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The Relationship of Fractal Dimension and Osseointegration: A Retrospective Radiologic Clinical Trial

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ABSTRACT
Objective: The objective of this study was to evaluate the density of alveolar bone in the peri-implant area using fractal analysis on orthopantomograms, both prior to and following clinical osseointegration. **Material and Methods:** Orthopantomograms were performed prior to the implant surgery and again four months postoperatively. Regions of interest at the mesial, distal, and apical sites of the implants were identified for analysis. The method by White and Rudolph was employed to calculate the fractal dimension. Subsequently, fractal dimension values were compared across all recorded measurements. **Results:** Statistical analyses revealed significant correlations between the mesial measurements before and after surgery, as well as between the distal measurements pre- and post-operatively, compared to the apical measurements over the same periods. Further subgroup analyses identified significant correlations in pre- and post-operative fractal dimension values specifically within the female subgroup, with notable distinctions observed between pre-mesial, post-mesial, and the average values before and after surgery ($p<0.05$). Moreover, substantial differences were detected between the jaws ($p<0.05$) and the specific locations within the jaws ($p>0.05$), regarding the fractal dimensions measured pre- and post-operatively. **Conclusion:** Fractal analysis has demonstrated its reliability as a method for both clinical and radiological assessment of osseointegration.
Keywords: Dental implants, Fractal dimension, Orthopantomogram, Osseointegration.

Fraktal Boyut ve Ossentegrasyon İlişkisi: Retrospektif Radyolojik Klinik Deneme

ÖZ
Amaç: Bu çalışmanın amacı, klinik ossentegrasyon öncesi ve sonrasında ortopantomogramlar üzerinde fraktal analiz kullanarak alveolar kemik yoğunluğunu değerlendirmektir. **Gereç ve Yöntem:** İmplant cerrahisi öncesinde ve ameliyattan dört ay sonra ortopantomogramlar çekildi. İmplantların mezial, distal ve apikal bölgelerinde analiz için ilgi alanları belirlendi. Fraktal boyut hesaplamak için White ve Rudolph yöntemi kullanıldı. Daha sonra, kaydedilen tüm ölçümlerde fraktal boyut değerleri karşılaştırıldı. **Bulgular:** İstatistiksel analizler, cerrahi öncesi ve sonrası mezial ölçümler arasında, aynı dönemlerde apikal ölçümlere kıyasla distal ölçümler arasında önemli korelasyonlar ortaya koydu. Daha fazla alt grup analizleri, özellikle kadın alt grubu içinde cerrahi öncesi ve sonrası fraktal boyut değerlerinde önemli korelasyonlar saptadı; cerrahi öncesi-mezial, cerrahi sonrası-mezial ve cerrahi öncesi ve sonrası ortalama değerler arasında belirgin farklar gözlemlendi ($p<0.05$). Ayrıca, çeneler arasında ($p<0.05$) ve çeneler içindeki spesifik lokasyonlar arasında ($p>0.05$), cerrahi öncesi ve sonrası ölçülen fraktal boyutlar açısından önemli farklar tespit edildi. **Sonuç:** Fraktal analiz, klinik ve radyolojik ossentegrasyon değerlendirmesi için güvenilir bir yöntem olarak kendini kanıtlamıştır.
Anahtar Kelimeler: Diş implantları, Fraktal boyut, Ortopantomogram, Ossentegrasyon.

