data and post-operative data. Different studies compare different deviations but mainly there are four types of deviations:

Depth deviation: Deviation in apical-coronal direction (mm)

Lateral deviation: Mesial-distal and buccal-lingual direction (mm)

Global deviation: Overall 3D distance regarding apical and coronal deviation (mm)

Angular deviation: The angle in 3D space between center axes (degree) (Emery et al., 2016).

Some studies compared freehand surgery and dynamic navigation on study models. One study reported 4.2 ± 1.8° angular deviation for dynamic navigation and 11.2 ± 5° for freehand surgery (Hoffmann et al., 2005). Another model study found 1.6° angular deviation for dynamic and 9.7° for freehand surgery (Jorba-García et al., 2019). A clinical study of 28 edentulous, 125 dentulous patients who were treated with dynamic navigation has reported the difference between virtual plan and final implant position. This study measured 0.71 mm deviation at the entry point (lateral), 1.00 mm at apical, and 2.26° deviation (Stefanelli et al., 2019). Another clinical study including 86 implants measured 0,72 mm lateral deviation at implant shoulder, 0.69 mm at apical, and 5.33° angular deviation (Aydemir et al., 2020). Another author had reported similar results with a multicenter prospective clinical study (Block et al., 2017).Dynamic navigation ensures more accurate angular positioning and parallelism of implants when compared to freehand surgery both in clinical and in vitro studies (Hoffmann et al., 2005; Kramer et al., 2005; Block et al., 2017). But apicocoronally dynamic navigation is still not reliable enough. Some studies reported wide range values like (0 to 1,6 mm), (0 to 3.3 mm), (0,1 to 1.8 mm) in depth deviation (Hoffmann et al., 2005; Somogyi-Ganss et al., 2015; Jorba-García et al., 2019).

This is the reason why every planning software has at least a 2 mm safety zone around the virtual implant. Software are still improving to compensate for this deviation. Some possible error sources that may lead to increased deviations in dynamic navigation are voxel settings, slice thickness, patient-related motion or metal artifacts, and non-rigid fixation of fiducial marker clip or screws during CBCT scan may cause problems during STL and DICOM superimposition procedure. Errors during digital planning, limits of optical tracking, software-oriented deviations, and the difficulty of manipulation while keeping the eye on screen might also influence the accuracy.

Dynamic navigation is used daily in neurosurgery, ophthalmology, and some other medical branches. Since introduced to dentistry, this technology didn't become popular immediately because of the high investment costs and increased operative time but nowadays dynamic navigation surgery is getting more attention due to the advantages of the technique.

3. Static guided surgery

Currently, static guidance is widely used in implant dentistry. Implant placement using a static guide requires a CBCT scan with a proper field of view and impressions of the upper and lower jaws. Impressions can be obtained by either conventional or digital techniques. If a conventional technique is preferred, the cast should be digitized by an extraoral desktop scanner to be able to obtain a digital file. Direct digitization of intraoral surface geometries with an intraoral scanner is also possible. These digitization methods both present a 3D model, therefore a virtual wax-up can be designed to be merged with the CBCT scan. After the merge of data sets, virtual planning can be performed ideally using the implant planning software. Angulation, depth, diameter, and length of each implant can be specifically determined. It is possible to simulate different abutment options and multiple measurements can be performed to be able to position the critical abutment-implant shoulder connection optimally for creating a proper emergence profile. When the planning is finalized this information is used to design a surgical guide. The guide can be either milled or produced by stereolithography, the most known rapid prototyping technology (Somogyi-Ganss et al., 2015; Gallardo et al., 2017).

The static guide technique is commonly used for minimal invasive flapless surgery but the system also allows to open a flap if necessary (Fig. 3, 4).

Fig. 3. CEREC Guide, Dentsply Sirona

Fig. 4. Ideal implant positioning

For drilling through the guide, special long drilling burs are mandatory. Sleeves or drill keys are positioned on the guide which leads the drill to perform the osteotomy at the same depth and angulation as it is in planning software. There is a physical stop on the template, therefore a static guide doesn't allow to change the position of the implant during surgery. If a necessity to make a change in the implant positioning occurs, another guide must be produced (D'haese et al., 2000; Vercruyssen et al., 2015).

There are different protocols for edentulous and partially dentulous patients as it is in dynamic navigation. For partially dentulous patients, the impressions of jaws and CBCT scans are enough to produce a surgical guide. We have to use scan prosthesis when dealing with edentulous cases. The reason for producing a scan prosthesis is that the acrylic resin used in traditional removable prosthesis cannot be easily segmented on

CBCT. The soft tissue segmentation can be extremely difficult if a scan prosthesis is not used.

Two different approaches for edentulous cases are reported:

1. Single scan: A duplicate of a future prosthesis with a radiopaque material is produced and a CBCT scan is performed with this scan prosthesis. A radio-opaque scan prosthesis must be a copy of the final prosthesis and consist of 10% BaSO4 and a methylmethacrylate mixture.

2. Double scan: Radio-opaque markers are fixed on the scan prosthesis. First, the scan prosthesis has to be scanned with an increased radiation dose, secondly, the patient should be scanned with a standard radiation dose while wearing the scan prosthesis. Attention should be paid to the marker's rigid fixation. Also, the scan prosthesis should be placed in the mouth with a rigid bite index. Afterward, two scans are merged in software, and planning is performed (Verde et al., 1993; D'haese et al., 2000; Vercruyssen et al., 2014b; Witherington et al., 2017; Schubert et al., 2019).

Studies didn't define a specific learning curve for static guided surgery. Although the efficiency of the operator seems to improve with repeating applications, still a typical learning curve is not defined. Repeated use of static guides seems to improve angular and depth deviation. As it is in dynamic systems, both experienced and novice operators can achieve fewer positional deviation when compared to freehand surgery (Vasak et al., 2011; Vercruyssen et al., 2015; Cassetta et al., 2020).

Different types of static guidance depending on tissue support is defined in literature (Fortin et al., 2004; Van Assche et al., 2012; Gallardo et al., 2017).

3.1. Bone supported surgical guides

The surgical template must be placed on the bone after reflecting a full-thickness flap which usually extends 2-3 mm beyond the template. Bone supported surgical guides can be defined as the first version of surgical templates for edentulous cases. The main advantage of a bone-supported guide is the easy visualization of the operation site and control of the drilling depth. But this type of guide requires invasive surgery regarding the wide flap elevation. Postoperative discomfort is inevitable and decreased blood supply is a risk factor for postoperative healing (Rosenfeld et al., 2006; Gallardo et al., 2017).

Bone supported guides have to be screwed to the bone for stability. The absence of fixation screws and the need for replacement of different guides during surgery are considered to affect precision. Stabilization of template is difficult, guide tends to move coronally while drilling. Additionally, interference occurs between the guide and bone after the flap elevation. As a result, more pronounced deviation values are reported in the literature for bone supported guides than mucosa and tooth-supported guides (Arısan et al., 2010).

3.2. Mucosa supported surgical guides

Mucosa-supported surgical guides are commonly used for edentulous cases as they are capable of performing flapless surgery. The use of a mucosa-supported single guide to place implants without flap reflecting might help to reduce the total time of operation, postoperative pain, and some other complications (Fortin et al., 2006; Hultin et al., 2006; Divakar et al., 2020). However, another study conducted by Vercryusse with 311 implants comparing the patient outcome of conventional surgery, bone supported and mucosa supported flapless surgery didn't agree with previous findings (Vercryussen et al., 2014c). This study doesn't report a significant difference between the postoperative discomfort of guided surgery compared to conventional methods. Patients treated with conventional methods reported prolonged pain than patients treated with the flapless guided surgery. This might have occurred due to the operation time. It has been demonstrated that longer operative time caused more postoperative discomfort (Sato et al., 2009). Flapless approach with mucosa supported guides seem to reduce the operative time when compared to bone supported guides (Arısan et al., 2010).

Operators should be aware of the criteria when deciding on a flapless surgery. Flapless surgery is possible in limited cases only with adequate attached gingiva and enough bone volume. Flanagan suggested at least 5 mm bone width and 4 mm keratinized tissue, Malo and Jesch reported at least 6 mm width of bone and 6 mm keratinized tissue is needed for flapless surgery (Flanagan et al., 2007; Malo et al., 2016; Jesch et al., 2018). Another study reported a minimum width of 4 mm attached gingiva and alveolar bone thickness over 4 mm are suitable for flapless surgery (Arısan et al., 2010).

The vascular structure remains healthy and this is supposed to improve peri-implant tissue stability (Campelo et al., 2002; Becker et al., 2005). Flap reflection might have disturbed the vascular network. Nevertheless, some of the keratinized tissue is removed by a punch during flapless surgery and this also may risk peri-implant tissues (Schrott et al., 2009).

Precise positioning of the surgical guide is an important aspect and can affect accuracy. The guide should be perfectly positioned and stabilized firmly after the punching with fixation screws. Stabilization of the guide is one of the most critical clinical points during guided implant placement. Stabilization should be secured with at least 3 fixation pins. A study in 2014 reported surgical guides in edentulous patients must be fixed using at least three pins to minimize errors in the positioning of implants (Casetta et al.,2014a) (Fig. 5).

The distribution and even fixation order of pins influence the accuracy. Posterior pins are recommended to be placed into bone before anterior ones (Verde et al., 1993; Vercruyssen et al., 2014b). A properly fixed guide presented 1.66 mm deviation at coronal, 2.09 mm deviation at apical, and 4.09 degrees angular deviation. When the surgical guide is not fixed, 1.68 mm coronal deviation, 2.26 mm apical deviation, and 5.62 degrees angular deviation were recorded (Casetta et al., 2014b).

Accuracy can also be influenced by mucosal thickness, smoking habit, bone density, type of jaw (upper or lower), and implant length (Casetta et al., 2013; Vercruyssen et al., 2014b; Seo et al., 2018).

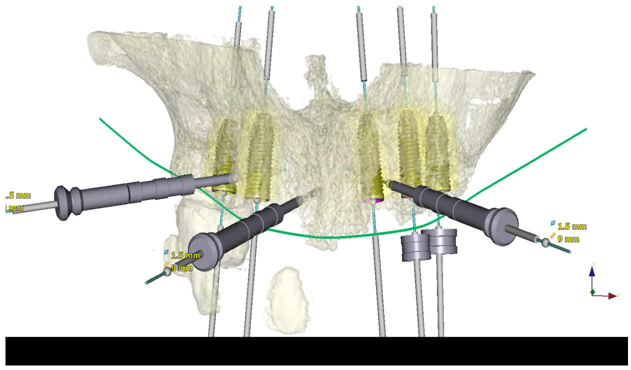

Fig. 5. Fixation pins at planning stage

Mucosa thickness has a critical role in the accuracy of this type of guide. Overall deviation increases as the mucosa thickness increases. The apical deviation is reported to be greater than the coronal deviation in various studies (Widmann et al., 2006; Vasak et al., 2011; Gallardo et al., 2017; Seo et al., 2018). A study presented that smokers have relatively thicker mucosal tissues compared with non-smokers, which may lead to less stability of the surgical guide. The same study found that if tissue thickness is more than 3.5 mm, a flap has to be reflected (Schnutenhaus et al., 2016). The local anesthesia may also cause swelling of tissue and the fit of the guide template may be affected (D'haese et al., 2012).

Accuracy of type of jaw (upper or lower) was evaluated in some studies. When working on a mandible with a mucosa supported guide, the operator should be aware of the possibility of guide displacement since the supporting area is smaller. Tahmaseb (2014) reported no difference between maxilla and mandible in a systematic review. Another important point is the bony structure. Maxilla is supposed to have more impact on the deviations between virtual plan and realization. The reason might be the lower resistance of spongiose bone when compared to cortical bone (Marlière et al., 2018). Schelbert et al. (2019) presented in a study with partially and fully edentulous patients that maxilla has a greater deviation than the mandible. Additionally, augmented implant sites showed less depth deviation. Accomplishing template stability for mucosa supported guides is more difficult than teeth guided when dealing with edentulous patients. Therefore, no consensus yet is available about the effect on the accuracy of the type of the jaw.

D'haese et al. (2012) reported implant length also influence accuracy outcome. They found a statistically significant difference in the global apical deviation for longer implants. Vercruyssen et al. (2015) did not confirm this finding and could not find a correlation between implant height and deviation amount. Valente et al. (2009) conducted an in vivo multicenter study and reported that the type of implant did not cause a significant difference in accuracy.

3.3. Tooth supported surgical guides

The accuracy of tooth-supported surgical guides is reported to be superior to that of bone and mucosa supported guides on literature. If a patient has at least 3 or 4 periodontally healthy teeth without mobility, the rigid tooth support offers an advantage for reducing the movement of the guide (Van Assche et al., 2012; Tahmaseb et al., 2014; Pozzi et al.,2016; Gallardo et al., 2017; El Kholy et al., 2019).

Ozan (2019) found the angular deviations of final implant positions compared to virtual planning as 2.91 ± 1.3°, 4.63 ± 2.6°, and 4.51 ± 2.1° with tooth-supported, bone- supported, and mucosa-supported guides, respectively. Tooth supported guides are reported to provide more accurate results than mucosa or mucosa and pin supported guides (Ozan et al., 2009; Tahmaseb et al., 2014 and 2018; Gallardo et al., 2017).

Surgical guides can also be classified as full guidance or partial guidance. Partial guidance (pilot drill guidance or half guidance) allows us to use only a single pilot drill or to perform the complete osteotomy guided, but the implant should be placed freehand. Fully guidance allows all osteotomy and implant delivery steps through the guide. Although Wei Geng et al. (2015) compared the accuracy of these and didn't find a significant difference, Kühl et al. (2013) and Ramos et al. (2017) have reported better accuracy for fully guided systems.

Fully guided surgery showed less deviation values when compared with partial-guided surgery, but clinically both techniques are acceptable. Partially guided templates can also facilitate optimal implant placement and can simplify the surgical procedure. Fully guided systems may provide more accurate results when working with irregular bone quality, where some movements during implant placement may result in higher deviations. The only pilot drill partial guidance may have an advantage of reducing irrigation problems and when limited mouth opening exhibits (Verde et al.,1993; Kühl et al., 2013; Geng et al., 2015). Another classification is a single type or multiple type guide, describing the number of templates necessary for the surgery. A single type guide is considered to be more accurate than a multiple type for bone supported guides. Single type allows guided osteotomy and implant placement through only one template. Metal cylinder tubes called master tubes are adhesively fixed in the resin guide. The tolerance between the master tube and the internal tube and the drills may affect the accuracy of single guides (Cassetta et al., 2013).

3.4. Possible error sources

Jung et al. (2009) reported the deviation may increase due to the limited access, poor visualization, patient movements during surgery. Ramos et al. (2017) confirmed this finding in a meta-analysis comparing in vivo, ex vivo, and in vitro studies. In vitro studies have resulted better in accuracy because they don't have clinically challenge conditions.

The digital workflow steps should be carefully controlled to minimize the deviation. CBCT data acquisition, intraoral scanning, digital planning, guide production via milling or 3D printing are the steps of digital workflow where system errors may occur. Patient motion artifacts or metal artifacts may affect accuracy. During acquisition and software processing, an error of 0.5 mm deviation is reported. Additionally stereolithography material and the fit between the tubes of the guide and drills also may affect the result. Manufacturing errors can have a cumulative effect, and cause a deviation and the clinical result might be negatively affected (Reddy et al.,1994; Stumpel et al., 2012; Vercruyssen et al., 2015; Marlière et al., 2018).

4. Guide Production

Guides can be manufactured manually or using computer-assisted design and computer-assisted manufacturing (CAD/CAM) by a fully digital workflow. Computer-aided guides are usually produced by milling machines or rapid prototyping technologies (Fig. 6).

Fig. 6. Milling of a surgical guide

Rapid prototyping technique is commercially the most preferred technique in digital guide production (D'haese et al., 2000). Tahmaseb et al. (2018) recently documented in a meta-analysis of 20 clinical studies 2136 of 2135 guides were produced by this technology. Farley et al. (2013) showed in a split-mouth study that digital guides achieve better accuracy outcomes than the model-based as all steps are controlled digitally. An in vitro study reported that the intaglio surface dimension and tube deviation might be affected by the layer thickness of printing material and angulation parameter during production. If the printing layer was selected 50 µm, dimensional intaglio deviations and tube angular deviations were reduced. Faster printing was possible using a layer of printing 100 µm but thicker layers might have a negative influence on accuracy. Moreover, printing at different angulation parameters also changed the result. Printing at a 90° setting allowed more templates to be printed in a shorter time. As a result, increasing the angle and printing layer may affect the accuracy of printing (DalalN et al., 2020).

5. Clinical implications

Tahmaseb et al. (2018) reported in a meta-analysis of 20 clinical studies a total error of 1.2 mm at the coronal, 1.4 mm at the apical, and angular deviation of 3.5° for guided surgery. Partial edentulous cases presented more accurate results than full edentulous cases. The accuracy of implant surgery with computer-assisted navigation systems were shown to be superior to free-hand surgery (Tahmaseb et al., 2014). Jung et al. (2009) compared the accuracy of dynamic navigation and static guidance. Precision observed was higher in dynamic systems but the difference might be a result of the fact that most of studies were in vitro conditions. A real comparison between dynamic and static surgery is yet not possible.

