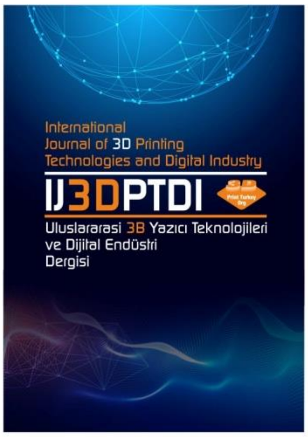

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THE EVALUATION OF MORPHOMETRY OF THREE-DIMENSIONAL RADIUS BONE MODELS USING OPEN-SOURCE MEDICAL PROGRAMS

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ABSTRACT

The use of three-dimensional (3D) models, created using data obtained from radiological images, has significantly increased in recent years across the fields of medicine and health. The digitization of these models primarily utilizes open-source or commercial software. However, while the use of commercial software presents a significant economic burden, questions remain regarding model accuracy and output quality in open-source solutions. Therefore, this study aims to evaluate the morphometric accuracy of 3D radius models created using open-source medical software (InVesalius®, ITK-SNAP®, Seg3D®, and 3D Slicer®) by comparing them with gold standard (dry bone) measurements. Computed Tomography images of 15 dry human radius bones were used to generate the 3D digital models. These images were used to obtain 3D digital models via four different open-source software programs. Model lengths were calculated using MeshLab®, and volumes were calculated using Mimics® software. For gold standard comparison, the actual bone lengths were measured using digital calipers, and volumes were measured based on the Archimedes Principle.As a result, successful 3D digital radius models were created with all four programs. When the obtained measurements were compared with the gold standard values, no statistically significant difference was found between the programs ($p > 0.05$). Nevertheless, only the 3D Slicer® software demonstrated a high level of agreement in volume measurements (Cronbach's Alpha: 0.996; 95% CI: 0.988–0.999), standing out among the open-source medical software options.

Keywords: 3D Modeling, Bland-Altman Analysis, Morphometry, Software, Radius

1. INTRODUCTION

Technological developments, which we feel rapidly in the fields of medicine and health, trigger the emergence of different methods in the practice routine [1]. Measurement and imaging methods, test, analysis, and monitoring devices used in the health sector are developing and increasing, and as a result, the medical literature is expanding day by day. Developments in the field of biomedicine also show parallelism with the development of information technologies [2]. In particular, 3D images obtained from radiological images are of great importance in the fields of health and education. Because the integration of 3D imaging technologies and radiology provides great advantages: observer objectivity, non-invasiveness, storing data in a digital environment for many years, and transferring it to other centers over the internet [3]. Apart from these, virtual operating rooms have started to be created in many institutions with surgical simulations using medical image data and computer-aided models [4]. However, special screens and equipment are used for these simulations. These limitations are overcome with 3D digital models and physical models created from these models [5]. At the same time, rapid prototyping is possible with the application of 3D printing technologies, and the productivity rate increases. Thus, patient-specific 3D models are produced to assist surgical interventions. 3D models also have the potential to optimize surgical planning, assistant training, informing patients, producing personal prostheses, and more [6].

3D printers generally use the Standard Triangle Language (STL) file type, which is the common output of 3D modeling software [7]. When the studies in the literature are examined, it has been observed that open source and commercial software with different licensing methods are generally used for 3D viewing and 3D printing of two-dimensional medical images [8-10]. The high cost of software, hardware, and raw materials required in the production process of anatomical models created with 3D modeling causes limitations in the use of these programs in the field of medicine and health [11]. However, open-source and operating system-independent applications that can run on any platform are an alternative preferable by users [11, 12].In this context, open-source software provides cost-effective, accessible, and flexible solutions, making their accurate validation against gold standard measurements crucial for widespread implementation.

While many studies report the successful creation of 3D models, most focus on commercial programs and often do not analyze the agreement of the created models with real anatomical structures [8-12].

To address this gap, this study is one of the limited efforts to directly compare the morphometric accuracy of multiple open-source software packages using measurements derived from actual dry bones as the gold standard. This comprehensive approach is essential to determine the reliability and interchangeability of these accessible tools.

For this reason, in this study, it was aimed to evaluate the morphometric accuracy of 3D radius bone models using four different open-source medical programs (InVesalius®, ITK-SNAP®, Seg3D®, and 3D Slicer®) and assess their agreement with real bone measurements.