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INTRODUCTION

The success of dental implants is contingent upon a multitude of variables, including implant type, patient-specific factors, surgical technique, the quality of the alveolar bone, and the process of achieving proper osseointegration (Lee et al., 2010). Osseointegration is defined as the direct structural and functional connection between the alveolar bone and the implant surface, distinguished by the absence of fibrous connective tissue (Mu, Lee, Park, & Moon, 2013; Tözüm, Bal, Turkyilmaz, Gülay, & Tulunoglu, 2010). The condition of the alveolar bone surrounding the implant is influenced by various factors such as trabecular architecture, structural integrity, mineral density, and the presence of microdamage (Çakur et al., 2008). A range of diagnostic tools is available for the assessment of bone osseointegration and quality (Tözüm et al., 2010). While dual-energy X-ray absorptiometry (DXA) is recognized for its efficacy in measuring bone mineral density, its application is limited by its inability to generate cross-sectional images. Conversely, cone-beam computed tomography (CBCT) and orthopantomograms (OPG) are widely utilized imaging techniques in the field of implantology (Jeong, Kim, Oh, & Jeong, 2013). To assess the quality of bone, measurements such as the Mandibular Cortical Index (MCI), which evaluates the thickness and morphology of the mandibular cortex, and fractal dimension (FD) values are frequently employed (Milillo et al., 2016).

Initially, Mandelbrot introduced fractal analysis (FA) as a technique to describe natural structures that do not conform to traditional geometric shapes (Geraets & Van der Stelt, 2014). Mandelbrot quantified the complexity of objects, whose dimensions do not align with standard units, through the concept of FD. Mandelbrot highlighted that FD, indicative of an object's degree of complexity, remains constant despite changes in scale. Thus, FA emerged as a mathematical approach enabling the quantitative depiction of intricate structures and patterns that cannot be defined by whole dimensions (Mandelbrot & Wheeler, 1982). FA has found extensive application in the medical domain, facilitating the diagnosis of diseases and the assessment of their severity and progression. Previous studies have established the use of FA in assessing bone quality; however, there remains a gap in its application to the comparative analysis of peri-implant alveolar bone density across different stages of osseointegration. Specifically, the trabecular architecture of cancellous alveolar bone, characterized by interconnected structures, proves conducive for fractal pattern analysis (Fazzalari & Parkinson, 1996).

The application of FA to periapical and OPG radiographs allows for the detection of variations in trabecular bone density and bone tissue demineralization (Oliveira et al., 2013). Within the field of dentistry, FA has been employed to study early periodontal alterations in alveolar bone, osteoporosis-related pathologies, the bone surrounding implant sites, and the severity of temporomandibular joint dysfunction (Arsan, Kose, Cene, & Ozcan, 2017; Soğur & Baksı, 2014).

The aim of this study was to utilize OPG imaging to compare the alveolar bone density in the peri-implant area, employing FA, for dental implants both before and following osseointegration.

MATERIALS AND METHODS

Patient selection

This retrospective study received ethical approval from the Ethics Board and Commissions of Nuh Naci Yazgan University, Kayseri, Turkey (Approval Number: 2022/8839). The research utilized OPGs obtained from patients who presented with complaints of missing teeth at the Faculty of Dentistry, Nuh Naci Yazgan University.

Inclusion criteria

1-Implant surgeries followed a submerged protocol.
2-A minimum waiting period of 4 months after implant surgery.
3-The age of the participants in the study is between 20–60 years
4-ASA I –II patients
5-Patient records without prosthetic loading
6-A minimum waiting period of 6 weeks after tooth extraction before implantation.

Exclusion criteria

1-Records of patients with any grafting procedure on dental implants
2-Records of patients who have previously had dental implants in the same area and lost their implants for any reason
3-Implants lost when wearing a healing cap

Surgical protocol

A single surgeon applied all the dental implant surgery to 29 patients.

Radiographic evaluation

All data were amassed within a computerized framework. The OPGs corresponding to each dental implant underwent evaluation for the determination of the FD. The parameters for exposure were uniformly set at 66–75 kVp, 10–14 mA, and a duration of 16 seconds across all images, by the guidelines provided in the reference manual for the KaVO OP 3D Pro system (PaloDEx Group Oy, Tuusula, Finland). The Frankfort horizontal plane was maintained equidistant, while the sagittal plane was aligned perpendicularly to the ground level. Images, boasting a resolution of 5.5 LP/mm, encompassing a grayscale range of 0-128 levels, and a pixel dimension of 2976 × 1536 (horizontal × vertical), were exported as TIFF files for further analysis.