Chen et al. (2018) compared horizontal deviation at the apical when using the dynamic navigation system, static guidance, and freehand implant placement. Deviations at apical point measured were (1.35 ± 0.55 mm), (1.50 ± 0.79 mm) and (2 ± 0.79 mm) respectively. The dynamic navigation system showed 4.45 ± 1.97°, static guidance showed 6.02 ± 3.71°, and free-hand surgery showed 9.26 ± 3.62° angular deviation.

6. Conclusion

Based on the literature we can conclude that both dynamic and static guided surgery is helpful for optimizing implant position when compared to freehand surgery. But each step of the digital workflow must be carefully processed to minimize errors for successful treatment outcomes. Prosthetically driven implant placement using computer software can provide predictable prosthetic outcomes and minimize biological complications. Moreover, reducing bone augmentation and sinus floor elevation procedures are possible by optimizing the implant position. Computer-assisted guided surgery options promise to add value to implantology for clinicians even in difficult cases. Despite digital workflow assures a precise implant placement, the deviation between the virtual plan and the realized position of implants is inevitable. Operators should be aware of possible errors that may occur during the workflow to be able to keep the deviation values in a clinically acceptable range.

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Review Article

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A review of the use of artificial intelligence in orthodontics

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Abstract
The clinical use of artificial intelligence technology in orthodontics has increased significantly in recent years. Artificial intelligence can be utilized in almost every part of orthodontic workflow. It is an important decision-making aid as well as being a tool for building more efficient treatment methods. The use of artificial intelligence reduces costs, accelerates the diagnosis and treatment process and reduces or even eliminates the need for manpower. This review article evaluates the current literature on artificial intelligence and machine learning in the field of orthodontics. The areas that the artificial intelligence is still absent have also been discussed in detail. Despite its shortcomings, artificial intelligence is considered to be a fundamental part of orthodontic practice in the near future.

Keywords: artificial intelligence, digital orthodontics, machine learning, orthodontics

1. Introduction

Digital data processing technologies in medical and dental fields have gained attention in the last two decades. Utilization of digital technology, especially artificial intelligence (AI) technology, can help to reduce the cost and duration of treatment, the need for human expertise and the number of medical error cases. This approach also has a revolutionary potential in public health scenarios in developing countries.

Artificial intelligence, which was brought forward by McCarthy in 1956, can be described as the behavior of the non-biologic beings which has the capacity to perceive complex environments, learn and react accordingly (Nilsson and Nilsson, 1998). Artificial intelligence does not necessarily mimic the human brain, it is rather a problem-solving tool which has its own set of rules. Studies have been conducted to achieve human-like behaviors with AI and it has been found that computers exceed human results in many parameters (Faber et al., 2019). Artificial intelligence technology has been used in a wide spectrum from differential diagnosis and radiographic interpretation to restorative treatment in dental field (Khanna, 2010). Dental management software, which uses AI to gather and store the patient data, is available in the market. In this point, artificial intelligence can be used to generate complete detailed virtual databases which are easily accessible. Interactive and voice recognizing interfaces help dental clinicians to easily complete some complex tasks. Software with AI technology can document the necessary data and transfer them to the clinician faster and more efficiently than its human counterparts (Kannan, 2017). With its unique learning ability, AI can be trained to perform different tasks. It can be integrated into dental imaging systems to identify even the smallest deviations which human eye cannot recognize. With this outstanding ability, it can easily be used to make accurate diagnosis of cephalometric landmarks (Tong et al., 1989).

Artificial intelligence-based software systems have significant and modificative role in the field of orthodontics and they are considered as the future of dental applications. For this reason, we aimed to review the literature on the use of AI technology in the orthodontic field (Table 1). Artificial intelligence is used in every area of orthodontics from patient communication and diagnosis to treatment processes. Orthodontic software programs which use AI technologies are based on "machine learning" technology. "The machine" uses raw data to collect information from a database in machine learning technology. These software programs can analyze diagnostic dental radiographs and photos, also they can give guidance to the dentists, during 3D intraoral scanning, to reach an ideal model easily (Kattadiyil et al., 2014). The use of AI can be divided into two main application areas in orthodontics in particular: diagnosis and treatment (Fig. 1).

2. Artificial intelligence and orthodontic diagnosis

Patient data, carefully obtained from an adequate database containing a detailed list of the patient's problems, form the basis of correct and accurate orthodontic diagnosis. The orthodontic diagnostic database can be obtained from written or verbal interview data; clinical examination and examination of patient records including dental impressions, radiographs, and diagnostic photographs (Proffit et al., 2018).

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Table 1. Current literature on the use of artificial intelligence in orthodontic

Year	Author	Article
2002	Akçam et al.	Fuzzy modelling for selecting headgear types
2006	Noroozi et al.	Orthodontic treatment planning software
2006	Zarei et al.	An intelligent system for prediction of orthodontic treatment outcome
2009	Kim et al.	Prognosis prediction for class III malocclusion treatment by feature wrapping method
2009	Tanikawa et al.	Automated cephalometry: system performance reliability using landmark-dependent criteria
2010	Khanna et al.	Artificial intelligence: contemporary applications and future compass
2010	Mario et al.	Paraconsistent artificial neural network as auxiliary in cephalometric diagnosis
2010	Tanikawa et al.	Automatic recognition of anatomic features on cephalograms of preadolescent children
2010	Xie et al.	Artificial neural network modeling for deciding if extractions are necessary prior to orthodontic treatment
2010	Yagi et al.	Decision-making system for orthodontic treatment planning based on direct implementation of expertise knowledge
2011	Auconi et al.	A network approach to orthodontic diagnosis
2011	Banumathi et al.	Diagnosis of dental deformities in cephalometry images using support vector machine
2014	Buschang et al.	Predicted and actual end-of-treatment occlusion produced with aligner therapy
2014	Yu et al.	Evaluation of facial attractiveness for patients with malocclusion: a machine-learning technique employing Procrustes
2015	Auconi et al.	Prediction of Class III treatment outcomes through orthodontic data mining.
2015	Gupta et al.	A knowledge-based algorithm for automatic detection of cephalometric landmarks on CBCT images
2016	Jung et al.	New approach for the diagnosis of extractions with neural network machine learning
2016	Nino-Sandoval et al.	An automatic method for skeletal patterns classification using craniomaxillary variables on a Colombian population
2016	Wang et al.	Objective method for evaluating orthodontic treatment from the lay perspective: An eye-tracking study
2017	Grünheid et al.	How accurate is Invisalign in nonextraction cases? Are predicted tooth positions achieved?
2017	Kannan et al.	Artificial Intelligence-Applications in Healthcare
2017	Lee et al.	Fully automated deep learning system for bone age assessment
2017	Murata et al.	Towards a fully automated diagnostic system for orthodontic treatment in dentistry
2017	Nino-Sandoval et al.	Use of automated learning techniques for predicting mandibular morphology in skeletal class I, II and III.
2017	Spampinato et al.	Deep learning for automated skeletal bone age assessment in X-ray images
2018	Iglovikov et al.	Paediatric bone age assessment using deep convolutional neural networks
2018	Larson et al.	Performance of a deep-learning neural network model in assessing skeletal maturity on pediatric hand radiographs
2018	Montúfar et al.	Automatic 3-dimensional cephalometric landmarking based on active shape models in related projections
2018	Montúfar et al.	Hybrid approach for automatic cephalometric landmark annotation on cone-beam computed tomography volumes
2019	Faber et al.	Artificial intelligence in orthodontics
2019	Kök et al.	Usage and comparison of artificial intelligence algorithms for determination of growth and development by cervical vertebrae stages in orthodontics.
2019	Patcas et al.	Applying artificial intelligence to assess the impact of orthognathic treatment on facial attractiveness and estimated age
2020	Kunz et al.	Artificial intelligence in orthodontics: Evaluation of a fully automated cephalometric analysis using a customized convolutional neural network
2020	Lee et al.	Deep Convolutional Neural Networks Based Analysis of Cephalometric Radiographs for Differential Diagnosis of Orthognathic Surgery Indications

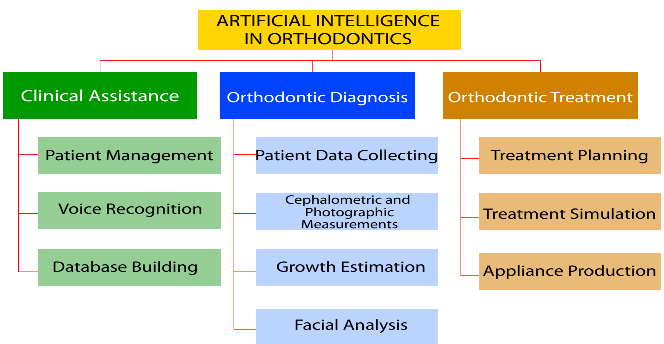

Fig. 1. The areas of orthodontics that artificial intelligence was used

Clinicians experience some time and accuracy constraints in patient evaluation process. For the reason that patient evaluation and getting patient records are time-consuming steps, automation of diagnosis and imaging is essential to increase the speed and accuracy of the evaluation (Murata et al., 2017).

The need of a thorough simultaneous evaluation of different parts of facial structures from different aspects makes orthodontic diagnosis a challenging task. Digital dentistry tools have enabled the collection of patient data on a digital platform and the creation of a digital database that can be used for diagnosis and treatment. Although digital data acquisition accelerated the speed of diagnosis and treatment phases, it still does not eliminate the need for an expert clinician for analysis and decision-making steps (Yagi et al., 2010). The automation systems which use AI and machine learning technologies remarkably have decreased the evaluation workload and prevented the diagnostic variations (Murata et al., 2017).

Different algorithms of AI systems were tested in several studies in the orthodontic field. All these algorithms needed a big database of patient examination records as input. The results showed that the use of AI during diagnosis reduced the need for an expert clinician and the number of diagnostic errors. The researchers concluded that the AI applications were promising in orthodontic field (Kim et al., 2009; Yagi et al., 2010; Auconi et al., 2011;; Niño-Sandoval et al., 2016; Wang et al., 2016; Murata et al., 2017).

Noroozi et al. (2006) described a software which used "fuzzy logic" concept. The software took graphical and numeric patient data as input and could recommend treatment plan for non-surgical orthodontic patients. Fuzzy logic enables the software work with the nominal parameters. Human brain is naturally accustomed to these "fuzzy" parameters. The authors asserted that the software program could suggest treatment options even for the specific situations like missing teeth.

3. Automated cephalometric tracing

Tracing of cephalometric radiographs can either be done manually or digitally with computer aid. Although the use of computers for cephalometric tracing aims to save time by reducing tracking errors and increasing the diagnostic value of cephalometric analysis, the inconsistency in identifying anatomical landmarks is still a major source of random error (Miller et al., 1971).

In order to overcome this problem, efforts have been made to automate cephalometric analysis with the aim of reducing errors and the time required for analysis (Hutton et al., 2000).

Levy-Mandel et al. (1985) conducted the first study on automatic extraction of anatomical landmarks on lateral cephalometric radiographs. They preprocessed the image with an edge-detector and knowledge-based line-following algorithm, involving a production system with organized sets of rules and a simple interpreter, was subsequently applied. Automated cephalometric tracing was subsequently studied by several other researchers and proved to perform as successfully as expert dentists and could be used to accelerate the cephalometric diagnostic phase (Tanikawa et al., 2009, 2010; Mario et al., 2010; Banumathi et al., 2011; Gupta et al., 2015; Montúfar et al., 2018a, 2018b; Kunz et al., 2020). Although AI systems have not been utilized for fully automated cephalometric tracing yet, they have reached the maturity to be used in some existing cephalometric software programs to suggest possible locations of anatomical structures.

Lee et al. (2020) used deep convolutional neural network-based analysis for automated cephalometric tracing. Authors asserted that the developed software had a high success rate (over 90%) in differential diagnosis of cephalometric landmarks. The automated tracing module was integrated into a recent web-based software. The web-based software can also detect soft tissue profile in profile photographs and with its orthognathic surgery planning module, it can simulate possible soft tissue changes after planned orthognathic treatment.

4. Estimation of growth and development

Timing is one of the main components of orthodontic treatment. Growth and development can be estimated by anthropometric indicators like chronologic age, menarche, vocal changes, height increase and skeletal maturation (skeletal age) (Hägg and Taranger, 1982). Radiographs are widely used for detection of skeletal maturation indicators (Hägg and Taranger, 1980). Deep learning (a machine learning algorithm that uses multiple layers to progressively extract higher level features from the raw input) and AI technologies were used by several authors to automate the age estimation by examining hand and wrist radiographs. With deep learning ability, AI systems can evaluate the radiographs after the input of a vast database consists of race, age, and gender. Results show that the AI systems can evaluate the skeletal maturity with a performance like a radiologist (Lee et al., 2017; Spampinato et al., 2017; Iglovikov et al., 2018; Larson et al., 2018).

Maturation levels of cervical vertebrae are also used for assessment of skeletal maturity. Kök et al. (2019) compared seven different, widely used AI algorithms to estimate cervical vertebrae maturation levels. Artificial Neural Networks (ANN) algorithm, which is a mathematical model of human nervous system formed by artificial nerve cells, showed better results. The authors concluded that ANN could be used in the future applications for determining cervical vertebrae stage.

5. Facial proportions

Evaluation of facial proportions includes measurement of ratios and linear lengths between facial structures. Although lateral cephalometric radiographs and profile photographs are widely used for linear assessments, it is difficult to perform sensitive measurements because of the magnification differences. Ratios and angular measurements are independent of dimensions and generally used for photographic assessment.

Measurements of "ideal" facial proportions are currently used by surgeons and orthodontists to comprehend the ideals of beauty and reproduce aesthetically "beautiful" proportions (Harrar et al., 2018). However, the classical rules of ideal facial aesthetics have some deficiencies in reflecting the beauty perception of the population because facial beauty is a very subjective concept and there is not widely used and validated set of rules for facial aesthetics, which is approved by the population. (Knight and Keith, 2005; Yin et al., 2014).

Today, AI applications do not only perform basic tasks such as optical facial recognition, but they are also matured enough to simulate much complex cognitive tasks including analysis and interpretation of facial data. Studies in this field showed that AI systems seemed to be promising tools to build a validated formula for the human perception of facial attractiveness (Patcas et al., 2019; Yu et al., 2014).

6. Artificial intelligence and orthodontic treatment planning

Extraction decision

Planning phase is the most significant and critical part of orthodontic treatment. Extractions should be carefully planned due to their irreversible nature. Clinicians come to the stage of deciding to extractions after combining the patient data derived from clinical evaluations, diagnostic photographs, dental models and radiographs with their clinical expertise. Although practitioners with less experience can learn from the decisions of their more experienced colleagues, the lack of a standard assessment method for the decision-making process requires a different approach. Neural networks were used to mimic human decision-making process for orthodontic extractions. Sagittal, vertical and molar relationships, tooth inclinations, overjet, overbite, protrusion index, soft tissue characteristics and patient complaints were given as input. Artificial intelligence system can then guide the clinician to decide the extraction, based on the analysis fed from the mentioned inputs. Studies showed that artificial intelligence systems can assist clinicians by preventing errors in decision step and can provide 80 to 90% accuracy when making an orthodontic extraction decision (Jung and Kim, 2016; Xie et al., 2010).

Appliance selection

Headgears are widely used as an extraoral anchorage device for growth modification, and they also provide force for molar distalization. Although they are typically used for the Class II patients with increased overbite and overjet and decreased mandibular plane angle, case selection is still challenging for inexperienced clinicians especially when planning the “borderline” or “marginal” cases because the decision-making process to choose an appropriate headgear type is considered more appropriate to be treated not separately, but rather in a continuous manner, that is, fuzzy logic.

Akçam and Tanaka (2002) developed a professional system based on fuzzy logic, which could infer an optimum selection of headgear type for orthodontic patients. The model in their study used overjet, overbite, and mandibular plane angle as input parameters. System used three different fuzzy logic clusters to choose from low, medium, or high pull headgear types. Eight expert orthodontists evaluated the headgear recommendation for 85 patients. Average satisfaction rate of the examiners was as high as 95,6%. Therefore, the usefulness of the proposed inference logic system was confirmed.

Estimation of treatment results and appliance production

Multi-regression models are used in the dental and medical field to assess the relationship between a range of features and the outcomes. This technique has the potential to identify the best predictors and it also offers a model that expresses the dependent variables in terms of correlated independent variables. On the other hand, it has some shortcomings, such as limitations in identifying all possible outcomes and establishing a linear relationship between variables and their outcomes (Zarei et al., 2006).