2. MATERIAL AND METHOD

2.1. Data Collection and Image Capture

For the study, necessary permissions were obtained from the Afyonkarahisar Health Sciences University (AFSU) Clinical Research Ethics Committee (Decision No: 192, Date: 05.03.2021).

For this study, 15 human radius bones with similar geometric properties, well preserved, dry, and used for educational purposes were obtained from the anatomy department. In the Radiology department, the radius bones were randomly aligned side by side with a space between them and images were obtained with a multislice Computer Tomography (CT) device (Toshiba Aquilion Prime®, Japan). Scans were performed in the axial, coronal, and sagittal planes. Scanning parameters were as follows: 1 mm slice thickness, 120 kV tube voltage, 0.5 x 80 mm collimation, 370 mm field of view, 512 x 512 matrix, 0.35 s rotation speed, 15 mm/s table speed, and scan time of 2-4 seconds. The radiological images obtained as a result of the scan were saved in Digital Imaging and Communications in Medicine (DICOM) format. Subsequently, the DICOM data was transferred to the personal computer.

2.2. Image Post-Processing and Creation of 3D Model

Four widely used open-source medical software programs ((InVesalius® 3.1.1 (www.cti.gov.br), ITK-SNAP® 3.8.0 (http://www.itksnap.org), Seg3D® 2.5.0 (https://www.sci.utah.edu), 3D Slicer® version 4.11.20210626 (www.slicer.org)) were randomly selected from among image processing programs (The image processing programs used in the study are open source and do not require computer systems with high quality and graphic features. In addition, these programs are supported by all operating models and can convert DICOM to STL). DICOM data obtained from CT scan was transferred to four different open-source image processing programs. The transferred files in DICOM format were converted into 3D models in STL file format for each bone after certain hierarchical processes with the help of image processing programs. Parameters were chosen, aimed at optimizing the 3D rendering process, quality, and conversion to STL format, in order to obtain the best possible 3D digital models for each software platform. All segmentation procedures were prepared and standardized by a single researcher with sufficient technical knowledge and experience regarding the software utilized. Semi-automatic segmentation procedure was applied for the 3D reconstruction of the radius. Specifically, initial segmentation was achieved by setting an intensity threshold appropriate for dense cortical bone, typically ranging from 200 to 1000 Hounsfield Units (HU) across all programs. Following thresholding, the region-growing tool was employed to refine the bone contour, and manual editing (e.g., painting and erasing of stray voxels) was applied to the mask to ensure the exclusion of non-osseous structures and enhance the accuracy of the 3D reconstruction.

As a result, a total of 60 3D digital radius bone models, 15 in each, were obtained with the help of four different image processing programs.

2.3. Validity Analysis and Morphometric Measurements of 3D Models Created from Real Bones

2.3.1. Volume measurements

While the volume of 15 radius bones was measured using the Archimedes Principle [13], the digital 3D radius models were imported into the Mimics® software program (Materialize, Belgium), and the volume of the models was calculated automatically (Fig. 1).

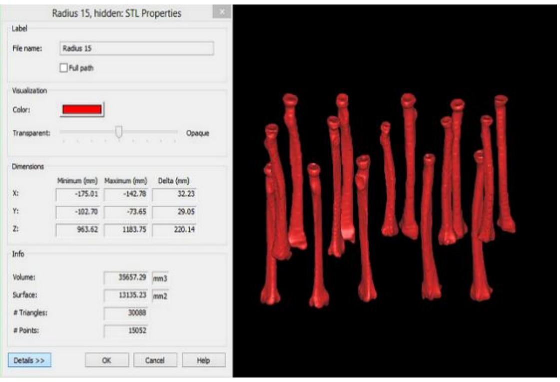

Figure 1. Volume measurements of 3D radius models in Mimics program®.

2.3.2. Length and width measurements

While the length and width of 15 radius bones were measured with a digital caliper, the length and width of the digital 3D radius models were measured with MeshLab® 2022.02 (Visual Computing Lab, ISTI-CNR, Pisa, Italy), a software measurement tool. All physical measurements (digital caliper) and digital measurements (MeshLab®) were performed by a single, trained observer. The observer performing the digital measurements was blinded to the software program used to generate each specific model. The measured parameters were; length of the radius bone, diameter of radial head, thickness of radial head, distance between radial tuberosity and head, width of ulnar notch, radius width at the level of dorsal tubercle (Fig. 2).