Clinical evaluation

Four months post-implantation, the reverse torque values for all implants were assessed. Implants exhibiting a torque value exceeding 25 Ncm and displaying radiological evidence of healthy bone healing were deemed to have achieved clinical osseointegration. All implants included in the study were observed to meet these criteria, with no instances of implant failure reported.

Fractal dimension measurement

In the study conducted by Zeytinoglu et al., three regions of interest (ROIs) were delineated on the OPGs for each implant at the mesial, distal, and apical positions, defined as rectangles measuring 10 × 30 pixels (Zeytinoğlu, İlhan, Dündar, & Boyacioğlu, 2015). The software's polygon tool was employed to select ROIs maximizing proximity to the implants while excluding the roots, periodontal ligament, and lamina dura of adjacent natural teeth. The selected ROIs were then cropped and replicated for analysis. To mitigate brightness variations attributable to soft tissue thickness, a Gaussian blur filter was applied. The blurred image was subtracted from the original to produce a new image file, where a standard mean pixel value of 128 was established. Utilizing a brightness threshold of 128, the software's thresholding tool converted the image to binary format, where pixel values at or below 128 were rendered black, representing trabeculae and bone marrow, while all other values turned white. To minimize noise, the image underwent further processing, including degradation, enlargement, and color inversion, resulting in white areas denoting bone marrow and darker regions signifying trabecular bone. The image was skeletonized until there was only one central line in the left pixels. The box-counting feature was used to calculate the values of FD. Squares with pixel sizes of 2, 3, 4, 6, 8, 12, 16, 32, and 64 were systematically placed on the image. For each pixel size, the total number of squares and the number of squares with trabeculae were counted. A logarithmic scale graph of the FD values was created (Figure 1)

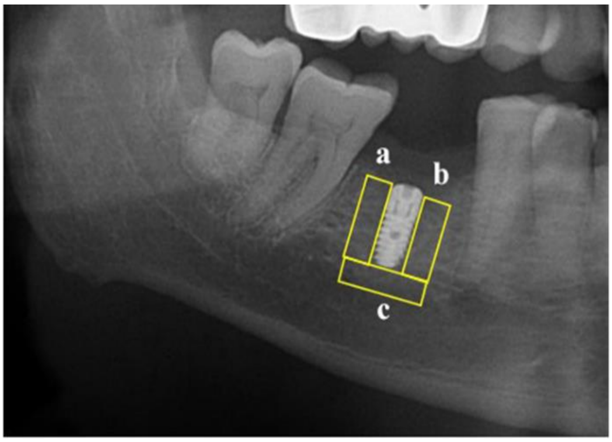

Figure 1. The logarithmic scale graph of the fractal dimension values.

In this study, OPGs captured before and after implantation were systematically compared. Despite the lack of standardized guidelines in the literature for the placement of ROIs on panoramic radiographs, our study adopted specific measures to ensure consistency. For pre-implant OPGs, ROIs were strategically located at equivalent positions by designating the initiation point of the pilot drill for the implant to be 4 mm distant from the root of the adjacent tooth. Additionally, the placement of implants was carefully adjusted to maintain a 2 mm gap from the roots of neighboring teeth. For edentulous patients, reference points for implant placement were determined based on identifiable anatomical landmarks. The uniformity of ROI locations was verified through measurements of implant distances to adjacent structures and anatomical landmarks on the panoramic images, utilizing the ImageJ software (available at https://imagej.nih.gov/ij/download.html, National Institutes of Health, Bethesda, MD, USA). All FAs were conducted by the same researcher using the same computer, employing the methodology outlined by White and Rudolph for the evaluation of FDs (Figure 2) (Cesur et al. 2020).

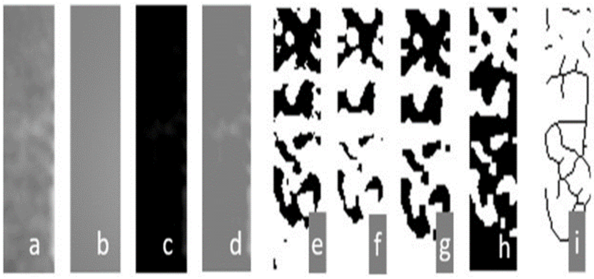

Figure 2. Selection of ROIs.