Artificial neural networks were cited as good candidates to develop a predictive model for orthodontic therapy, thanks to their ability to detect complex non-linear relationships between inputs and outputs. Artificial neural networks were shown to have the ability to learn and generalize beyond the situations they were faced with (Zarei et al., 2006).

There are studies in the literature which showed that the treatment results of Class II and Class III patients could be simulated by utilizing artificial neural networks technique. The researchers conclude that the neural networks technique is a promising tool which can be used for simulation of different malocclusion models (Zarei et al., 2006; Auconi et al., 2015).

Simulation of orthodontic treatment has gained popularity by clear aligner systems produced by a digital process.

Moving the teeth with “tooth positioning appliances” through sequential stages which are formed by “set-ups” on plaster models was a concept introduced by Kesling (1945). The major drawback of this technique was that there was a need to manually subdivide the movement into small increments by different plaster set-ups for each increment (Faltin et al., 2003).

The introduction of the Invisalign system in 1997, which was the first treatment technique in the field of orthodontics using digital 3D technology, made Kesling's idea much more practical. Instead of requiring a new model for each step of the treatment, Invisalign used a set of algorithms to generate altered digital 3D models to produce a set of aligners. The system digitally simulated incremental movements of the teeth. Based on input data and statistical analysis, AI software helps to estimate tooth movement and the outcome of orthodontic treatment. Similar software programs are used for production of different orthodontic appliances (Vecsei et al., 2017). To have a valid and effective aligner treatment, it is essential to have comparable predicted and actual outcomes (Buschang et al., 2014). The tooth control capability and outcome prediction of this AI-based digital system have been discussed extensively in the previous literature.

A case report by Faltin et al. (2003) compared the estimated end results provided by the ClinCheck software, the software for planning Invisalign treatments, to actual clinical results and concluded that the similarities between virtual and clinical results seemed to be satisfying. As a result, treatment and the treatment plan with the system were proved to have a reliable estimation capability.

In two more recent papers Buschang et al. (2014) and Grünheid et al. (2017) again compared ClinCheck treatment results to clinical results with the aim of testing the simulation capacity of the software. They found that although the software was successful in simulating simpler treatment plans, there were significant differences between the simulation and clinical results in more complex treatments. The ClinCheck software showed extremely limited reliability when it came to simulation of extraction therapy. ClinCheck models failed to accurately reflect patients' final occlusion in complex treatments.

7. Conclusion

It is quite clear that AI technology has a significant impact on the dental field, and so far, there have been major investments in this field. Although early attempts showed apparent deficiency, improvement in AI area is accelerating. Artificial intelligence can be a useful and practical tool for minimizing errors and improving patient care.

One of the most common criticisms against AI technology stems from the fear that corporate initiatives will exclude expert clinicians from the healthcare system and reduce treatment costs by using AI systems. Furthermore, it is difficult to say that this is an unnecessary fear because recent developments show that attempts in this direction have already started. Although it is still clear that AI is not likely to replace clinicians in the near future, the increasing use of digital 3D technologies in orthodontics shows that AI technology, which helps in interpretation of complex data, will also keep attracting increasing attention.

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Education and learning in digital dentistry

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Abstract
Digital dentistry includes a wide range of technologies that bring communication, documentation, production and distribution under the umbrella of computer-based algorithms in dental treatments. It also plays an important role in shaping innovation and student experience in dentistry education. Since learning methods and tools continue to advance, an understanding of educational methodologies themselves, as well as those who use them to teach and learn, is crucial to optimizing educational effectiveness. In undergraduate dental laboratory training, digital simulation technologies have already been implemented to dental faculties and their curriculums in several countries. These simulation technologies include digital microscopes, virtual pathology slides, digital X-ray images, digital dental skill training machines, digital assessment systems, and robot patients. In this article an overview to the digital dentistry education was reported.

Keywords: digital dentistry, dental education, digital preclinical education, digital simulation technologies

1. Introduction

Generation Y (millennium generation) is the expression used to describe a person who generally reached adulthood in the early 21st century and was born in the period of the early 1980s to the early 2000s (Jackson et al., 2018). Most dental students belong to the millennial generation came to the campus in 2000 (Blue and Henson, 2015). This generation, born in the age of rapid technological advancements and has different features that may require former educators to adapt their teaching strategies to the most effective way (Turner et al., 2016; Jackson et al., 2018). Their unique characteristics, diversities and expectations for the learning environment are challenging the faculties to reconsider their traditional pedagogy as well as the learning environments offered to students (Blue and Henson, 2015).

Technology is perhaps the most distinctive feature of the Millennial generation. Because of personal computers are indispensable for this generation and are always with them, this generation awaits an environment enriched with multimedia in the classroom. Interestingly, professors using multimedia (YouTube, movie clips, etc.) saw better student test scores in quizzes and examinations (Wilson and Gerber, 2008; Blue and Henson, 2015). Technology allows Millenails in constant contact with each other and the world around them, and blurs the lines between work and life (Blue and Henson, 2015).

In addition, the use of technology can allow direct observation of students' studying habits and generate objective data to help optimize and personalize dental education. (Jackson et al., 2011; Jackson et al., 2018). It is important that the faculty “frames” the course and supports student interactions by providing resources and opportunities. In addition, the faculty should develop a conceptual rationale for incorporating technology into its teaching and determining how it fits into teaching and learning philosophies. In other words, technology should only be used if it improves teaching and learning, not for its own sake (Blue and Henson, 2015).

2. What is digital dentistry?

Digital technologies have gained great importance in recent years and play an important role in the development of dentistry. Today, in dentistry applications; communication and access to information are increasingly computer-aided, digital radiology and photography have become widespread in diagnosis, and dental treatments are mostly based on digital methods for processes such as impression taking, treatment planning and implant surgery (van der Zande et al., 2013).

The spread of digital technologies in dentistry began in the early 1990s with the introduction of digital radiography, and the first versions of intraoral scanning and computer-assisted design, computer-assisted manufacturing (CAD/CAM) crowns. With the development of cone-beam computed tomography (CBCT), the three-dimensional images of the

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craniofacial region became the precursor of a second wave of excitement as it offered new advantages in diagnosis and treatment. When improvements in hardware, software and materials were combined in the early 2000s, new successes in clinical dentistry were realized. Same-day, chairside restorations of remarkable dimensional and esthetic fidelity were obtainable. Guided implant surgeries provided enhanced therapeutic workflow and safety (Cooper, 2019).

3. Digital dentistry education

Today, technology is playing an important role in driving innovation and shaping student experience in dentistry education. As learning methods and tools continue to advance understanding educational methodologies is crucial to optimizing educational effectiveness, (Jackson et al., 2018). Innovations such as virtual anatomy, haptic feedback tools, and improved digital charting methods offer many opportunities to make pre-clinical education more efficient. In restorative dentistry and prosthodontics, digital assessment tools allow students to evaluate their performance in real-time without direct supervision. Digital communication tools in clinics provide remote supervision or advanced local management of supervision. In addition to these advantages, digital technology poses significant challenges for curriculum management, and the overlap of analog and digital educational objectives requires adaptation. In addition, if digital technology is adopted in restorative and prosthodontics education, most of the dental stones, waxes, casting alloys and traditional dental materials will not be used and the value of traditional dental materials will decrease.

In the age of big data and analytics, perhaps students will need more computer programming knowledge to support evidence-based decision making and to fully discover the information needed, and therefore will need to take computer courses. In this way, digital technology can become an educational goal and desired competence that will replace other parts of the curriculum. Another concern is that students' patient interaction skills may suffer if they interface with technology more than with surrogate patients, faculty, and peers. There is also another concern that students will not develop the manual dexterity required to perform dental procedures at defined competency levels using analog procedures. Finally, as a result of the inability to achieve technological developments in education in low socioeconomic income societies, potential social injustice may arise or increase (Cooper, 2019).

4. Digital simulation technologies in dental education

The use of digital simulation technologies in undergraduate dental laboratory training has already been implemented to their professional curricula in various countries (the United States, Germany, Australia, the UK and China). These simulation technologies include digital microscopes, virtual pathology slides, digital X-ray images, and digital preclinical laboratory training systems and robot patients (Ren et al., 2017).

Digital microscopes

Light microscopy is an analog technology that has been used in dentistry education for a long time, especially in the fields of histology and pathology. The latest technological advances have enabled computers to turn into microscopes, making the transition from light microscopy to digital microscopy (DM). DM is a technology that uses the computer to analyze a slide specimen. Following traditional slide preparation, slides are digitally scanned at a high resolution, making the sample suitable for computer analysis and interpretation (Farah and Maybury, 2009; McCready and Jham, 2013).

Recent studies have shown that DM has become increasingly important in many academic fields due to its popularity among students and logistical advantages. In studies where DM and traditional light microscopy were used simultaneously, students have repeatedly shown a preference for the use of DM. Students also reported that DM improved their oral and maxillofacial pathology learning positively and had a higher educational value even when the resolution and quality of the images were similar to their light microscopy counterparts (Weaker and Herbert, 2009; Szymas and Lundin, 2011; McCready and Jham, 2013).

Virtual pathology slides

Virtual pathology slides are high-resolution scanned images of glass microscope slides that can be viewed using an Internet browser (Fred and Dee, 2009). Students can analyze and interpret slides on the computer, and it means that virtual slides can be accessed at anytime from anywhere, without the risk of slide breakage or loss (Farah and Maybury, 2009; Ren et al., 2017).

This training model allowed educators to label virtual slides with arrows, circles, and text labels. Integration with a database structure allowed educators to easily link descriptive text specific to virtual slide in a separate browser window and create links to additional gross images and normal virtual slides (Fred and Dee, 2009).

Digital X-ray images

Dental digital radiographic images contain all non-film based methodologies and are often referred to as computed dental radiography, direct dental radiography or simply digital radiography (Mauriello and Platin, 2001). Digital radiography includes digital sensors instead of photographic film, which eliminates the need for chemical processing, enables the images to be transferred and enhanced digitally, and reduces the amount of radiation required. Today, digital X-ray images are widely used in dentistry education to teach oral radiographic anatomy and image interpretation (Vuchkova et al., 2012; Ren et al., 2017). According to the results of the study of Vuchkova et al. (2012) the digital method positively affected the learning process by providing the students to better interact with course material when compared to textbooks. They stated that this would be related to the students' intrinsic motivation for computer-based learning. In addition, students interpreted the use of digital methods as "interesting", "fun" and "not as boring as the textbook". As a result, they concluded that digital method is not quantitatively superior to conventional textbooks in assisting dental students, but there has been a strong preference for the digital tools as a source of learning and teaching in radiographic interpretation (Vuchkova et al., 2012).

Digital preclinical laboratory education

Simulation is a vital part of the learning of restorative dentistry. It provides the student with motor and procedural information that is otherwise impossible to learn. It is a way of ensuring patient safety while transferring those learned skills to clinical patient care. Dental training programs use simulation in a variety of ways to prepare the student for clinical activity. Basic restorative preclinical training generally focuses on standardized cavity preparation and restoration in teeth set in 'phantom heads' (Fugill, 2013).

Traditionally, mannequins have been used for clinical skill training, but the model is quite different from a real patient because it has no autonomous movement or speaking ability. This indicates that this kind of pre-clinical simulation training is inadequate (Tanzawa et al., 2012). The main disadvantages identified in the use of mannequins are:

i) lack of clinical reality,

ii) lack of testing communication skills,

iii) lack of patient management / behavior problems (Mossey et al., 2001).

Such practice sessions are supervised by clinical tutors, providing oral feedback to the students. The effectiveness of such sessions depends on the teacher's abilities and the number of tutors available to provide frequent feedback to assess students' learning progression (de Peralta et al., 2017). In order to overcome these deficiencies, simulations using advanced technology in recent years have come to the fore in the field of dentistry (Buchanan, 2001; Imber et al., 2003, Wierinck et al., 2007). The use of simulation training has become an integral part of dental education and has been practiced in dental schools throughout the world (Roy et al., 2017). Virtual reality simulators (VRS) provide benefits to traditional simulation teaching such as providing unlimited virtual teeth, immediate objective individual feedback, and unlimited user practice while reliably tracking students' progress (Gal et al., 2011). These simulated models allow instructors to explain and improve on students' hand-eye coordination and dexterity, but it is difficult to explain the verbal definition of tactile sensation. Simulation exercises including new technologies and haptic (tactile) and virtual laboratory environments have been developed, and these technologies have been reported to increase motor skills and student effectiveness while reducing time spent in faculty. Popular dental VRS systems include the Virtual Reality Dental Training Systems (VRDTS) for caries removal and periodontium measurement, the Iowa Dental Surgical Simulator (IDSS) for caries detection, PerioSim for subgingival calculus detection, and Dental Trainer for cavity preparation (Roy et al., 2017).

Lieberment and Erdelt (2020) investigated the acceptance of preclinical students for learning dental morphologies in VR and stated that the VR dental learning environment led to a much better understanding of the dental morphology by 34.9% of the students and to a better understanding by 57.1%. This illustrates the high acceptance as learning environment by the students, since the teeth can be spatially enlarged and viewed inter-actively. Also, the handling of the controllers and VR head-sets are no obstacle to the students. After a short orientation phase of about 30 seconds, all students were able to move around well in the VR dental learning environment and interact with the objects.

Buchanan stated that when students are trained with VRS, they learn faster, perform more operations per hour, gain the same level of proficiency as traditional pre-clinical laboratories, and request more evaluation on the computer, thereby shortening the teacher-student evaluation period (Buchanan, 2004).

Blended learning designs in the form of virtual reality provide instant feedback between the student and the educator, ensuring that the time spent in the laboratory is completely productive. Since the student has developed his/her fine motor skills sufficiently, he/she can safely switch move into clinical practice (Roy et al., 2017). Virtual designs allow preparations to be displayed in many ways and at various magnification rates controlled by the operator. This can enable students to understand the design and preparation of the cavity critically by themselves (Robinson et al., 2001). At the same time, the virtual mouth and the image of the tooth provide feedback on the real-time spent on the tooth analogue during the tooth preparation. The ability to record and replay individual applications is an encouraging development for this technique (Norman and Schmidt, 1992).

The HapTEL project is part of the Technology-Enhanced Learning Programme jointly funded by the UK Economic and Social Research Council and the UK Engineering and Physical Sciences Research Council (Arevalo et al., 2013). Ria et al. (2018) tested a scoring system to assess the learning progression of novice dental students using haptic virtual workstations. They found that the HapTEL VRS system usage improved the students' performance on simulated cavity preparation after practicing over two sessions.

Digital preparation assistant systems have been introduced in the last few years to improve students' learning process. In these systems, such as the PREPassist system (Kavo, Germany), students can evaluate the quality of their preparations using a computer. The system creates visualizations of different preparations of resin teeth using a CCD camera. Using this system may lead to more effective, more objective and ultimately more efficient learning of operative skills (Kournetas et al., 2004).

In recent years, especially in Japan, robotic simulated patients with the ability to move independently, secrete saliva and limited talk with the trainee has been introduced (Eaton et al., 2008; Tanzawa et al. 2012). The reasons for producing robot patients are: (i) to reproduce the oral maxillofacial anatomy for dental treatment; (ii) the whole body can be presented; (iii) autonomous movement can be produced via the robotic system; and (iv) to enable conversation with the trainee (Tanzawa et al., 2012).

5. Conclusion

In today's dentistry education, digital microscopes, virtual pathology slides, digital radiography and chairside applications of restorative and prosthetic procedures have strengthened their position, while virtual reality, haptic-enhanced VR simulations and robot patients used in pre-clinical laboratory education systems are still in the initial stage and increasing interest in their future development is apparent. Many research questions still need to be answered to accept these technological advancements more broadly in dentistry education. Expansion of software to increase the number of dental procedures available would also be advantageous. Many research questions have yet to be answered both to direct these technological developments and to establish a wider acceptance of simulation in dental education.

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Review Article

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Digital applications in endodontics: An update and review

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Abstract

The aim of this review was to provide an overview of the applications of digital dentistry technologies in endodontics, such as digital two-dimensional (2-D) and three-dimensional (3-D) imaging techniques, computer aided diagnosis (CAD) and improvement of artificial intelligence (AI) models, computer-controlled access cavity designs and 3-D printing applications. Advantages and disadvantages of these newly introduced technologies were discussed briefly with their indications. Apart from therapeutical or rehabilitative procedures, the use of digital technologies adapted for student training and research simulations were also presented.

Keywords: computer aided applications, computerized dentistry, cone-beam computed tomography, endodontology

1. Introduction

The discipline of endodontics focuses on the etiology, diagnosis, prevention and treatment of diseases of the human dental pulp and periradicular tissues in relation with their morphology, physiology and pathology (American Association of Endodontists, 2016). Endodontic treatments might aim to maintain the vitality of the pulp, to preserve and restore the pulpless tooth by the proper shaping, cleaning and filling of root canals or to replace damaged tooth structures by biologically-based procedures (American Association of Endodontists, 2016a; 2016b). Endodontics has benefited from the developments in digital dentistry due to the requirement of a proper visualization technique to reveal root canal anatomy and periradicular structures by means of digital 2-dimensional (2-D) radiography and cone-beam computed tomography (CBCT). Recently, the developments in the digital applications also enabled the developments of clinical techniques that include artificial intelligence aided diagnosis and guided access cavity preparations to directly access to root canals even in obliterated roots. The applications of digital technology in endodontics from diagnosis to clinical applications along with their advantages and disadvantages are covered in this review article.