Figure 2. A) Measurement of radius length with digital caliper a: Length of the radius bone, b: Diameter of radial head, c: Thickness of radial head, d: Distance between radial tuberosity and head, e: Width of ulnar notch B) f: Radius width at the level of dorsal tubercle.

2.4. Statistical Analysis

The comparison of the volume, length, and width values of 15 radius bones and digital radius models created by four different open-source medical programs between the groups was made with the Statistical Package for the Social Sciences (SPSS) 25.0 package program (IBM, USA). Since the sample size could not meet the parametric test assumptions, the Kruskal-Wallis Test, one of the non-parametric tests, was used for statistical analysis. Medians and interquartile ranges (IQR) were calculated. Values with $p < 0.05$ were considered statistically significant.

At the same time, the validity analysis of the measurement values obtained from four different open-source medical programs with the control group was evaluated by Bland-Altman analysis. The Intraclass Correlation Coefficient (ICC) test was used in the reliability analysis. In the Bland-Altman test, the data for the difference between two measurements were calculated and the Simple Scatter Plot was drawn. The reliability (r) value in the ICC test was interpreted according to the literature [14-17].

3. RESULTS AND DISCUSSION

In the study, the median and interquartile ranges were calculated by measuring the volume, length, and width of digital 3D radius models created with 15 radius bones and four different medical programs (Table 1). Linear and volume measurements were statistically compared between study groups. As a result, the differences between study group measurements were found to be statistically insignificant ($p>0.05$).

In addition, when the agreement between the models created with four different software programs and real bones was evaluated, high agreement was found in the volume measurements made with the 3D Slicer® (Fig. 3). No agreement was found in linear measurements (Fig. 4). After obtaining these data, the reliability of the volume measurements calculated with the 3D Slicer® program was examined. ICC test was applied for reliability. There was a high agreement between real bone and 3D Slicer® software program on the volume measurements (Cronbach Alpha: 0.996 (CI 95%: 0.988-0.999)). The level of statistical significance was set at $p < 0.05$.

Table 1. Morphometric measurement analysis of radius models.

Parameters	Unit	Control [Median(IQR)]	InVesalius® [Median(IQR)]	ITK-SNAP® [Median(IQR)]	Seg3D® [Median(IQR)]	3D Slicer® [Median(IQR)]	p values
V	mm³	38070 (15670)	41634.01(20663.64)	40766.24(19851.04)	39054.58(21588.24)	39335.11(14847.35)	p=0.707
L1	mm	227.21(22)	225.34(20.43)	225.26(20.94)	225.77(22.15)	225.48(21.34)	p=0.989
D1	mm	18.75(4.15)	19.29(3.18)	19.14(3.52)	19.13(4.3)	19.36(4.62)	p=0.978
L2	mm	8.83(1.81)	8.52(1.87)	8.26(2.58)	8.23(0.99)	8.7(1.74)	p=0.841
L3	mm	12.14(2.94)	11.92(2.53)	12.4(1.84)	12.27(1.68)	11.69(2.38)	p=0.807
W1	mm	17.65(5.02)	16.01(4.35)	16.47(3.7)	16.2(4.04)	17.08(4.04)	p=0.931
W2	mm	29.41(4.88)	29.99(4.66)	29.69(4.97)	29.89(5.07)	29.41(3.27)	p=0.956

Abbreviation: Medians and interquartile ranges of morphometric measurements [Median(IQR)]. V: Volume, L1: Length of the radius bone, D1: Diameter of radial head, L2: Thickness of radial head, L3: Distance between radial tuberosity and head, W1: Width of ulnar notch, W2: Radius width at the level of dorsal tubercle

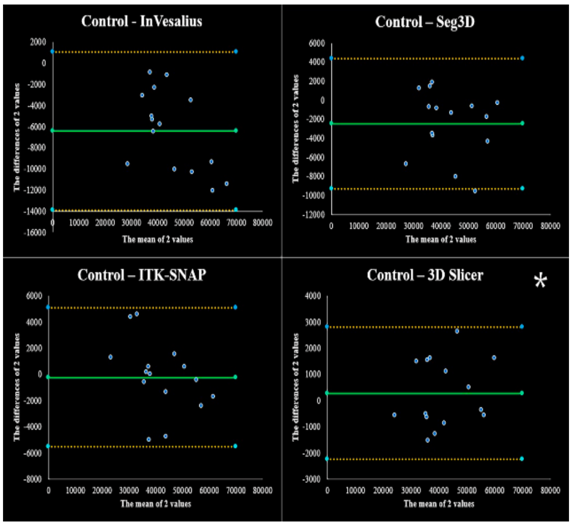

Figure 3. Demonstrating the validity agreement between the Bland-Altman analysis (Scatter Dot graphs) and the Archimedes Principle (gold standard) for radius volumes measured with open-source medical programs. Note: The reliability coefficient for the 3D Slicer method was found to be high (Cronbach Alpha: 0.996 (CI 95%: 0.988-0.999)).