Statistical analysis

In a preliminary pilot study involving 12 patients with a total of 55 implants, the average FD was calculated to be 1.19±0.07. This pilot study's findings were consistent with Spearman's scale, indicating an estimated standard deviation of 0.07. Utilizing these parameters, the effect size was set at 0.27, with an alpha level (α) of 0.05 and a power of 0.85, for the sample size calculation conducted with the GPower 3.1.9 software (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany), resulting in a required sample size of 93 for the present study. Data analysis was performed using the Turcosa software (Turcosa Analytics Ltd. Co., Turkey). The distribution normality of the data was assessed with Shapiro-Wilk's test and Q-Q plots, revealing a non-normal distribution. Spearman correlation analysis was employed to investigate the relationships between the mesial, distal, apical, and average dimensions of the implants (mesial pre- and post-, distal pre- and post-, apical pre- and post-, and overall pre- and post-implantation). The study included 14 male and 15 female patients, with 48 implants in male patients and 45 in female patients analyzed. Implant outcomes were compared between genders. Spearman's correlation coefficient was utilized for all subgroup analyses, including pre- and post-implantation comparisons. The Mann-Whitney U test facilitated comparisons between genders and jaws, while the Kruskal–Wallis test was applied for analyses across different regions. A p-value of <0.05 was considered statistically significant. Post-hoc evaluations were conducted using the GPower 3.1.9 software (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany).

RESULTS

In this study, 93 implants were evaluated in 29 patients (14 males and 15 females), with an age range of 29 – 68 years (mean age, 49.4±10.7). The descriptive statistics for the study are presented in Table 1.

The overall analysis of the results is as follows:

1. A positive, weak, and statistically significant correlation was determined between the mesial-before and mesial-after variables (r=0.3166, p=0.002).
2. A significant correlation was determined between the distal-before and distal-after variables. (r=0.1567, p=0.004).
3. A positive, weak, and statistically significant correlation was determined between the apex variables before and after the apex variables (r=0.2921, p=0.004). (Figure 3).

The results of the analyses related to gender, edentulous area, edentulous jaw, and systemic conditions are as follows.

Gender in analyses

In gender-specific analyses, a statistically significant correlation was observed in the changes pre- and post-implantation exclusively among female patients, with the following notable results: A positive, moderate, and statistically significant association was identified between the mesial-pre and mesial-post variables in women (r=0.5323, p=0.041). Furthermore, a positive, strong, and statistically significant correlation was found between the distal-pre and distal-post variables in females (r=0.6586, p=0.008). Additionally, a strong and statistically significant positive correlation was noted between the average pre- and post-variables in females (r=0.6279, p=0.012). Upon analyzing the data from male patients exclusively, no significant differences emerged. However, when comparing between genders, each variable was examined individually. A statistically significant difference was noted in the distribution of mesial-post values, with males exhibiting higher values (1.405) compared to females (1.23) (p<0.001). Similarly, a significant disparity was observed in the distribution of average post-implantation values, with male patients showing higher averages (1.3483) than their female counterparts (1.2733) (p=0.002).

Analysis of edentulous areas

There was no statistically significant difference in the inter-regional comparison of all variables (p>0.05)

Anterior region

The analysis revealed a positive, moderate, and statistically significant association between the mesial-pre and mesial-post variables (r=0.4005, p=0.035). Furthermore, the correlation between the distal-pre and distal-post variables was positive, although weak, yet statistically significant (r=0.3777, p=0.048). Additionally, the relationship between the average values before and after was strong, positive, and statistically significant (r=0.617, p=0.001).

In the premolar region

The apex variables before and after the apex in the premolar area had a positive, moderate, and statistically significant correlation (r=0.5818, p=0.001).

In the molar region

The mesial-before and -post variables had a positive, moderate, and statistically significant correlation (r= 0.3969, p=0.018).