2. Digital radiography

The use of periapical radiographs has become an indispensable part of endodontic practice since Kells calculated working length of a root canal using a lead wire in 1899 (Jacobsohn and Fedran, 1995). Imaging techniques have been widely used in endodontics to evaluate dental and alveolar hard tissue morphology and pathological changes preoperatively, to determine working length of root canals and locate intracanal objects intraoperatively and to evaluate the root canal filling and periapical healings postoperatively.

Digital radiography systems have replaced the conventional systems with the latest developments with the upcoming advantages of image processing. In conventional systems, X-ray film is the place where the image is occurred and stored; whereas in digital systems, X-ray beam falling on the detector is converted into electrical energy and digitized. The resulting image is stored in a different digital medium and can be processed further. Most important feature of digital systems is the lower radiation dose compared to conventional radiography (Petrikowski, 2005). Digital radiographic systems can be classified as direct and indirect systems according to the transformation technique that converts X-ray beam to electrical signals (Wakoh and Kuroyanagi, 2001). In direct digital techniques, a photoconductor is used that can convert X-ray directly into electrical current, thereby enabling an instant image formation on the computer screen immediately after exposure (Parks and Williamson, 2002; Kurt and Nalçacı, 2016). Radio visiography (RVG) is the most known direct digital radiography system and composed of X-ray unit, electronic timer, intraoral sensor and processing unit (Mouyen et al., 1989).

Indirect digital systems are referred as photostimulable phosphor (PSP) plates and require an extra processing step compared to direct technique (Parks and Williamson, 2002). The latent image occurs within energetic phosphor electrons, which will be stimulated by red laser beam during processing in order to be digitally manipulated to be exposed on computer's display. In terms of handling, PSP is similar to

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conventional intraoral radiography, it is practical and user-friendly (Yorkston, 2007).

In digital radiography, image contrast and brightness can be changed on the screen regardless of the kilovoltage peak and milliampere-seconds used during exposure due to the wide dynamic range (Yaffe and Rowlands, 1997; Berkhout et al., 2004). This feature largely eliminated radiographic repetitions due to insufficient exposure parameters. Digital techniques require less radiation dose than conventional techniques however, wide dynamic range also brings the risk of unnecessary radiation, which violates "As low as reasonably achievable" (ALARA) principle (International Commission on Radiological Protection, 1973; Berkhout et al., 2004). There are recommended measures to be taken to eliminate the risk of overexposure (Seibert and Morin, 2011). The optimal exposure factors determined according to the patient size should be recorded on the device for operator to select appropriate parameters. The exposure index should be displayed on the radiography device screen and the values shown should be checked. The use of devices with high detective quantum efficiency value indicating the X-ray sensitivity of the detector and the use of noise reduction algorithms in preprocessing enables to obtain low noise radiographs at standard doses (Schuncke and Neitzel, 2005; Seibert and Morin, 2011).

The most important disadvantage of periapical radiographs, whether obtained in conventional or digital techniques, is that it provides a compressed 2-D image of a 3-dimensional (3-D) object. Diagnostic ability of periapical radiographs is limited to show spatial relationship between roots and their periapical structures, actual dimension and location of a periapical lesions and root resorptions (Gröndahl and Huumonen, 2004). Multiple radiographs with varying angulations are suggested to obtain more data for assessment however, this does not guarantee the correct diagnosis of all relevant anatomy or pathology (Cotti and Campisi, 2004; Gümrü and Tarçın, 2013). Geometric distortion of the radiographic image is another important limitation, that damages the diagnostic ability of periapical radiographs (Gümrü and Tarçın, 2013).

3. Cone-beam computed tomography (CBCT)

The introduction of CBCT specifically for the imaging of dental and maxillofacial structures in 1998 caused a paradigm shift from 2-D to 3-D approach for wide range of applications from diagnostic to intraoperative guidance of surgical procedures (Mozzo et al., 1998). CBCT differs from conventional CTs by the rotation of the detector and X-ray source around a stabilized patient. CBCT has also advantages of lower radiation dose, less expensive equipment, less room space, less time for scanning compared to CT. X-ray beam is cone-shaped and captures a cylindrical data volume, identified as the field of view (FOV), which can be determined according to the region of interest. CBCT has been reported to provide images with higher quality for the assessment of dental structures than medical CT.

CBCT overcomes the disadvantages of 2-D radiography, such as elimination of superimposition of anatomical structures by assessing structures in slices with three orthogonal planes individually. Actual spatial relations and dimensions of periapical lesions can be visualized accurately, although spatial resolution is lower than conventional film based or digital periapical radiographs (Farman and Farman, 2005). Image quality is also affected by noise and artifacts such as scatter and beam hardening, which are partially prevented by artifact reducing algorithms during image reconstruction (Scarfe et al., 2009; Schulze et al., 2011).

CBCT has been reported to show higher sensitivity and specificity for the diagnosis of apical periodontitis than periapical radiographs (Patel and Horner, 2009; Davies et al., 2015). A novel classification as an update of periapical index has also been suggested using CBCT scans (Estrela et al., 2008). CBCT can also provide valuable information regarding the relationship of root tip or periapical pathology with adjacent anatomical structures when planning surgical intervention (Patel et al., 2019) (Fig. 1). It might be useful to improve the diagnosis and management of root resorptions (Patel et al., 2019). Moreover, diagnosis of dental anomalies of shape such as dens invaginatus or presence of extra roots can be improved by the use of CBCT (Patel, 2010; Keskin and Özdemir, 2018). *In vivo* CBCT studies have proposed a correlation between posttreatment apical periodontitis and undetected untreated root canals (Karabucak et al., 2016; Costa et al., 2019; Baruwa et al., 2020). CBCT was also used to assess root canal treatment quality in relation with periapical pathosis and prevalence of extra canals in larger populations in cross sectional studies (Wu et al., 2017; Martins et al., 2020; Meirinhos et al., 2020). Although CBCT is the only 3-D imaging technique suitable for clinical use, the accuracy of CBCT in revealing root canal anatomy in vitro studies falls behind micro-computed tomography (micro-CT). CBCT provided limited efficiency to distinguish different canal configurations according to the Vertucci classification (Vertucci, 2005; Ordinola-Zapata et al., 2017). CBCT detected main canals but failed to visualize fine anatomical structures connecting canals and changing their configurations and led to inaccurate diagnosis regarding canal configuration (Ordinola-Zapata et al. 2017; Tolentino et al., 2018; 2020). It has been reported that despite high resolution parameters CBCT has limited ability to visualize isthmuses in apical third, where isthmus diameter would be smaller than voxel size. Authors emphasized that CBCT image of the root canals might not reflect the actual complexity of apical anatomy (Tolentino et al., 2020).

The radiation dose might pose as a risk factor for CBCT in case of unnecessary referrals as a result of lack of proper education and awareness (Setzer et al., 2017; Krug et al., 2019). The American Association of Endodontists (AAE) and European Society of Endodontology published and updated position statements on the use of CBCT in endodontics (Fayad et al., 2015; Patel et al., 2019). The most important conclusion was that CBCT should not be used routinely and should only be considered when meticulous clinical and 2-D radiological examinations were inconclusive to clarify complex situations in accordance with ALARA principles. CBCT should not be regarded as an alternative to conventional radiographic examination techniques but rather as a complementary tool (Jung et al., 2012).

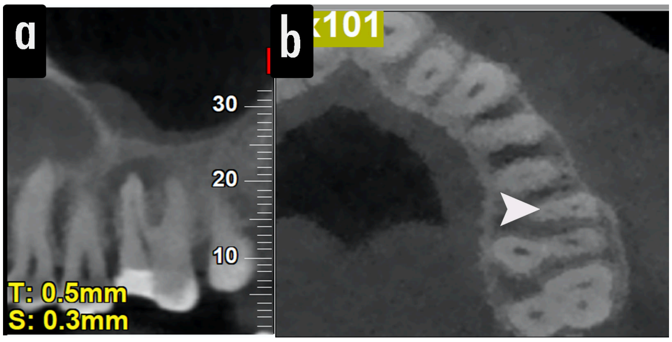

Fig. 1. Evaluation of different cross-sectional images obtained by CBCT allowed to evaluate the extent and location of periapical pathosis related to the mesiobuccal root of maxillary first molar (a), examination of axial cross section also revealed the presence of a second mesiobuccal root canal (depicted with white arrowhead) (b)

4. Computer aided diagnosis (CAD)

Despite advances in imaging technology, final diagnosis and treatment planning is based on the clinician's decision that may be prone to human error. The human error can cause the clinician to deviate from choosing the most optimal treatment option. CAD aims to perform a quantitative analysis and provide an objective report using computer algorithms.

CAD has been used widely in medical radiology and is relatively novel in dentistry. A caries detector program was developed in the late 90s that analyzed the radiography of the tooth and reported whether there was any caries, whether it was a simple decalcification or carious and whether it needed restoration or not (Gakenheimer, 2002). Neural network models for the diagnosis of interproximal carious lesions on periapical radiographs have been developed (Devito et al., 2008; Lee et al., 2018). CAD has also been developed to be used intraoperatively for real time detection of root canal orifices in combination with intraoral camera (Brüllmann et al., 2011). High sensitivity was reported for orifice detection software, which can assist students and practitioners without experience for detection of extra canal orifices (Brüllmann et al., 2011).

CAD has mainly focused on the development of artificial intelligence for the assessment of periapical lesions using digital periapical radiographs, panoramic radiographs and CBCT images (Katsumata and Fujita, 2014; Okada et al., 2015; Ekert et al., 2019; Orhan et al., 2020). These models provide objective data regarding the size of the periapical lesions and their classification, however in the lack of histological examination the true nature of the lesions is not decisive only based on their radiological appearance.

Overall, CAD should be considered as a tool that will assist the clinician for interpretation of clinical and radiological findings more objectively and combine them with the data obtained with the patient anamnesis and main complaint.

5. Guided endodontics

Root canal treatment of a calcified root canal, which means the total or partial blockage of root canal space due to mineralization or calcification, is considered as a high-difficulty case according to the AAE (Langeland et al., 1971; American Association of Endodontists, 2006). Localization of a canal orifice and negotiation through apical are particularly challenging and access attempts might result in unnecessary loss of dentin or even root perforation (Cvek et al., 1982; Kvinnsland et al., 1989). Guided endodontics concept is suggested to prevent these complications, shorten the treatment time, and increase the success rate of root canal treated calcified teeth by bringing together the technology of CBCT, 3-D printing and digital intraoral impression or scanners (Krastl et al., 2016; van der Meer et al., 2016; Zehnder et al., 2016). Today, applications of guided endodontics are also used in the treatments of anomalous teeth such as dens invaginatus and dens evaginatus, during apical surgery and preparation of ultraconservative access cavities (Pinsky et al., 2007; Zubizarreta et al., 2015; Mena-Alvarez et al., 2017; Ahn et al., 2018). A high resolution CBCT and a digital impression of the teeth are acquired and co-registered using a special image processing software (Moreno-Rabie et al., 2020). Obtained data is used to design a template that will provide guidance for accurate treatment of root canals with correct pathway. The designed template is manufactured with 3-D printer or milling. Manufactured template is placed on the teeth and further treatment burs and files are guided by the template (Zehnder et al., 2016; Moreno-Rabie et al., 2020). Clinicians can adapt burs specific for the case or use commercially available access burs with long shafts and small head such as Munce Discovery burs (CJM Engineering, Santa Barbara, CA, USA) (Connert et al., 2017; Connert et al., 2018; Torres et al., 2019). The use of ultrasonic tips is also reported (Shi et al., 2018). The term “Microguided endodontics” emerged with the adaptation of minimally invasive techniques to the methodology in the treatment of smaller roots (Connert et al., 2017; Connert et al., 2018).

Recently, a new method using computer-aided dynamic navigation has been suggested for guided endodontics (Chong et al., 2019). A mobile unit including an overhead light, stereoscopic motion-tracking camera and computer with implant planning software is used for real time guidance of handpiece calibrated on a previously determined reference point. This technique also requires high resolution CBCT images to display the suggested pathway and motion of the drills within canals. The motion tracking camera guides the handpiece while providing visual feedbacks with color codes (Chong et al., 2019).

The guided access cavity preparation has been reported to be accurate irrespective of the operator experience with a higher success rate in locating canals compared to conventional technique (Zehnder et al., 2016; Connert et al., 2017). Preclinical studies and case reports suggest guided endodontics provides predictable outcome with lower risk of iatrogenic complications (van der Meer et al., 2016; Connert et al., 2017; Connert et al., 2018; Torres et al., 2019; Moreno-Rabie et al., 2020). Further controlled studies with larger sample size are required for the assessment of its efficiency.

6. 3-D Printing

The use of 3-D printing technology in endodontics is not only limited with the applications of guided access cavity preparations. 3-D printing was initially termed as additive manufacturing, which means creating an object by incremental deposition of the selected material. 3-D printing applications employ different technologies including fused deposition modelling, digital light processing, stereolithography apparatus (SLA), MultiJet printing, PolyJet printing, ColorJet printing, and selective laser melting (Abduo et al., 2014; Anderson et al., 2018). Stereolithography apparatus has been the first and most commonly used technology in dentistry.

Prior to the use of CBCT, CT files were used to produce planning models in surgical procedures, however CBCT data have been widely used today (Mankovich et al., 1990; Bill et al., 1995). In addition to being a more accurate source for 3D printing applications, CBCT has also expanded its use with previously mentioned advantages such as reduced radiation dose, shorter scanning time and reduced cost (Scarfe et al., 2006; Cotton et al., 2007).

3-D printing has been applied for guided endodontic access, autotransplantation, endodontic surgery applications, education and research simulations (Keightley et al., 2010; Shahbazian et al., 2010; Ordinola-Zapata et al., 2014; Krastl et al., 2016; Zehnder et al., 2016; Gok et al., 2017). Guided endodontics applications are covered previously in this article. In autotransplantation applications, 3-D printing manufactures teeth replicas to be fitted in the recipient bone prior to extraction. This pre-fitting prevents the trauma of periodontal ligament of the transplanted teeth and shortens the procedure time, thereby improve the treatment outcome (Honda et al., 2010; Keightley et al., 2010; Shahbazian et al., 2010). A systematic review reported an increased success rate up to 91% due to rapid application of teeth to the recipient site with extraoral time less than 1 minute and without periodontal ligament trauma (Verweij et al., 2017).

Preparation of surgical templates allowed for precise orientation, angulation and depth during osteotomy increasing clinical efficiency with minimizing risk of sinus perforation (Pinsky et al., 2007; Strbac et al., 2017). The precision of the procedure is especially important for the survival of teeth with problematic roots with difficult accessibility for resection (Pinsky et al., 2007).

3-D printing may be useful for dental education to demonstrate and simulate teeth with certain features. The use of artificial teeth for simulation exercises has been found superior than the use of extracted teeth (Kfir et al., 2013; Bahcall, 2014; Kato and Kamio, 2015). Apart from standardization of exercise materials, they might help to simulate anomalous teeth or root canals with a predetermined configuration, which could be rarely found in natural teeth. The printing material could be a problem to simulate dental hard tissues, however new materials are developed with similar hardness to dentine (Robberecht et al., 2017). A recent study developed a cost-effective modular 3-D print model manufactured from SLA, for the study with real or artificial teeth mounted on phantom heads to improve preclinical exercises with a better simulation of clinical scenarios (Hanafi et al., 2020).

Simulation of tooth models with certain morphologies also provided in vitro studies to evaluate the efficacy of different endodontic procedures (Ordinola-Zapata et al., 2014; Eken et al., 2016; Gok et al., 2017; Mohmmed et al., 2017; Yahata et al., 2017). Specimens with C-shaped canals were manufactured based on a single tooth with required anatomy and efficacy of different root canal filling techniques were compared (Gok et al., 2017). Use of 3-D printed specimens also eliminated the problems related with collection of extracted teeth.

7. Restoration of endodontically treated teeth with computer aided design-computer aided manufacturing (CAD-CAM)

The success of root canal treatment depends on the quality of the coronal restoration, which should support the remaining tissues in functional and aesthetical means (Faria et al., 2011). Design and selection of coronal restoration is mainly determined by the amount of remaining dental structures and ranges from conservative inlays to coronaradicular restorations. Indirect restorations have become popular due to the innovations in chairside CAD-CAM units with intraoral digital scanners for the manufacture of permanent restorations in a single visit in the cases with extensive tooth tissue loss. Indirect inlay, onlay, and overlay restorations are termed according to the remaining cavity shape and manufactured from gold, composite and ceramic (Felden et al., 1998; Schulz et al., 2003). The manufacturing stages of the restoration include scanning the cavity, designing the restoration, and producing the restoration in a central milling center or in laboratory or by chairside CAM units. Chairside CAD-CAM technology enabled design of a specific monoblock restoration that contains whole crown and a protruding apical core termed as “endocrown” (Bindl and Mormann, 1999; Otto, 2004) (Fig. 2). Today, endocrowns are advocated for the restoration of endodontically treated teeth with extensive tissue loss instead of post and core restorations for the advantage of reduced chair time and less preparation of remaining tooth structure (Sedrez-Porto et al., 2016).