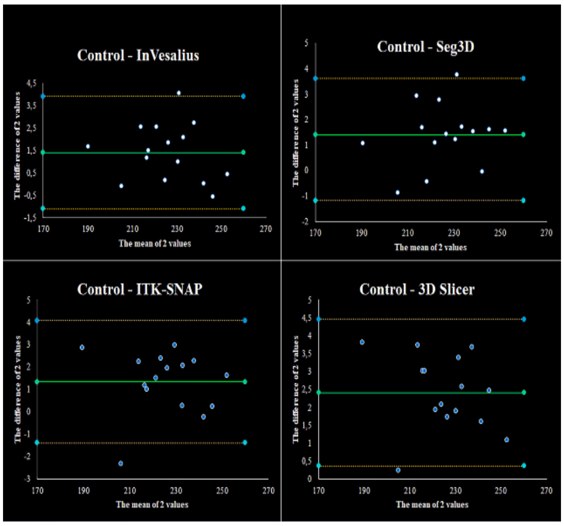

Figure 4. Demonstration of validity agreement between the Bland-Altman analysis (Scatter Plot graphs) and radius lengths measured with a digital caliper and open-source medical programs.

Medical education and health care are affected by scientific developments, as in all other fields, and the use of technology becomes inevitable in the field of medicine [1]. With the increasing use of multimedia in recent years, 3D applications are being used more and more in modern medical education and health [2]. Today, medical fields where 3D anatomical models are used include surgical planning, patient-specific implant, orthosis and prosthesis production, tissue and organ production by bioprinting method, modern medical education, forensic medicine, and criminology applications [18-20].

In particular, 3D anatomical model applications are becoming popular in the field of orthopedics. Because in orthopedic surgeries (especially in fracture surgeries), the fragmentation of the fractures and the dispersion in the fracture fragments within the joint surfaces complicate the surgical procedures and cause prolongation of the operation time. While this situation negatively affects surgical success, it also prolongs the rehabilitation period [21]. In addition, with 3D models, deformities can be examined more comprehensively and in detail by rotating 360°. Thus, the least risky planning and rehearsals can be made [22, 23]. In fact, patient-specific surgical applications can be preferred by giving more detailed information about the operation to the patient and the patient's relatives [24, 25].

The literature studies, which include the mentioned 3D model applications, are briefly compiled. In a study, a biomodel of the radius was created preoperatively with 3D printing technology for the surgery of the malunion of a distal radius fracture. Researchers stated that preoperative planning has improved with the use of the biomodel and that the produced model does not pose a problem in terms of cost [26]. Chen et al. (2019) included 48 patients with distal radius fractures in their study. In the preoperative period, 3D models of the distal radius of the patients were created. In the study, the operation times, blood loss volumes, and frequency of fluoroscopy use of routine treatments and surgeries using 3D printing technology were compared. As a result, significant improvements have been made in all parameters evaluated in surgeries using 3D printing technology [25].

Youman et al. (2021), on the other hand, evaluated the feasibility of using models produced with 3D printer technology in the pathology course. Structures of osteochondroma and osteosarcoma pathologies were created on 3D models. As a result, they stated that 3D models offer a more advantageous learning activity than two-dimensional image data and can be used as an effective educational material [27].