Analysis of jaw-based variables

The distal-before and distal-post variables showed a positive, although weak, and statistically significant connection in the maxilla (r=0.2671, p=0.047). The relationship between the apex variables before and after the apex was positive, weak, and statistically significant (r p=0.3447, p=0.009). The correlation between the mean values before and after the variables was favorable, moderate, and statistically significant (r=0.406, p=0.001). The analysis revealed significant differences in the distribution of all variables between the jaw categories, as detailed below:

A statistically significant difference was noted in the distribution of apex-before values, with the mandible category exhibiting a tendency towards higher values (1.34) compared to the maxilla category (1.275) (p=0.023). The distribution of mean-before values also showed a significant disparity, with values in the mandible category (1.32) tending to exceed those in the maxilla category (1.275) (p=0.008).

A statistically significant difference was observed in the mesial-post distribution, with the mandible category presenting higher values (1.4) compared to the maxilla category (1.255) (p=0.002). The distal-post distribution differed significantly between jaw categories, with the mandible category showing higher values (1.38) than the maxilla category (1.31) (p=0.047). A significant variation was identified in the apex-post distribution, where the mandible category's values (1.37) were higher than those in the maxilla category (1.245) (p=0.003).

Lastly, a statistically significant difference was found in the mean-post distribution, with the mandible category achieving higher values (1.35) compared to the maxilla category (1.27) (p<0.001).

Post-hoc test results

While the post-hoc power of this study was 0.85 in the correlation analyses involving 93 implants, the power of the correlation analysis results was found to be lower in the gender comparison, inter-regional comparison, and inter-jaw comparison, in which subgroups were examined. Specifically, the power of the results presented for 48 implants in males was 0.60, whereas the power of the results presented for 45 implants in females was 0.58. Additionally, the power of the study was found to be 0.36 according to the Mann-Whitney U test for the comparison between genders. When examining different regions, the power of the anterior region was 0.42, the premolar region was 0.44, and the molar region was 0.49. Furthermore, in this study, the power of the Kruskal–Wallis test results was found to be 0.63 in the inter-regional comparison of variables. Regarding the comparison between jaws, the power of the results presented for the 56 implants was 0.66, while for the 37 implants, it was 0.51. Finally, the power of the study was found to be 0.35 according to the Mann-Whitney U test for the comparison between jaw.