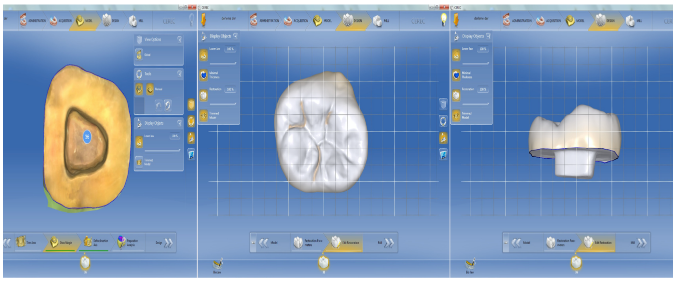

Fig. 2. Design and manufacturing of an endocrown restoration by a chairside CAD-CAM unit with an intraoral digital scanner can be completed in a single session.

8. Conclusion

The scope of digital applications in endodontics reaches far beyond digital radiographic techniques for improved 2-D and 3-D visualization. The improvements of the digital techniques and their introduction to endodontic procedures would certainly reduce treatment times as well as clinician's fatigue. The manufacturing of templates and models preoperatively would also decrease iatrogenic complications and improve treatment satisfaction irrespective of the clinician's experience. Combined use of digital techniques intraoperatively allows the survival of teeth that would otherwise be extracted or damaged due to increased complication rates.

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What does complete digital workflow mean for dentistry?

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Abstract

The introduction of computer-aided manufacturing technologies and further developments have changed the routine workflow in dentistry, and dentists are now rapidly shifting from conventional to digital. As a result, intra-oral scanners have become a standard device in dental clinics even though they have a considerable cost. One of the important reasons of this digital transition is to ensure standardized-quality manufacturing with a shorter chair time, which is promised by complete digital workflow. So, what does complete digital workflow mean for dentistry? This review elaborately answers to this question and summarizes the stages of complete digital workflow in dental applications.

Keywords: complete digital workflow, computer-aided manufacturing, digital dentistry, digital impression

1. Introduction

The introduction of computer-aided design and computer-aided manufacturing (CAD-CAM) systems along with technological developments in the 21st century have completely changed the world and started the digital revolution. In this new digital age, software's are constantly being updated, and new technological developments emerge with each passing day. However, the main question is that What does digital mean? Digital can be theoretically defined as the data processing between the 1 and 0, but literally means the way to do more with less effort (Dörner and Edelman, 2015). As for dentistry, it means science-based planning, standardized quality and reproducibility in manufacturing, ease of communication, shorter chair time, patient comfort and satisfaction, predictable treatment results, continuous and objective education, and auto-controlled treatment modality (Mangano et al., 2017; Rekow, 2020).

The decision of which stage the digital workflow will be used at is up to the dentists. Dentists may whether to proceed digitally after the impression process (semi-digital workflow) or from the beginning of treatment (complete digital workflow) (Joda et al., 2017c). Complete digital workflow followed in fabrication of both tooth-borne and implant-supported restorations consists of three stages: (1) digitization of intra-oral structures or prosthetic components (2) computer-aided design (CAD), (3) computer-aided manufacturing (CAM) (Alghazzawi, 2016). This workflow also involves a computer-aided implant surgery (CAIS) stage in implant treatments, and there is a lot of research on this subject (Widmann and Bale, 2006; Arısan et al., 2010a; Arısan et al., 2010b; Stapleton et al., 2014; Coachman et al., 2017; Joda et al., 2018)

Complete digital workflow can be perfectly utilized if the dentists and dental technicians follow the true guidelines, know the limitations of the system that they used, and act as a team. This review briefly explains the stages and limitations of complete digital workflow in both tooth-borne and implant-supported restorations (Fig. 1).

2. Computer-aided implant surgery

To ensure the optimum esthetic outcomes, dental implants should be placed in ideal position (Grunder et al., 2005). In single implant sites, the implants should be placed 1.5 to 2 mm more palatal than the expected buccal emergence profile and 3 mm more apical to cemento-enamel junction of adjacent teeth (Buser et al., 2004), and at least 1.5 mm away from the adjacent teeth (Esposito et al., 1993). Also, the minimum inter-implant distance should be 3 mm when the multiple implants are placed (Tarnow et al., 2000). In free-handed implant surgeries, adjacent teeth act as natural guides for correct positioning. However, the ideal positioning of dental implants is challenging in edentulous jaws due to lack of anatomical landmarks. (Arısan et al., 2010b). The use of surgical implant guides provides significant advantages in such cases (Arısan et al., 2010a). The fabrication of surgical guides can be conducted with complete digital workflow and this includes several steps

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as follows: (1) intra-oral scanning and exporting the scan data as standard tessellation language (.stl) file format, (2) cone-beam computed tomography (CBCT) evaluation and exporting the DICOM data, (3) superimposition of .stl and DICOM data by using the guide software, (4) virtual set-up, (5) virtual positioning of implants, (6) exporting and fabrication of three-dimensional (3D) guide model (Margvelashvili-Malament and Att, 2019). This workflow is defined as static computer-aided implant surgery (s-CAIS) (Joda et al., 2018; Tahmaseb et al., 2018). Moreover, the virtual positioning of implant can be conducted by using denture-like radiographic templates, which includes radiopaque landmarks, and this is also called prosthetically driven and computer guided implant planning or prosthetically driven implant surgery (Katsoulis et al., 2009; D'haese et al., 2017). An alternative digital workflow for implant surgeries is the dynamic navigation systems, which are based on motion-tracking technology. The navigation systems allow real-time tracking of implant drills (D'haese et al., 2017). Dynamic navigation also allows changing the surgical plan, and this is an important advantage for the benefit of patients (Block and Emery, 2016).

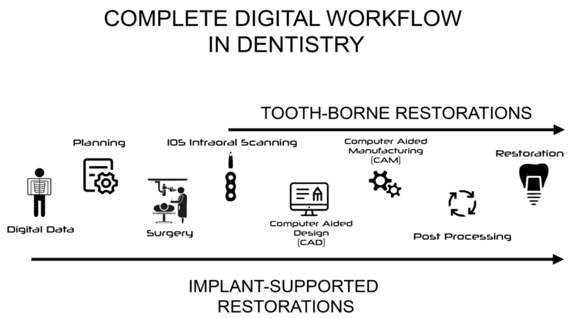

Fig. 1. Complete digital workflow in dentistry

3. Intra-oral digitization

In tooth-borne restorations, the complete digital workflow begins with the use of intraoral scanner (IOS), and this is termed as computer-aided impressioning (CAI) (Patzelt et al., 2013). CAI eliminates the expansion, shrinkage, and distortion of both cast models and elastomeric impressions and offers a repeatable workflow (Patzelt et al., 2014a; Ting-Shu and Jian, 2015; Mangano et al., 2017). Today, many dental clinics use the IOSs in routine clinical practice. Dentists, who consider buying an IOS, question digital impressions in terms of accuracy, time efficiency, and patient comfort. In the available literature, sufficient data exist that answer to these questions.

Several studies evaluated the accuracy of digital impressions, and the common view is that single-tooth or partial-arch impressions are a valid alternative to conventional impressions, whereas the full-arch digital impressions are still questionable (Ender et al., 2016a; Ender et al., 2016b; Ahlholm et al., 2018; Ender et al., 2019), and this is also valid for full-arch implant impressions (Ender and Mehl, 2015; Mangano et al., 2017).

In digital implant impressions, scan bodies are used instead of impression copings, which are used in conventional implant impressions. A scan body simply consists of three parts: upper part (scan region), middle part (body), and apical part (base) (Fig. 2). The base part can be metal, titanium (Ti) or polyetheretherketone (PEEK), whereas the scan region is mostly PEEK (Mizumoto and Yilmaz, 2018). One of the main advantages of the digital implant impressions with scan bodies is that angulation of implants has no significant effect on impression accuracy (Giménez et al., 2015). However, the visibility of the scan bodies may have an impact on accuracy, particularly when the implants are deeply placed. Moreover, it has been reported that the first scanned quadrant achieves better accuracy than the second quadrant; and therefore, it is recommended to start the scanning process from the restoration site in partial restorations (Gimenez-Gonzalez et al., 2017).

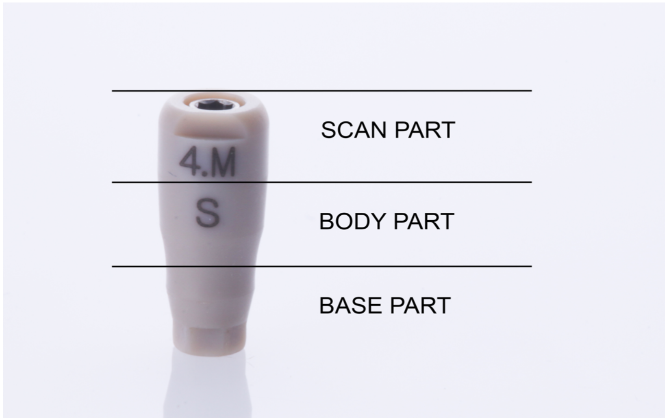

Fig. 2. Parts of implant scan bodies

Furthermore, the scanning strategies and scanning software's also influence the accuracy of digital impressions (Ender and Mehl, 2013; Haddadi et al., 2018; Ender et al., 2019). The scanning strategies are specific to the IOS system; and therefore, clinicians should follow the manufacturer's guidelines to obtain optimum accuracy results (Ender et al., 2019).

As for time efficiency and patient comfort, digital impression techniques have been reported to be preferable in tooth-borne restorations (Patzelt et al., 2014b; Yuzbasioglu et al., 2014), and in single-implant cases. A quadrant-like intra-oral scanning process is sufficient to record the single-implant sites rather than taking full-arch conventional impressions (Joda and Brägger, 2015; Joda et al., 2017b; Mühlemann et al., 2018). However, this may not be valid for full-arch digital implant impressions (Sailer et al., 2019). Besides, time efficiency and patient comfort is up to the dentists' skills and experience as well (Giménez et al., 2015; Gimenez-Gonzalez et al., 2017). The duration of scanning process may prolong in the first digital impression trials and prolonged impression time may discomfort patients, but over time this will gradually decrease parallel to the learning curve (Mangano et al., 2017).

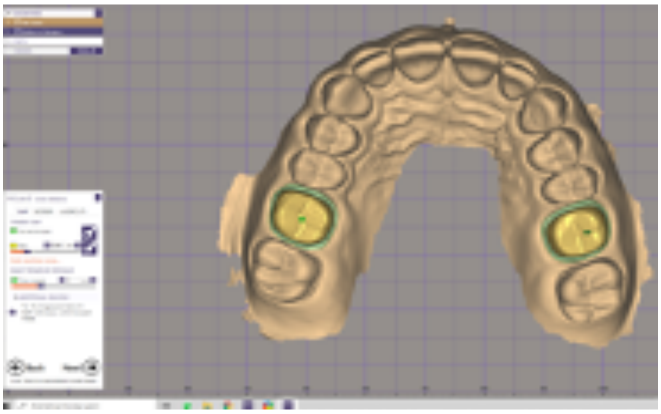

Fig. 3. Designing parameters in CAD software

4. Digital design process

Once the digital impression process is completed, the scan data can be directly transferred to milling device, if available in the clinic, or sent to the dental laboratory via the IOS's software network (Selz et al., 2016). Another option is to export the scan data as .stl file format and send to the laboratory via internet network (Ting-Shu and Jian, 2015; Alghazzawi, 2016). Today, a majority of IOS manufacturers allows to export .stl files, and this makes the digital workflow more accessible. When the designer technician imported the .stl file into the CAD software, another adventure begins. The CAD software automatically creates a crown morphology over the prepared tooth or implant abutment; however, each design should be modified manually because the tooth morphology is unique for each patient. One of the important advantages of digital design is that the CAD software allows the designer to imitate the individual morphological features, particularly in the occlusal region, by selecting the biogeneric copy tool (Alghazzawi, 2016). Thus, restorations can be designed according to habitual occlusion of each patient. Also, the designer can control several parameters (Fig. 3), such as the level of adjacent and antagonist contacts, cement film thickness, and margin design (Tapiea et al., 2015). These parameters can be set according to the clinicians' requests. Moreover, the current CAD software's include virtual articulator and facebow modules (Fig. 4), which allow to adjust the occlusal contacts in accordance with actual mandibular movements, and this minimizes the final occlusal adjustments in the patients' mouth.

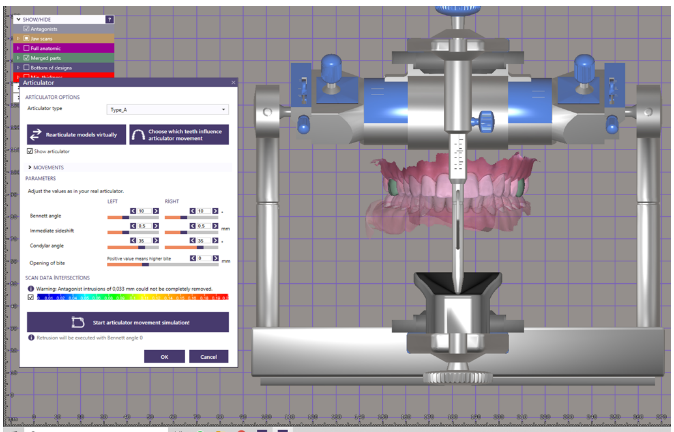

Fig. 4. Use of virtual articulator module in CAD software

5. Digital manufacturing

Computer-aided manufacturing is the last stage of the complete digital workflow. In this stage, the CAD data transform into an actual restoration. This process can be conducted by using subtractive or additive manufacturing systems (Van Noort, 2012; Alghazzawi, 2016). In subtractive manufacturing, the restorations are fabricated by milling (metal, zirconia, PMMA, composite resin) or grinding (ceramics) large solid blocks with using sharp cutting tools (Alghazzawi, 2016). Unlike subtractive systems, additive manufacturing is the process based on joining materials to fabricate objects from 3D models (Van Noort, 2012; Alghazzawi, 2016). Which system to use generally depends on the material used and the workflow followed. With the spread of the complete digital workflow in dentistry, the use of monolithic restorations has increased (Joda and Brägger, 2016; Joda et al., 2017a; De Angelis et al., 2020), and this requires the use of milling systems. Currently, additive manufacturing is not a valid method for processing dental ceramics. Additive manufacturing solutions are generally used in direct metal laser sintering/melting of metal frameworks and 3D printing of temporary restorations, complete dentures, digital models, surgical guides, custom trays, and wax patterns (Van Noort, 2012; Alghazzawi, 2016).

The design and manufacturing stages of complete digital workflow can be completed in either dental clinics or dental laboratories. Dental clinics may have their own design software and milling systems, and thus, they can have the chance to fabricate ceramic restorations on the same day along with tooth preparations, that is also called as chairside workflow (Fasbinder, 2006; Fasbinder, 2013). However, milling machines, which are promoted for dental clinics, generally have four axes milling units and less cutting tools; therefore, the milling accuracy is lower than five axes milling units, which are used in dental laboratories (Alghazzawi, 2016). For this reason, chairside workflow is not efficient in all cases, particularly in fabrication of full-arch restorations, which need high milling precision. Full-arch restorations are mostly fabricated in dental laboratories because they provide industrial manufacturing solutions with high precision rate (Miyazaki and Hotta, 2011; Alghazzawi, 2016).

5. Conclusion

The digital workflow journey involves several steps, and each step has its own learning curve. Clinicians and dental technicians must know the limitations of the system they used, and they should be patient to gain a certain level of experience. Computer-aided dentistry constantly evolves, and software's are updated day by day. To improve the accuracy and feasibility of digital workflow, manufacturers require technical and clinical feedbacks. If the clinicians report the clinical outcomes in a constructive manner, many problems experienced in the complete digital workflow would be overcome in the future.

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Review Article

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Monolithic CAD/CAM restorations-Esthetic zone applications

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Abstract

Computer-aided design and manufacturing technology has been closely associated with implant-supported restoration. The digital systems which are used for restorative purposes comprise data acquisition, processing, and manufacturing using subtractive or additive methods. Advancements in digital dentistry are closely related to developments in optical scanning, computer-based digital algorithms and fabricating techniques in terms of accuracy and reliability which helped the development of novel ceramic materials with high esthetics and strength for versatile clinical applications. Time efficiency, cost effectivity, durability and biomimetic properties of machine-made restorations necessitate monolithic materials to serve this purpose. Contemporary ceramic materials are being widely used for rehabilitation of dentition from a single unit to full arch cases. This review aims to give an insight about optical properties and clinical use of monolithic materials.