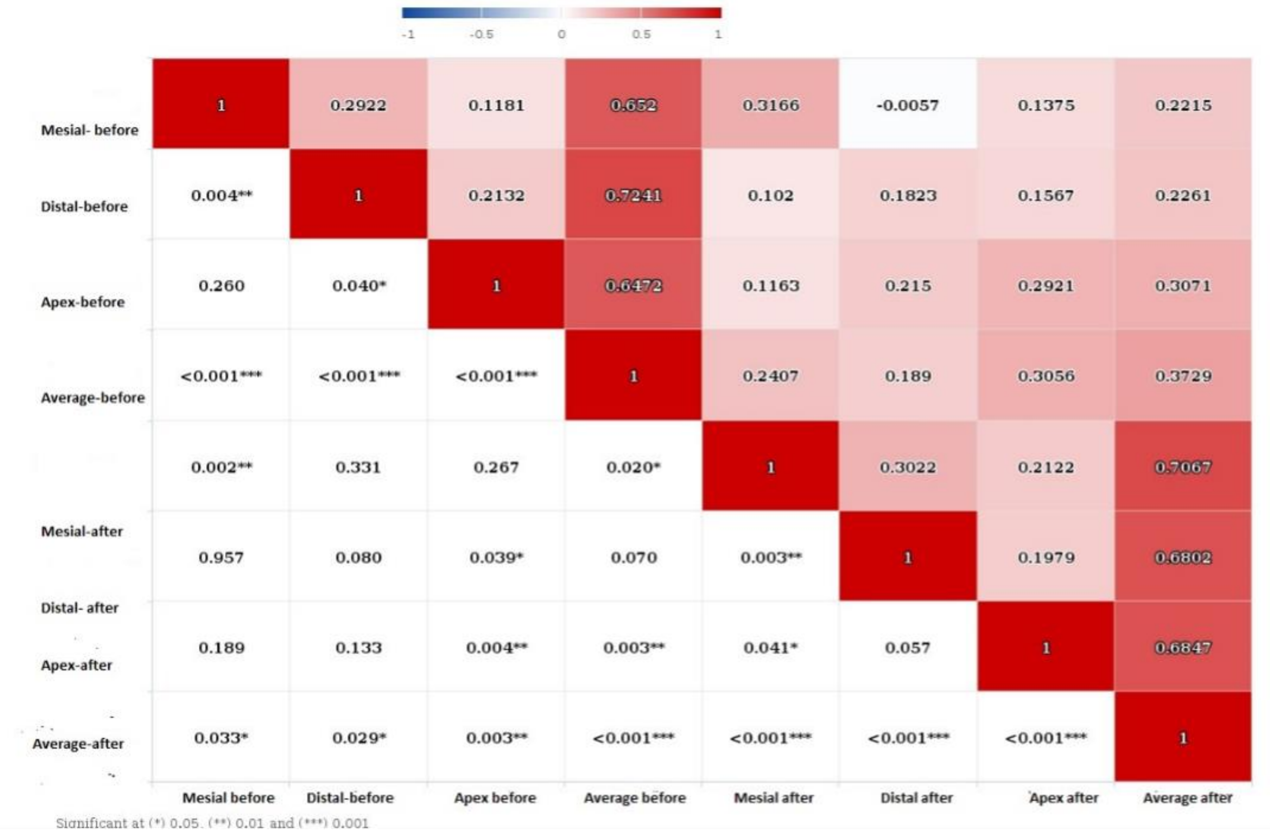

Figure 3. Statistical distribution of relations between variables.

Table 1. Descriptive statistic.

Variable	N	Mesial- before Mean ±SD (Median)	Distal-before Mean ±SD (Median)	Apex- before Mean ±SD (Median)	Average- before Mean ±SD (Median)	Mesial-after Mean ±SD (Median)	Distal-after Mean ±SD (Median)	Apex- after Mean ±SD (Median)	Average-after Mean ±SD (Median)
Gender									
Male	48	1.3±0.1 (1.3)	1.3±0.1 (1.31)	1.3±0.1 (1.3)	1.3±0.09 (1.3)	1.37±0.1 (1.4)	1.33±0.1 (1.36)	1.32±0.1 (1.33)	1.30±0.08 (1.34)
Female	45	1.26±0.1 (1.27)	1.31±0.1 (1.33)	1.29±0.1 (1.31)	1.29± 0.08 (1.29)	1.25±0.1 (1.23)	1.33±0.1 (1.34)	1.27±0.1 (1.27)	1.28±0.08 (1.27)
Region									
Anterior	28	1.3±0.1 (1.29)	1.3±0.13 (1.31)	1.29±0.11 (1.3)	1.3±0.08 (1.31)	1.34±0.1 (1.39)	1.3±0.13 (1.32)	1.27±0.2 (1.23)	1.3±0.1 (1.3)
Premolar	30	1.26±0.1 (1.26)	1.29±0.1 (1.3)	1.28± 0.1 (1.28)	1.27±0.08 (1.27)	1.26±0.13 (1.24)	1.33±0.1 (1.38)	1.3±0.1 (1.3)	1.3±0.07 (1.3)
Molar	35	1.3±0.1) 1.31	1.3± 0.1 (1.33)	1.3±0.2 (1.34)	1.31±0.01 (1.3)	1.33±0.1 (1.34)	1.33±0.1 (1.35)	1.3± 0.1 (1.34)	1.33±0.09 (1.33)
Jaw									
Maxilla	56	1.27±0.1 (1.27)	1.29±0.13 (1.28)	1.27±0.1 (1.28)	1.28±0.08 (1.28)	1.27±0.1) (1.26)	1.3±0.1 (1.31)	1.26±0.1 (1.25)	1.28±0.08 (1.27)
Mandible	37	1.3±0.1 (1.3)	1.33±0.1 (1.33)	1.34±0.1 (1.34)	1.33±0.08 (1.32)	1.37±0.1 (1.4)	1.36±0.1 (1.38)	1.35±0.1 (1.37)	1.36±0.08 (1.35)
Total	93	1.28±0.1 (1.3)	1.3±0.1 (1.32)	1.3±0.1 (1.3)	1.3±0.09 (1.3)	1.3±0.1 (1.32)	1.33±0.1 (1.35)	1.3±0.1 (1.3)	1.3±0.09 (1.3)

DISCUSSION

In the comprehensive analysis of the study group, without segmentation into subgroups, a correlation was discerned between pre- and post-implantation values, indicating changes over time. In the gender-specific subgroup analysis, a similar correlation was specifically identified among female participants. Further, significant differences were observed in the mesial pre- and post-implantation values, as well as the mean pre- and post-implantation values, between male and female participants. When examining the data according to different jaws, correlations between pre- and post-implantation values were noted within each jaw category, accompanied by statistically significant distinctions between these groups. Moreover, in the analysis focused on the location within the jaws, correlations were found between pre- and post-implantation values in specific edentulous regions, although the differences between these regional groups did not reach statistical significance.

Osseointegration, a complex biological process, is defined by the establishment of a direct interface between an implant and bone, devoid of any intervening soft tissue (R. Gupta, N. Gupta, Kurt, & Weber, 2023). To thoroughly elucidate osseointegration, it is imperative to not only demonstrate this direct bone connection histologically but also to evaluate its clinical parameters. Accordingly, in this study, osseointegration was assessed through both clinical examinations and radiological analyses.

Sanchez pioneered the application of FA within the field of dentistry, marking a significant contribution to dental research. Their study was instrumental in identifying variations in FD pre- and post-implant placement, underscoring the potential of FA as a tool for assessing osseointegration (Sánchez & Uzcátegui, 2011). Subsequently, Lee et al. embarked on research aimed at delineating the association between primary implant stability and FD. Their findings elucidated a notable correlation between FD values and implant stability quotient (ISQ) scores, highlighting a stronger association in the mandible as opposed to the maxilla (Lee et al., 2010).

Willing et al. reported that FD scores in the peri-implant area exhibited an increase over up to 2 years following implant placement. They posited that FD scores could serve as a valuable diagnostic indicator in OPG for monitoring changes during the follow-up period (Wilding et al., 1995). Similarly, Mu et al. discovered a statistically significant alteration in the FD within the peri-implant region, comparing measurements taken just prior to implant loading with those obtained 12 months post-loading (Mu et al., 2013).

Despite demonstrating changes in alveolar bone during osseointegration, previous studies have not ascertained the impact of these changes on different jaws, various locations within the jaws, different genders, or the presence of systemic diseases. Our study significantly differs from previous research as it incorporates all these previously mentioned characteristics into its analysis. Sansare et al. demonstrated a significant increase in the bony microstructure around the implant and the number of bone trabeculae after osseointegration (Sansare, Singh, & Karjodkar, 2012). Soylu et al. reported a decrease in FD one week after implant surgery, followed by an increase at two months. Heo et al. observed a reduction in FD within three days after orthognathic surgery (Heo et al., 2002; Soylu et al., 2021). Similar findings were observed in the present study. Based on the results of these investigations, FD can serve as a predictive indicator for osseointegration in radiographic images.

In our study, the loading time was established as four months after implant placement. Considering the existing literature on loading times, Fischer et al. recommended waiting at least 8 weeks for osseointegration before proceeding to the prosthetic phase (Obamiyi et al., 2018). Bornstein et al. demonstrated that bone tissue integration could be observed for at least a three-week healing period after extraction, indicating sufficient osseointegration based on FA parameters (Bornstein, Hart, Halbritter, Morton, & Buser, 2009). Similarly, Balsi et al. concluded that extraction sockets require a two-month recovery period post-extraction to accumulate adequate bone tissue. In the present study, an increase in the FD value was observed four months after implant placement, aligning with these findings. (S. Balshi, Allen, Wolfinger, & T. Balshi, 2005).