Keywords: cadcam, dental, dentistry, digital, monolithic

1. Introduction

Porcelain use in dental restorations started in 1950s by applying porcelain bonded to metal (Asgar, 1998). The castable Dicor® crown system was also developed in the 1950s by Corning Glass Works. Glass was strengthened with mica by using the lost-wax casting technique. The 'casted restoration' was heat-treated or cerammed to provide a controlled crystallization of the glass. The type of crystal formation examples is leucite, fluoromica glass, lithium disilicate, and apatite glass ceramics (Krishna et al., 2009).

To solve the thermal expansion mismatch problem between metals and feldspathic porcelains Leucite was added. Aim was to raise the coefficient of thermal expansion. The crystalline leucite phases tend to slow down crack propagation of feldspathic porcelain. High leucite-containing ceramics Empress® 1 and optimal pressable glass ceramics were introduced to the market in the late 1980s to be the first examples of pressable ceramic materials and that was a major step towards contemporary CAD CAM materials like Empress CAD.

The first computer-aided design/computer-aided manufactured (CAD/CAM) substructure material, Procera® AllCeram core, was produced by Nobel Biocare in the mid-1990s and consisted of 99.9% alumina core to which a feldspathic ceramic was layered. In 1998 IPS Empress II, a lithium disilicate ceramic material used as a single and multiple-unit framework indicated for the anterior region, was introduced by Ivoclar. The core required a layering with a veneer porcelain specially designed for the material. A five-year study revealed a 70% success rate was shown for five years as a fixed partial denture framework (Marquardt and Strub, 2006).

Lithium disilicate was re-introduced to the market in 2006 as a partially crystalized milling block (Cerec® for chairside and inLab® milling units for laboratories). The flexural strength of the material was very high compared to other all ceramic systems. Block option enabled CAD/CAM milling of a framework which allowed for cut-back and layering with porcelain or produce an implant abutment with a titanium base allowed many opportunities for digital dentistry. Monolithic dental restorations are the essence of high technology dental treatments with full digital workflow. They combine the strength and durability with natural optical properties. Choice for a monolithic dental restoration material is based on several factors; translucency of teeth, parafunctional habits, occlusal relations, opposing dentition and extent of restoration.

A full digital workflow in restorative procedures is defined as the production and delivery of a restoration without a physical model. Intraoral scanners are used for impression procedures. Design and planning are made virtually on a design software. CAD design is transferred to the milling machine. And the final product should not necessitate any manual material add-ons or model transfers. Final design and form of the restoration is milled or 3D printed. Only minor corrections and occlusal adjustments are performed. Following a mechanical polishing the restoration may or may not require a glaze and make-up procedure depending on the material choice

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and indication. After finalization of the restoration, the definitive restoration is delivered to the patient. Monolithic restorations' treatment range covers single veneers to full arch rehabilitations including implant supported restorations.

2.1. Advantages of monolithic restorations

Less preparation is needed due to lack of layering depending on the case. Even 0.1 mm thickness (contact lens) laminate veneers can be produced by combining CAD/CAM technologies with manual applications.

- Less prone to chipping and fractures
- Demonstrate adequate strength to withstand chewing forces
- Broad range of trancluceny and polychromatic properties help to cover esthetic cases.
- Cost-effectiveness
- Reproducibility. In case of debonding or documentation, virtual files allow to produce the exact replica of missing restoration regardless of the time and location for multiple occasions.
- Ability to produce the exact form created in a digital design software allows clinicians to achieve mock-up proposal in final restorations. This is very helpful for the acceptance of the case by the patients and increases patient satisfaction.
- Enables mirroring and copying existing restorations and dentition to increase acceptance of the patients.
- Digital workflows create the sensation of contribution to the treatment process by patients, this mutual cooperation increases patient satisfaction. Also helps to enhance the individual experience.
- Enable single-visit dentistry and chair-side applications. Permanent restorations can be produced and delivered to the patient when indicated in one appointment. It reduces the total chair-time and increases cost efficiency of dental practice.
- Chairside applications are also extremely useful in terms of preventing cross contamination as they do not require any transfer of the impressions to the dental laboratory. This feature will be more important and beneficial after Covid-19 pandemic.

2.2. Disadvantages and limitations

Inadequate for highly demanding esthetic cases when layering is obligatory to achieve harmony and individual characteristics. However, most of the monolithic restoration materials allow material add-ons to overcome this issue.

- Lithium disilicate monolithic restorations and most of the monolithic zirconia restorations with super-high transcluceny are limited to three-unit bridges.
- Translucent monolithic restorations cannot mask heavily coloured devital teeth and metal post-cores. Opaque core and layering are required
- The main objective of restoring a tooth or a dentition is creating function, esthetics, form and phonetic rehabilitation with long-standing, predictable reconstructions.

Today's state-of-the-art technology available in both realms is capable of yielding from above average to excellent esthetic results. Clinical choice between veneered restorations and monolithic restorations depends on:

- Location of the restoration
- Occlusal considerations
- Need for strength
- Esthetics
- Number of restorations
- Underlying tooth or implant

For veneered restorations, porcelain layer upon core material has a low flexural strength and may show porcelain chipping or fractures (Poggio et al., 2017). Monolithic restorations have a higher flexural strength (380-1000 MPa) and are indicated for almost every situation. Monolithic restorations are produced by CAD/CAM technology and less prone to complications when properly designed considering material requirements. Conventional powder/liquid layering porcelains show high level color and optical properties to match that of natural dentin and enamel very closely and this is a major advantage compared to monolithic restorations. The most challenging part of monolithic rehabilitations is undoubtedly achieving optimal esthetics, especially for demanding cases. But the esthetic paradigm for matching the shade and creating micro-detailed characterization shifted to form and optic properties, translucency in particular. Every year new materials are being introduced to the dental market to be compatible for CAD/CAM Technologies. Monolithic blocks and discs present improved shade and optical properties to eliminate veneering porcelain and minimize the use of surface stains. Success of any monolithic restoration in terms of shade and harmony relies on the correct determination of the degree of translucency. Translucency is defined as: allowing the fraction of light that is not reflected to penetrate its surface where it is mainly scattered and transmitted. Monolithic materials can represent various degrees of translucency as high translucency, medium translucency, low translucency, medium opacity, multi translucency, full opacity, bleach properties.

2.3. High translucency

Indicated when minimal preparation is required and there will be no change in the colour of underlying tooth. Requires up to 0.3 mm of reduction for laminate veneers to achieve adhesive bonding to enamel surface.

2.4. Medium translucency

Suitable for multidiastemata and almost every anterior case that requires partial change of colour. When the thickness of the restoration is below 0.8 mm material shows high translucency and has a complete masking capacity with a minimum of 1.0 mm thickness.

2.5. Low translucency

Indications are limited when low translucent monolithic materials have been chosen. Lack of incisal translucency for lithium disilicate restorations reduces natural mimicry. Low translucent materials are suitable for posterior area especially for TiBase implant crowns.

2.6. Polychromatic blocks

Polychromatic feldspathic blocks help to achieve optimal esthetic outcomes for single veneers or crowns in the anterior zone. Vita Triluxe, Cerec PC, IPS Empress CAD Multi are materials of choice when high strength of oxide ceramics is not required. Due to their low flexural strength minimal thickness should be 0.3 mm for laminate veneers. No need for crystallization firing facilitates use with manual polishing only. Not subject to dimensional change after firing. More durable than powder/liquid porcelains as the product is fully sintered and dense. Glaze firing increases flexural strength approximately 30 MPa. Indicated for veneers, full crowns, inlays and onlays.

2.7. Classification of monolithic restorative materials

Full ceramic restorations have been widely used for their high biocompatibility and esthetic superiorisities. However, until introduction of monolithic restorations combining strength and esthetics, their use was almost limited to anterior zone. Recent developments in materials extend the use of monolithic restorations in dental practice to a very broad range like one-piece implant supported full arch bridges. Another important advantage of monolithic restorations is the ability to create the same design in a reproducible manner. Monolithic CAD CAM restorations can be classified according to their processing routes or their composition. A brief information about most popular monolithic CAD/CAM materials can be found on Table 1. Regarding composition, contemporary CAD CAM monolithic materials are classified to three main groups; glass ceramics, resin-matrix ceramics and oxide ceramics.

2.8. Glass ceramics

Silica: VITA Mark II is the first CAD/CAM fine structure feldspar ceramic. Silica ceramics can represent two crystallization patterns; with a sodium potassium aluminum silicate peak. It has low characteristic strength of 118.65 MPa (Wendler et al., 2017). Feldspathic ceramics are considered as the best biomimetic materials. CAD/CAM feldspathic blocks are being used for single crowns, porcelain veneers, inlays, onlays and endocrowns with a high survival rate (Wiedhahn et al., 2005; Otto and Schneider, 2008; Otto and Mormann, 2015). They offer high translucency and good esthetics but their low flexural strength and brittleness require adhesive bonding (Beier and Dumfahrt, 2014).

There are different types of feldspathic ceramic blocks according to their optical properties as monochromatic, dichromatic and polychromatic. Different thicknesses of porcelain laminate veneers produced from monolithic feldspathic blocks are significantly effective on shade and masking underlying substrate. Veneers with a thickness less than 0.7 mm cannot mask the underlying tooth colour. Conventional feldspathic ceramics belong to this material group and considered as the most esthetic materials to achieve a natural enamel look thanks to their translucency and opalescence.

Leucite reinforced glass ceramic: Empress CAD (Ivoclar Vivadent) is the most popular example of this material group. This material is an early generation CAD/CAM block containing leucite crystals up to 40% embedded in a feldspathic glass ceramic. Leucite reveals a dentritical growth through surface crystallization of glass particles in powdered glass by bulky crystallization of monolithic glasses having TiO_2 and CeO_2 as nucleating agents. Flexural strength of leucite reinforced glass ceramics is 185 MPa and they show a low characteristic strength of 187.7 MPa (Wendler et al., 2017). LRGCs exist in high translucent (HT), low transcluent (LT) and polychromatic (PC) forms in terms of light transmitting properties. LRGCs are indicated for anterior veneers, crowns and posterior inlays/onlays due to their increased strength compared to feldspathic ceramics and their translucency. They reveal a 96.4% survival rate for five years according to Nejatidanesh et al. (2018) (Fig. 1).

Fig. 1. IPS Empress CAD PLVs on teeth 31 and 41

Lithium disilicate ceramic: IPS E.max CAD. They reveal needle like particles (0.5 to 4 μm) with different orientations. Milled LiDiSil is exposed to a 2 stage crystallization. After sinterization, the final flexural strength is 530 MPa and also shows a high characteristic strength of 609.80 MPa according to Wendler et al. (2017). Shade and transclucency variety accompanying high strength makes this material indicated for anterior and posterior single crowns, inlays, onlays, veneers and 3 unit bridges terminating at 2nd premolar. LDSCs exist in various translucencies like HT, LT, MT (medium translucency), MO (medium opacity) and HO (high opacity) (Fig. 2).

Fig. 2. Lithium Disilicate MT PLVs on teeth 11-21

Table 1. CAD CAM monolithic materials

Material Group	Material	Brand	Strength (MPa)	Indications	Milling Condition	Block/Disc	Crsytallization Firing	Glaze Firing Option	Shade Range	Transclucency	Add-on	Documentation
Glass Ceramic	Silica / Feldspar Ceramic	CEREC Blocs C Dentsply Sirona	120	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown	Wet	Block	N	Y	A1, A2, A3.5, A4, B1, B2, B3, C2, C3, D3 (VITA) BL2 (IVOCLAR)	HT with chameleon effect	Possible	
Glass Ceramic	Silica / Feldspar Ceramic	CEREC Blocs C PC Dentsply Sirona	120	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown	Wet	Block	N	Y	A1, A2, A3.5, A4, B1, B2, B3, C2, C3, D3 (VITA) BL2 (IVOCLAR)	Polychromatic	Possible	
Glass Ceramic	Silica / Feldspar Ceramic	CEREC Blocs C IN Dentsply Sirona	120	Veneer, Anterior Crown, Posterior Crown	Wet	Block	N	Y	A1, A2, A3.5, A4, B2, B3, BL2, C2, C3, D3	Polychromatic with dentin core	Possible	
Glass Ceramic	Silica / Feldspar Ceramic	VITABLOC S Mark II VITA	140-160	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown	Wet	Block	N	Y	All Classic and 3D Master VITA Shades	Monochromatic translucent	Possible	
Glass Ceramic	Silica / Feldspar Ceramic	VITABLOC S Triluxe VITA	140-160	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown	Wet	Block	N	Y	A1, A2, A3, 1M2C, 2M2C, 3M2C	Polychromatic 3 shade intensity layers	Possible	
Glass Ceramic	Silica / Feldspar Ceramic	VITABLOC S Triluxe Forte VITA	140-160	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown	Wet	Block	N	Y	A1, A2, A3, A3.5 1M2C, 2M2C, 3M2C	Polychromatic 4 shade intensity layers	Possible	
Glass Ceramic	Silica / Feldspar Ceramic	VITABLOC S RealLife	140-160	Veneer, Anterior Crown	Wet	Block	N	Y	0M1, 1M1, 1M2, 2M1, 2M2, 3M2	Polychromatic with dentin core	Possible	
Glass Ceramic	Leucite reinforced Glass-Ceramic	IPS Empress CAD	185	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown	Wet	Block	N	Y	All Classic VITA Shades BL1, BL2, BL3, BL4 (Ivoclar)	HT-LT-Multichromatic	Possible	
Glass Ceramic	Leucite reinforced feldspar ceramic	GC Initial LRF GC	250	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown	Wet	Block	N	Y	A1, A2, A3, A3.5, B1, Bleach	HT-LT	Possible	
Glass Ceramic	Lithium disilicate Glass-Ceramic	IPS e.max CAD Ivoclar Vivadent	530	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown, 3- unit bridges, TiBase abutment	Wet	Block	Y	Y	A1, A2, A3, A3.5, A4, B1, B2, B3, B4, C1, C2, C3, C4, D2, D3, D4 ((VITA) BL1, BL2, BL3, BL4 (IVOCLAR)	HT-LT-MT-MO	Possible	
Glass Ceramic	Lithium disilicate Glass-Ceramic	Obsidian Glidewell	385	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown	Wet	Block	Y	Y	A1, A2, A3, A3.5, B1, B2, B3, C1, C2, C3, D2, D3, (VITA BL1, BL4 (IVOCLAR)	Not specified (MT)	Possible	
Glass Ceramic	Lithium aluminosilicate	n!ce Straumann	350	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown, TiBase abutment	Wet	Block	Optional	Y	A1, A2, A3, A3.5, B1, B2, B4, Bleach	LT-HT	Not possible	
Glass Ceramic	Lithium disilicate Glass-Ceramic	Amber Mill Haas	450	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown, 3- unit bridges	Wet	Block /Disc	Y	Y	All VITA Classic Shades W1, W2, W3, W4	HT-LT-MT-MO	Possible	
Glass Ceramic	Zirconia reinforced lithium silicate	CELTRA DUO Dentsply Sirona	210 (370 after firing)	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown	Wet	Block	Optional	Y	A1, A2, A3, A3.5, B1, B2, C1, C2, D2, D3, BL2, BL3	LT-HT	Possible	
Glass Ceramic	Zirconia reinforced lithium silicate	VITA Suprinity PC VITA	360	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown	Wet	Block	Y	Y	A1, A2, A3, A3.5, B2, C2, D2 0M1, 1M1, 1M2, 2M2, 3M2, 4M2	HT-T	Possible	
Resin-Matrix Ceramic	Resin-nanoceramic	Lava Ultimate 3M	200	Veneer, Inlay, Onlay (limited use)	Wet	Block	N	N	A1, A2, A3, B1 (HT) A1, A2, A3, A3.5, B1, C2, D2, BL (LT)	HT-LT	Possible (only composite)	
Resin-Matrix Ceramic	Hybrid ceramic resin	Tetric CAD Ivoclar Vivadent	272	Inlay, Onlay, Veneer	Wet	Block	N	N	A1, A2, A3, A3.5 Bleach	HT-MT	Possible (only composite)	