Osseointegration is influenced by both bone metabolism and patient-related factors. Mangano et al. noted that bone metabolism may vary according to sex (F. Mangano, Oskouei, Paz, N. Mangano, & C. Mangano, 2018). August et al. further elucidated that low estrogen levels and associated bone alterations could constitute significant risk factors for endosseous implant failure (August, Chung, Chang, & Glowacki, 2001). However, Chen et al. showed that, although ISQ scores were lower in females compared to males, the difference was not statistically significant (Chen, Lyons, Tawse-Smith, & Ma, 2019). In our study, a statistically significant difference in FA was observed between males and females, specifically in the mesial-after and average-after measurements.

When reviewing the literature, it has been established through various studies that oral hygiene habits and smoking can influence osseointegration, with significant sex-related differences observed in these environmental factors (Castellanos & Cosano et al., 2019). Therefore, in our study, we conducted a gender-based analysis. Our current research is more comprehensive compared to the previously mentioned studies as it examines various jaws, locations within the jaws, gender-related factors, and elucidates their limitations more clearly. In this regard, our study stands out as unique.

Koh et al. asserted that the assessment of FA should be limited to the mandible, as the visibility of trabecular patterns is clearer in this region (Koh, Park, & Kim, 2012). Conversely, Diana et al. reported in their study that FA of the surrounding alveolar bone could be conducted on implants in both jaws, without distinguishing between the maxilla and mandible. In our study, we investigated the changes in FA in both jaws during osseointegration.

When analyzing the fundamentals of our study methodology and considering the local factors affecting osseointegration, it became apparent that teeth are situated in various locations within the alveolar bone, affecting outcomes (Ruggiero, Mehrotra, Rosenberg, & Engroff, 2004). Misc et al. discovered variations in bone quality across different jaws and locations within each jaw. Specifically, they found that the anterior mandible consisted of D2 bone, the posterior mandible and anterior maxilla were composed of D3 bone, and the posterior maxilla was made up of D3-D4 bone. Bone quality, influenced by numerous factors including trabecular structure and changes in bone architecture, can impact FA results (Ibrahim et al., 2014).

The present study identified statistically significant differences in FA between the maxilla and mandible. However, no statistically significant differences were observed between the anterior, premolar, or molar areas in the inter-jaw comparison. Based on the results observed within subgroups of these variables, the robustness of the findings was assessed through post-hoc tests. Future studies will aim to increase the sample size within these groups to obtain more precise results with higher power values, thereby enhancing the overall reliability and validity of the findings. To assert complete osseointegration in dental implant applications, it is necessary to demonstrate the bone-implant interface connection histologically alongside clinical parameters. However, this practice is often impractical in clinical settings. In this study, we evaluated osseointegration through clinical and radiological assessments; therefore, the term "osseointegration" in this context refers to clinical-level osseointegration or implant stability.

Limitations and Strengths

The strength of our study is that osteointegration can be evaluated clinically and radiologically. In addition, the maxilla and mandible were evaluated separately, and the jaws were further categorized into anterior, premolar, and molar regions. The current study had several limitations. Firstly, it included two FA assessments: one before and one after osseointegration. For a more comprehensive analysis, including a medium-term FA assessment is recommended. Secondly, including an additional parameter to assess implant stability, such as resonance frequency analysis measurements, would be beneficial.

CONCLUSIONS

FA serves as a reliable and non-intrusive method for identifying osseointegration within the peri-implant zone. Implementing this analysis in OPG images is believed to offer significant advantages to clinicians, particularly in terms of saving time and reducing costs.

Acknowledgements

None.

Conflict of Interest

No author has a conflict of interest.

Author Contributions

Plan, design: FA, TK; **Material, methods and data collection:** FA, TK, GI; **Data analysis and comments:** TK, GI; **Writing and corrections:** FA, GI.

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Ethical Approval

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