Resin-Matrix Ceramic	Dual-network Hybrid Ceramic	VITA ENAMIC VITA	150-160	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown, TiBase abutment	Wet	Block /Disc	N	N	0M1, 1M1, 1M2, 2M2, 3M2	HT-T	Possible (only composite)	
Resin-Matrix Ceramic	Hybrid Ceramic Polymer Structure	VITA ENAMIC multiColor VITA	150-160	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown, TiBase abutment	Wet	Block	N	N	1M1, 1M2, 2M2, 3M2, 4M2	6 layer gradient HT	Possible (only composite)	
Resin-Matrix Ceramic	Nano-particle filled Resin Ceramic	CERASMART Blocks GC	238	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown	Wet	Block	N	N	A1, A2, A3, A3.5, B1	HT-LT	Possible (only composite)	
Resin-Matrix Ceramic	Ceramic-Based hybrid	HC Blocks Shofu	191	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown	Wet	Block /Disc	N	N	A1, A2, A3, A3.5, B3, W2	HT-LT	Possible (only composite)	
Resin-Matrix Ceramic	Reinforced hybrid composite	Brilliant CRIOS Coltene	262	Veneer, Inlay, Onlay, Anterior Crown, Posterior Crown	Wet	Block /Disc	N	N	LT Bleach, A1, A2, A3, A3,5, B1, B2, B3, C2, HTA1, A2, A3, B1	HT-LT	Possible (only composite)	
Composite	Composite	Paradigm MZ 100 3M	146	Inlay, Onlay, Veneer	Wet	Block	N	N	A1, A2, A3, A3.5, B3, Enamel	T Chameleon effect	Possible (only composite)	
Oxide Ceramic	Monolithic Zirconia	inCoris TZI	900	Anterior Crown, Posterior Crown, Bridge, TiBase abutment	Wet or Dry	Block /Disc	Y	Y	A1, A2, A3, A4, B2, B3, C2, C3, D3	Translucent	Possible	
Oxide Ceramic	Super-Translucent Multilayered Zirconia	KATANA Kuraray	763	Anterior Crown, Posterior Crown, Bridge, TiBase abutment	Wet or Dry	Block /Disc	Y	Y	A1, A2, A3, A3.5, B1, B2, B3, C1, C2, C3, D2, D3, NW	HT-Polychromatic	Possible	
Oxide Ceramic	Multilayered Monolithic Zirconia	IPS e. max Multi ZirCaD Ivoclar	850	Anterior Crown, Posterior Crown, Bridge, TiBase abutment	Wet or Dry	Block /Disc	Y	Y	A1, A2, A3, B1, B2, C2, D2, Bleach	MT	Possible	
Oxide Ceramic	Monolithic Zirconia	BruxZir Glidewell	870	Anterior Crown, Bridge	Wet or Dry	Disc	Y	Y	All Classic and 3D Master VITA Shades	Polychromatic	Possible	
Oxide Ceramic	Super High Translucent Zirconia	Zolid fx White Amann Girrbach	700	Anterior crown, bridges Up to 3-unit bridges in molar area	Wet or Dry	Block /Disc	Y	Y	W	HT	Possible	
Oxide Ceramic	Super High Translucent Zirconia	Zolid fx White Amann Girrbach	700	Anterior crown, bridges Up to 3-unit bridges in molar area	Wet or Dry	Block /Disc	Y	Y	All Classic and 3D Master VITA Shades	HT-Polychromatic	Possible	
Oxide Ceramic	Monolithic Zirconia	Prettau Zirkonzahn	1200	Up to 14 unit bridges	Wet or Dry	Disc	Y	Y	All Classic and 3D Master VITA Shades	Translucent	Possible	

Material Group	Crystallization Firing	Glaze Firing Option	Shade Range	Translucency	Add-on	Documentation
Glass Ceramic	N	Y	A1, A2, A3, A3.5, A4, B1, B2, B3, C2, C3, D3 (VITA) BL2 (IVOCLAR)	HT with chameleon effect	Possible	
Glass Ceramic	N	Y	A1, A2, A3, A3.5, A4, B1, B2, B3, C2, C3, D3 (VITA) BL2 (IVOCLAR)	Polychromatic	Possible	
Glass Ceramic	N	Y	A1, A2, A3, A3.5, A4, B2, B3, BL2, C2, C3, D3	Polychromatic with dentin core	Possible	
Glass Ceramic	N	Y	All Classic and 3D Master VITA Shades	Monochromatic translucent	Possible	
Glass Ceramic	N	Y	A1, A2, A3, 1M2C, 2M2C, 3M2C	Polychromatic 3 shade intensity layers	Possible	
Glass Ceramic	N	Y	A1, A2, A3, A3.5 1M2C, 2M2C, 3M2C	Polychromatic 4 shade intensity layers	Possible	

Glass Ceramic	N	Y	0M1, 1M1, 1M2, 2M1, 2M2, 3M2	Polychromatic with dentin core	Possible
Glass Ceramic	N	Y	All Classic VITA Shades BL1, BL2, BL3, BL4 (Ivoclar)	HT - LT - Multichromatic	Possible
Glass Ceramic	N	Y	A1, A2, A3, A3.5, B1, Bleach	HT - LT	Possible
Glass Ceramic	Y	Y	A1, A2, A3, A3.5, A4, B1, B2, B3, B4, C1, C2, C3,C4, D2, D3, D4 ((VITA) BL1,BL2, BL3, BL4 (IVOCLAR)	HT - LT - MT - MO	Possible
Glass Ceramic	Y	Y	A1, A2, A3, A3.5, B1, B2, B3, C1, C2, C3, D2, D3 (VITA BL1,BL4 (IVOCLAR)	Not specified (MT)	Possible
Glass Ceramic	Optional	Y	A1, A2, A3, A3.5 B1, B2, B4, Bleach	LT - HT	Not possible
Glass Ceramic	Y	Y	All VITA Classic Shades W1, W2, W3, W4	HT - LT - MT - MO	Possible
Glass Ceramic	Optional	Y	A1, A2, A3, A3.5 B1, B2, C1, C2, D2, D3, BL2, BL3	LT - HT	Possible
Glass Ceramic	Y	Y	A1, A2, A3, A3.5, B2, C2, D2 0M1, 1M1, 1M2, 2M2, 3M2, 4M2	HT - T	Possible
Resin-Matrix Ceramic	N	N	A1, A2, A3, B1 (HT) A1, A2, A3, A3.5, B1, C2, D2, BL (LT)	HT - LT	Possible (only composite)
Resin-Matrix Ceramic	N	N	A1, A2, A3, A3.5 Bleach	HT - MT	Possible (only composite)
Resin-Matrix Ceramic	N	N	0M1, 1M1, 1M2, 2M2, 3M2	HT - T	Possible (only composite)
Resin-Matrix Ceramic	N	N	1M1, 1M2, 2M2, 3M2, 4M2	6 layer gradient HT	Possible (only composite)
Resin-Matrix Ceramic	N	N	A1, A2, A3, A3.5, B1	HT - LT	Possible (only composite)
Resin-Matrix Ceramic	N	N	A1, A2, A3, A3.5, B3, W2	HT - LT	Possible (only composite)
Resin-Matrix Ceramic	N	N	LT Bleach, A1, A2, A3, A3.5, B1, B2, B3, C2 HT A1, A2, A3, B1	HT - LT	Possible (only composite)
Composite	N	N	A1, A2, A3, A3.5, B3, Enamel	T Chameleon effect	Possible (only composite)
Oxide Ceramic	Y	Y	A1, A2, A3, A4, B2, B3, C2, C3, D3	Translucent	Possible
Oxide Ceramic	Y	Y	A1, A2, A3, A3.5 B1, B2, B3, C1, C2, C3, D2, D3, NW	HT - Polychromatic	Possible

Oxide Ceramic	Y	Y	A1, A2, A3, B1, B2, C2, D2, Bleach	MT	Possible	
Oxide Ceramic	Y	Y	All Classic and 3D Master VITA Shades	Polychromatic	Possible	
Oxide Ceramic	Y	Y	W	HT	Possible	
Oxide Ceramic	Y	Y	All Classic and 3D Master VITA Shades	HT - Polychromatic	Possible	
Oxide Ceramic	Y	Y	All Classic and 3D Master VITA Shades	Translucent	Possible	

Lithium silicate/phosphate glass ceramic: It is also known as zirconia reinforced lithium silicate. Vita Suprinity, Celtra and Celtra Duo belong to that material group. VITA Suprinity blocks are in a metasintered stage to facilitate grinding and later requires a final crystallization. Celtra Duo is in a fully sintered form and can be delivered to patient after mechanical polishing following milling. Flexural strength of LSPGCs averages 360 MPa. Characteristic strength reveals an intermediate range in comparison with silicate ceramics and zirconia (Celtra Duo: 565.87 MPa; VITA Suprinity: 573.03 MPa) (Wendler 2017).

The addition of ZrO_2 to lithium metasilicate and disilicate did not result in an increased strength or higher resistance to crack propagation as compared with LiDiSil. Multiple cracking and surface pitting were observed in SEM evaluation.

Thermal incompatibility between phases and related high local residual stresses that are relieved upon cooling by means of microcracking are possible reasons. (Wendler et al., 2017). In addition, damage induced to the presintered block by diamond coated grinding instruments during machining is another source of concern (Chavali et al., 2017).

Lithium aluminosilicate ceramic: Straumann Nice blocks. n!ce® is a lithium aluminosilicate ceramic reinforced with lithium disilicate and available in two levels of translucency: High Translucency and Low Translucency. LAC restorations can be seated using either adhesive or self-adhesive cementation. They can simply be polished, or stain and glaze can be applied if more pronounced characterization is wished. Layering or porcelain add-ons are not possible for this material. The flexural strength is 350 MPa according to the manufacturer. Immediate applications with titanium base abutments are the main indication for this type of material.

2.9. Resin-matrix ceramics

Resin based composites: (Predominant organic phase with fillers). Lava Ultimate contains dispersed nanometric colloidal silica and ZrO_2 spherical particles in agglomerated and non-agglomerated form (80% weight, 65% volume) embedded in a dimethacrylate resin. Flexural strength is 200 MPa.

Cerasmart, Brilliant Crios and Shofu Blocks are novel RBCs with a homogenous and evenly distributed ceramic network. RBCs should be pretreated through air-particle abrasion and application of a universal bonding agent.

Polymer-infiltrated ceramic network: (Predominant inorganic phase with high temperature/high pressure polymer infiltration). VITA Enamic is an amorphous structured material with no evidence of crystallization. Flexural strength is 160 MPa. Due to the dual network structure, crack propagation is mitigated by the interlinked polymer network. Hydrofluoric acid etching in combination with silane is recommended as a surface treatment prior to bonding.

2.10. Oxide ceramics

Zirconia is first introduced in early 1990s by CAD/CAM technology. It has a very high flexural strength (1200 MPa) and used as a framework material for fixed restorations for years. However the high opacity of the material required veneering and layering process for esthetics and complications like porcelain chipping and fractures are frequent. To overcome this problem and make use monolithic zirconia as a restoration translucent zirconia was developed. Translucent monolithic zirconia is produced by reducing particle dimensions of zirconium dioxide and binding with an agent through colloidal process to minimize the pores within the structure. Translucent zirconia can be used for anterior restorations up to 3 unit bridges as the flexural strength is significantly lower compared to conventional zirconia. The latest progress to increase the translucency is to stabilize the zirconia with a cubic crystalline phase. Increasing the yttria content to more than 8 mol% will stabilize the cubic phase (Zhang, 2014). There are different versions of “high-translucent” or “cubic-containing” zirconia on the market. These cubic zirconia samples are produced to have approximately 8 mol% yttria to 10 mol% yttria. (Lava™ Esthetic (3M ESPE); Katana™ Zirconia (UTML/STML) (Kuraray Noritake Dental Inc., kuraraynoritake.com); BruxZir® Anterior (Glidewell Laboratories); ArgenZ™ Anterior (Argen Corp., argen.com); and Imagine® (Jensen Corp.)).

2.11. Clinical performance and design requirements for monolithic restorations

As all monolithic restorations are being produced by CAD/CAM Technologies, the preparation design and parameters should be considered accordingly. Monolithic restorations use subtractive method for production which means that a block or a disc is milled by a 3-, 4- or 5-axis milling machine with appropriate burs. The axis content and bur design and diameter necessitates to apply adjusted principles for tooth preparation. Milling parameters affect the internal fit of the final restoration. Tooth preparations must be rounded to prevent stress and also should provide enough space for cementation and fit. Sharp corners and edges should be avoided. Preparation has a significant effect on the marginal fit of monolithic CAD/CAM crowns and finish line of choice is a chamfer or rounded shoulder for the best fit (Renne et al., 2012). Another important issue for success of monolithic materials is the thickness of the restoration. Material properties define the minimal thickness for strength and determine the thickness of the restorative material needed for change in the colour of underlying tooth structure. Masking with monolithic zirconia require a minimal thickness of 0.9 mm (Tabatabian et al., 2018) (Fig. 3).

Fig. 3. Masking effect of low translucent monolithic lithium disilicate restorations

Lithium disilicate restorations are shown to be a safe alternative to metal-ceramic 3-unit FDPs when manufacturer's recommendations are followed. Kern et al. (2012) demonstrated 100% survival rate for five years and 87.9% survival rate for ten years. The success rate of lithium disilicate FDPs was found to be 91.1% for five years and 69.8% for ten years. Sailer et al. (2015) showed all-ceramic single crowns to exhibit comparable survival rates to metal-ceramic single crowns after a mean observation period of at least 3 years. While leucite or lithium-disilicate reinforced glass-ceramic or oxide ceramic materials perform similarly well in anterior and posterior regions the mechanically weaker ceramics like the feldspathic or silica glass-ceramics can only be recommended for anterior with low functional loads (Sailer et al. 2015) (Fig. 4).

Fig. 4. VOD increased by monolithic restorations with a full digital workflow

3. Conclusion

Monolithic restorations are considered to be reliable and predictable for the rehabilitation of esthetic cases. Due to advances in technology and material developments, scientific documentation and evidence are limited for novel products. However, most of the products in the dental market have long term success and are being used with great confidence for daily practice.

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Artificial intelligence technologies in dentistry

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Abstract

One of the most important actors in the digitization process of our age has been the applications of artificial intelligence (AI). While the weak and strong AI sub-concepts and the different AI models within them are being utilized in many fields such as education, industry and medicine today, the interest of the dentistry field, which has started its integration into the digital world with CAD/CAM technology, in AI is increasing day by day. In different branches of dentistry; AI provides services to clinicians and researchers in many fields such as disease diagnosis, evaluation of the occurrence or recurrence of diseases such as oral cancer, and prediction of success in surgical and prosthetic treatments. In this article, studies in which AI models such as machine learning, convolutional neural networks have found research and usage areas on the basis of different branches of dentistry are reviewed.

Keywords: artificial intelligence, deep learning, dentistry, neural networks, prediction

1. Introduction

In dentistry, with the speed development of production options such as Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) and Rapid Prototyping (RP) methods, the digital workflow has found an important place in clinical routine (Miyazaki and Hotta, 2011). Besides, artificial intelligence (AI) and machine learning (ML) technologies involved in the dental production phase; have carried out the most radical change in radiological imaging and diagnostic methods (Jones et al., 2017).

Artificial intelligence is defined as the ability to interpret the data uploaded to a system with high trueness, to make use of this data to sustain learning, and to use the adaptation capacity of the system in this learning process to achieve certain goals (Kaplan and Haenlein, 2019). The term "AI" basically consists of two sub-concepts, weak and strong AI (Park and Park, 2018). Researchers who support the concept of weak AI say that a running AI program is essentially a simulation of a cognitive process, whereas it itself does not have a cognitive base; on the other hand, strong AI advocates claim that AI is actually a mind of a (not yet designed) program running on a (not yet written) machine. Unlike weak AI, it is anticipated that strong AI will have free will and conscience like humans and can make the distinction between right and wrong independently (Scerri and Gresch, 2020). However, today AI does not have access to such consciousness as this claim, so both the practices in daily life and the studies in medicine and dentistry are shaped by weak AI.

Weak AI studies aim to build algorithms that can be fed with some inputs and then make various estimations (Mupparapu et al., 2018). Machine learning, is one of its branches that provides a computer model in order to enable AI to learn and make predictions through recognizing objects like image, speech, face, etc. (Hashimoto et al., 2018). The main advantage of machine learning is that, just as radiologists are constantly trained to work on medical images, the newly designed AI model enables them to develop more and increase their level of learning with a large database of new images (Kohli et al., 2017).

Furthermore, data mining methods (DMM) are utilized for more complex predictions. They have recently become common in many disciplines, including biology, medicine and dentistry. In this method, support vector machine (SVM) and convolutional neural networks (CNN) are mainly used, and they form a more successful alternative in modeling the non-linear relationships between the predicted variable and input data (Witten et al., 2011).

CNN feed on very large data clusters, thus they can be very efficient. AI is able to produce better results in disciplines such as medicine and dentistry than specialist doctors, thanks to the fact that AI models can be trained with hundreds of thousands of clinical cases. Therefore, it can transcend even the best experts in terms of the experience of clinical diagnosis and treatment (Bouletreau et al., 2019). Many of the dentistry practices make use of CNN models that are individually

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created. Looking at the literature, it appears that the pre-trained CNN models used are AlexNet, VGG16, ResNet, U-net, GoogLeNet, VGG19, densenet and V-net (Schwendicke et al., 2019).

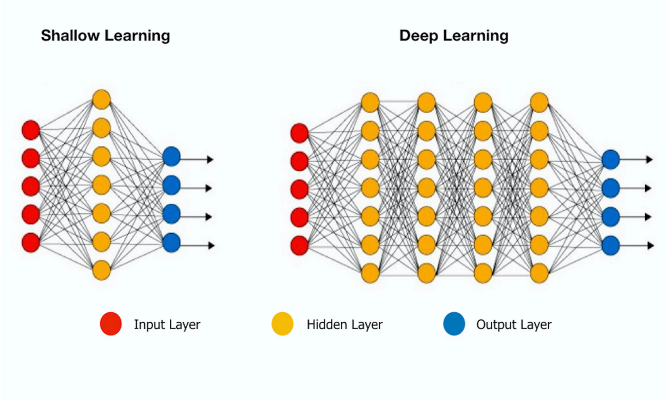

Fig. 1. Neural network designs

The accuracies of these networks depend on both the qualitative and quantitative features of training data that revises the weights of their attachments. Basic network structures with fewer layers are called "hallow learning" neural networks, while complex network structures with more layers are called "deep learning" (Burt et al., 2018) (Fig. 1). CNN based on deep learning, have started to gain a place in many fields of dentistry.

The aim of this study is to examine the applications of artificial intelligence that have been carried out in different branches of dentistry so far and which types of artificial intelligence are used in these studies.

2. Oral and maxillofacial radiology

In the fields of medicine and dentistry, many AI models have been produced to assess people's risk of getting sick, detect abnormal health data, diagnose and prognosis of diseases (Jiang et al., 2017; Litjens et al., 2017; Fazal et al., 2018). Since digital images are used for diagnosis in the field of radiology, it is quite easy to transfer these digital data into computer language. Thus, radiology is the most suitable branch of dentistry for AI use (Thrall et al., 2018). However, in order to make a high-accuracy prediction of 98% for deep learning accompanied by computed tomography data, it requires at least 1000 units and 4092 units for a success rate of 99.5%. (www.itnonline.com, 2020) (Fig. 2) As input data is increased, the success achieved in output increases (Cho et al., 2016).

Fig. 2. Deep learning reconstruction of computed tomography scan

Lee et al. (2020), pre-trained VGG16 networks with a limited training dataset by using deep CNN and evaluated the ability of this AI model to diagnose osteoporosis in dental panoramic radiography (DPR) images. While experimental results showed 84% accuracy, the researchers noted that DPR images had the potential to be used for prescreening of osteoporosis.

Kise et al. (2020), compared the diagnosis results of deep learning and three inexperienced radiologists on 100 patients who had been diagnosed with Sjogren Syndrome and 100 patients who had not been diagnosed before. As a result of the study obtained ultrasound images from salivary glands, deep learning had 89.5, 90.0 and 89.0% accuracy in parotid gland results, while radiologists had 76.7, 67.0 and 86.3% accurate diagnosis. Besides, Ekert et al. (2019) in the study they performed on panoramic radiographs, seven layers of the deep neural network were used in the Keras framework and it was reported that apical lesion detection could be made with high accuracy.

On the other hand, AI has also been found to provide good results in oral cancer prediction. In the study conducted by Alabi et al. (2019), artificial neural network (ANN) was trained with diagnostic parameters such as age, gender, T stage, WHO histologic grade, depth of invasion, tumor budding, the worst pattern of invasion, perineural invasion and lymphocytic host response in Microsoft Azure Machine Learning Studio (Azure ML 2019). In locoregional recurrence predictions performed on 311 patients, ANN was found to be successful at 92.7%, while the logistic regression model remained at 86.5% accuracy. In another study (Poedjiastoeti and Suebnukarn, 2018), the convolutional neural network (CNN) of The Google Net Inception-v3 architecture was compared with oral and maxillofacial specialists in the diagnosis of ameloblastoma and the keratocystic odontogenic tumor on panoramic radiography. CNN obtained diagnosis results with same accuracy in 38 seconds compared to the 23.1 minutes diagnostic time of the specialists. Therefore, AI may be a good alternative method to achieve a much faster diagnosis in oral cancer cases.

3. Oral and maxillofacial surgery

Zhang et al. (2018), estimated the amount of swelling with high accuracy that will occur in patients after mandibular third molar extractions, thanks to ANN working based on the conjugate gradient back-propagation algorithm. Besides, Kim et al. (2018), calculated the probability for the occurrence of bisphosphonate-related osteonecrosis after tooth extraction using five different machine learning methods based on drug holiday and CTX level values. As a result of the study, it was found that machine learning yielded better results than the conventional method, primarily the random forest model (97.3%) and ANN (91.5%).

Scrobotă et al. (2017), utilized fuzzy logic for predicting the risk of oxidative stress-related cancerization risk of the potentially malignant processes. The researchers noted that the system was highly successful in oral cancer screening. Polášková et al. (2013), developed a machine learning system (clinical decision support system) in a web application that gives recommendations on implant treatments. The system uses the data referencing anamnesis and medical examination such as 3-D measurements, information regarding treatment planning.

Artificial intelligence has also found extensive use in the field of maxillofacial surgery (www.dolphinimaging.it, 2020) (Fig. 3). In the study of Stehrer et al. (2019), among 950 patients undergoing orthognathic surgery between 2006 and 2017, training and test groups were created with 80% and 20% ratio in a Random Forest model. At the end of the study, a statistically significant correlation was determined between the estimated amount of blood loss and the amount of blood loss that occurred after the operations. In another study (Patcas et al., 2019), it was found out that the effect of orthognathic surgery on facial attractiveness and age estimation can be assessed fairly well with deep learning using Chicago Fire Dataset. Therefore, it is thought that in the near future deep learning algorithms trained with hundreds of thousands of clinical cases, will be equivalent to the best oral and maxillofacial surgeons, at least in diagnosing dento-facial dysmorphism; and the results that can be achieved in patients with orthognathic surgery can be predicted with high accuracy.

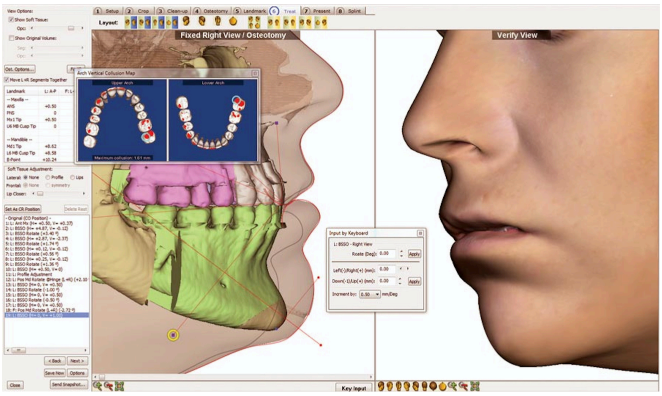

Fig. 3. 3D planning of maxillofacial surgery

4. Periodontics

Deep learning can be used to determine the prognosis of periodontally compromised teeth and to classify periodontal diseases. Lee et al. (2018), evaluated the prognosis of compromised teeth through periapical radiography by creating a deep CNN model with the Adam algorithm. They determined the prognosis with 81.0% accuracy in premolar and 76.7% accuracy in molar teeth. Furthermore, Kim et al. (2019) examined periodontal bone loss on panoramic radiographs using a deep learning-based DeNTNet system. DeNTNet system achieved a score of 0.75, while the performance of clinicians remained lower at 0.69.

Decision trees (DT), SVM and neural network (NN) have been used in current studies for the classification of periodontal diseases. Özden et al. (2015), formed a matrix with periodontium and bone loss data radiographically obtained from patients; and they identified 6 different classes. DT and SVM showed very successful results with calculation times of 7.00 and 19.91 seconds and 98% accuracy; while NN was the group that showed the worst correlation with 46% accuracy in this study. Nakano et al. (2014), performed oral halitosis classification by means of oral microbiota in saliva using DT, SVM and ANN methods. SVM yielded an accuracy level of >95% and it was reported that AI models using T-RFLP data may be useful in halitosis detection.

Currently, for the measurement of periodontal pockets, some researchers have been working on ultrasonographic probes that operate with non-invasive and pain-free techniques. To measure the depth, it applies echo waveforms that AI can then evaluate with the wavelet transformation technique. The model promptly offers the clinician two possible pocket depths with 90% legibility by using a binary classification algorithm (Rudd et al., 2009).

5. Pediatric dentistry

Looking at the current literature, it is pointed out that the branch in which AI finds perhaps the least use in pediatric dentistry. Baliga (2019), reported that early orthodontic movements can be performed with appliances customized by AI and pain control can be provided by using injection-free pedodontic practice with AI-based devices in pediatric dentistry.

6. Orthodontics

Four different NN models were used on 156 patients in a study that evaluated the diagnosis of tooth extraction before orthodontic treatment. The NN models were constructed with a back-propagation algorithm and the effectiveness of the models was evaluated. At the end of the study, the success rate of extraction vs non-extraction diagnosis was 93% (Jung and Kim, 2016). In addition to this study, Xie et al. (2010) conducted a study on 200 patients aged between 11-15 and the extraction decisions of NN models constructed with FORTRAN programming language and an orthodontist were compared. The researchers noted that the NN model yielded high accuracy with an 80% ratio.

Kunz et al. (2020), have developed an AI algorithm for automated cephalometric X-ray analysis. 12 experienced orthodontists identified 18 different landmarks on 1792 cephalometric X-rays to the AI model. At the end of the evaluation of 50 cephalometric X-rays, it was determined that the predictions carried out by the AI model did not differ statistically from the analysis carried out by orthodontists, which was accepted as the gold standard in orthodontics.

Frontal and profile pictures of 20 treated left-sided cleft patients and the control group of 10 healthy people were compared between VGG16 and the conventional rater group of lay people, orthodontists and oral surgeons, in terms of evaluation of facial attractiveness. AI evaluation of cleft patients (mean score: 4.75 ± 1.27) was similar to human ratings (lay people: 4.24 ± 0.81, orthodontists: 4.82 ± 0.94, oral surgeons: 4.74 ± 0.83); however, the results of people in the control group was higher at a statistically significant level. The researchers indicated the need for AI to be developed for safe use in facial attractiveness evaluation (Patcas et al., 2019).

Additionally, other studies have shown that fuzzy models can be used successfully for the assessment of the use of headgears by evaluating overjet, overbite and mandibular plane angle variables (Akçam and Takada, 2002) and to determine the cervical vertebral stage in patients with the cephalometric examination (Kök et al., 2019).

7. Endodontics

Kositbowornchai et al. (2013), have developed a probabilistic neural network that assesses whether tooth roots have a vertical fracture. As a result of testing the data, it was determined that the model can be detected with high sensitivity (98%), specificity (90.5%) and accuracy (95.7%). In another study conducted by Mallishery et al. (2019), 500 potential root canal patients were evaluated by both endodontists and ANN with the help of the standard American Association of Endodontists Endodontic Case Difficulty Assessment Form. The hidden and output layers have the rectified linear unit (ReLU) activation function, which is $f(x) = \max(0, x)$, and this function was used for the classification. The diagnosis determined by ANN was found to have 94.96% accuracy and it was stated that the degree of difficulty for these cases was able to be determined with high accuracy in endodontic terms.

ANN has also been applied in determining the working length of the root canal and locating minor apical foramen in the field of endodontics. In a study, the apical foramen on 50 human teeth before extraction was located by an endodontist with endodontic files and then by the ANN model in conjunction with the Otsu method. According to reference measurements made with a stereomicroscope, which is considered as the gold standard, the endodontist yielded results with 76% and ANN with 96% accuracy (Saghiri et al., 2012a). In another study conducted by also Saghiri et al. (2012b), apical foramen localization via radiography with ANN was performed with 93% accuracy. According to these data, it is stated that AI is one of the decision-making mechanisms that can be utilized in various clinical tables.

8. Restorative dentistry

Artificial intelligence is integrated into many systems, for instance intraoral scanners such as Cerec Primescan (Dentsply Sirona) and Trios 4 (3Shape) for removing the excessive images of intraoral scan and detect proximal caries. (my.cerec.com, 2020) (Fig. 4) NNs have been shown to be capable of high-accuracy caries detection with Near-Infrared-Light Transillumination (NILT) images (Schwendicke et al., 2020). Devito et al. (2008), compared NN to 24 examiners in terms of caries detection. The examiners were able to detect proximal caries with 71.7% and NN with 88.4% accuracy. Besides, the ANN model whose input fed with caries excavation methods and pre-streptococcus mutants for the detection of caries was introduced as an iOS application, entitled “Post-streptococcus mutans prediction (PSm)” (Javed et al., 2020).

Fig. 4. Full-arch maxillary scan

Haidan et al. (2014), evaluated the wear factors on dental surfaces of 96 patients using an ANN. Medical histories and data collected via eleven parameters were installed to an ANN software, Pythia. As a result of the study; age, consumption of pickles, oranges and acidic drinks and frequency of brushing were found the most effective factors in the wear of teeth surfaces. The researchers stated that 73.3% accuracy was achieved, and this value was clinically acceptable, while the dental wear assessment performed with ANN was timesaving.

Furthermore, in different studies, colorimetric values were used to predict the color change obtained by the bleaching system before the process (Thanathornwong et al., 2016). By using the initial chromatic values of a tooth, fuzzy logic can match the postbleaching CIELAB coordinates with the Vita shade to predict the approximate color of the tooth after bleaching (Herrera et al., 2010).

9. Prosthodontics

AI contributes to implant-supported fixed restoration production. After shaping the soft tissue with a temporary restoration, first soft tissue and then the scan body impressions are made. Then, two different images are superimposed on the CAD system with the help of AI and hybrid abutment production is performed in accordance with the soft tissue form (Mangano et al., 2019).

Yamaguchi et al. (2019), have developed a CNN model with the Keras library on top of TensorFlow in Python, which predicts the probability of debonding CAD/CAM composite resin crowns. Randomized 6480 training and validation images and 2160 test images were used to develop the model and the model was applied to the die images obtained with an intraoral scanner. As a result of the study; accuracy, precision, recall, F-measure values were found to be 98.5%, 97.0%, 100%, and

0.985% respectively, and the prediction level for debonding was detected successfully. Besides in another study, it has shown that a multilayer perceptron and Bayesian network using Verma and Pearl algorithm, can determine the most suitable type of restoration for different cases by predicting longevity (Aliaga et al., 2015).

Backpropagation of neural networks (BPNN) has been introduced to computer color matching in prosthodontics. The GA + BP system for color matching has been developed. The initial weights and threshold compared to conventional BPNN are primarily optimized by GA. It has been shown that BPNN improves convergence performance and stability by determining appropriate initial parameters rather than random selection of initial parameters and makes restoration's color matching more accurate (Li et al., 2015). The skin color of each region can also be determined with SVM and CNN models. Automatic analysis modules have been developed, especially in optical visagism systems through the use of skin color by eyewear virtual try-on software via a mobile device (Borza et al., 2018).

In the field of removable prosthodontics, it is possible to predict the changes of facial soft tissue that will occur in patients after complete denture applications with AI systems quickly and accurately (Cheng et al., 2015), and although it needs further development, AI can make case-specific removable partial prosthetics designs (Chen et al., 2016).

10.Temporomandibular disorders

Baş et al. (2012) measured the diagnostic determination ability of the neural networks (NN) on 58 patients after training the NN model with the clinical symptoms and diagnoses of 161 patients. They measured the sensitivity and specificity of ANN in determining TMD subgroups by comparing it with clinical diagnosis, which is considered the gold standard. The sensitivity and specificity of unilateral disc displacement with reduction detection of ANN were found to be 80% and 95%, while its without-reduction success was found to be 69% and 91%. Disc displacement sensitivity and specificity with bilateral reduction were 100% and 89%, while those without bilateral reduction were 37% and 100%. The success of disc displacement diagnosis with the reduction on one side and without-reduction on the other side remained at 44% and 93%. The researchers noted that ANN could help clinicians in the classification of TMD, with more input loading likely to increase accuracy.

There are also studies that have searched the effectiveness of AI-based Natural Language Processing (NLP) in diagnosing orofacial pain disorders. In their study Nam et al. (2018), after comparing the medical records of 29 TMD-mimicking patients with 290 genuine TMD patients, found out that the NLP model's success rate to predict TMD-mimicking condition is 96.6%, with 69.0% sensitivity and 99.3% specificity.

AI applications have not found enough place in dentistry clinical applications so far due to their technical difficulties and cost. However, AI models are expected to automatically diagnose diseases on 3-D images, to identify specific disease risks to individuals, and to contribute to clinicians in therapeutic applications by evaluating the prognoses of treatment types by feeding on more comprehensive data sets (Goldhahn et al., 2018).

11. Conclusion

AI technology, which is developing day by day, is expected to be given a greater role in the classification of diseases, utilization of treatment recommendations and prosthetic production stages soon. However, this requires that AI models prove their performance through clinical trials and their superior results on the success rate-time axis are supported by research data. The development of weak AI technologies continues to be human-oriented and may disrupt this process somewhat. If the use of strong AI is possible in the future, it will be possible to apply more accurate digital techniques rather than conventional techniques in dentistry as in all areas of life.

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