As mentioned above, success models have been created with 3D applications in literature studies. However, most of the software programs used in the studies were not evaluated in terms of economy, ease of use, and accessibility. Furthermore, the agreement of the models created with the real structures in most studies was not analyzed. For this reason, in our current study, the agreement of digital radius models created with four different open-source medical programs and real bones was evaluated. Based on the evaluation results, the 3D Slicer® program was determined to show high agreement with real bones in volumetric measurements. Linear measurements showed no agreement with any software program. But, the closest results belonged to the 3D Slicer® program. The observed lack of agreement in the linear measurements, unlike the volumetric measurements, can be attributed to several technical and morphological factors inherent to the 3D reconstruction process. Firstly, the complex curvature and intricate anatomical landmarks of the radius morphology (e.g., radial head diameter, ulnar notch width) are highly sensitive to errors induced during segmentation. Secondly, the fixed voxel size of the CT images may introduce inherent inaccuracy, particularly when attempting precise linear measurements on curved surfaces. Furthermore, the post-segmentation processes, such as mesh smoothing operations applied by the software to create visually appealing models, can subtly alter landmark locations and overall bone dimensions, leading to deviations when compared to the gold standard caliper measurements. Lastly, minor variations in segmentation success can disproportionately affect a point-to-point linear measurement compared to the overall volume calculation. In this context, the literature was searched and different anatomical structures and evaluation methodologies were examined with similar programs.

Poleti et al. (2016), in their in vitro study, evaluated 20 different morphometric measurements of 10 dry mandibles of the adult population with Dolphin® and InVesalius® programs, and the reliability of the programs was compared [28]. In another study, 3D models of 10 mandibles were created with CBCT (Cone Beam Computed Tomography). In their study, 35 morphometric measurements were compared with XoranCat®, RadiAnt®, and InVesalius® medical programs. There was no statistically significant difference between the measurements in both studies ($p>0.05$) [28,29].

Fyllingen et al. (2016), in their retrospective study, calculated tumor volumes from the models created by transforming the brain tumors of 20 patients into 3D models in BrainVoyager®, 3D Slicer®, and ITK-SNAP® programs. The calculated volumes were compared statistically and no significant difference was found ($p>0.05$) [30]. Virzì et al. (2020), in their study, created 3D models of the pelvis skeleton and organs with MRI (Magnetic Resonance Imaging) in different medical programs and evaluated the performances of the programs. As a result of the study, it was concluded that both Seg3D® and ITK-SNAP® seemed very useful, Myrian Studio® and ITK-SNAP® were the fastest programs in terms of segmentation process, and 3D Slicer® was the most appropriate medical program for the display of nerves in the pelvis [31].

Stawiski ve et al. (2017), in their study, calculated tumor volumes and compared by semi-automatic segmentation using ITK-Snap®, 3D Slicer®, and NIRFast® medical programs and the standard planimetric method. As a result of the comparison, it was stated that there was no statistically significant difference between the programs ($p>0.05$); it has been reported that the ITK-SNAP® program had the lowest error rate compared to the standard method [32]. Kollmann et al. (2020), in their study, calculated the volumes of brain tumor models created using BrainLab®, ITK-SNAP®, and OsiriX® and compared them with phantoms with predefined volumes. As a result of the comparisons, it was concluded that the difference between the volumes calculated by the programs and the phantom volumes was statistically significantly different ($p<0.05$) [33]. In our study, successful models were created with four different open-source programs. Similar to the literature, no statistically significant differences were found between software programs and real bones in terms of morphometrics. However, when its agreement with real bones (Bland-Altman analysis) was evaluated, only 3D Slicer® was determined as the agreement software program in volume measurements.

We think that the reason why our study results differ from some literature studies and our study limitations are due to the following parameters:

• The difference in the determined gold standard;

• The programs selected are different;

• Small sample size;

• CT images have a higher section thickness and fewer images;

• The control groups in the literature studies are other medical programs, and the agreement of these programs with real structures has not been tested;

• Preferring semi-automatic segmentation, which can be applied more easily, instead of manual segmentation, which yields more accurate results, when creating 3D digital models;

• The exact image of the models cannot be obtained due to the anatomical structure of the radius consisting of recesses and protrusions.

In this study is subject to several limitations. First, the sample size was limited by the availability of only 15 dry human radius bones that met the inclusion criteria for the study in our laboratory. This constraint restricts the generalizability of the findings and highlights the importance of future studies with larger sample sizes. Second, the 3D modeling was performed exclusively on the radius bone, which limits the generalization of the results to other types of bones. Third, the segmentation process may be investigator-dependent; this factor could influence the direct comparison of our results with those obtained using fully automated segmentation methods.

4. CONCLUSIONS

In our study, it was determined that 3D digital anatomical models can be easily and successfully designed using open-source medical programs. The resulting models offer profound implications for medical practice, potentially aiding in surgical strategy determination and the manufacturing of patient-specific devices (orthoses and prostheses), while also serving medical education by significantly reducing exposure to cadavers and harmful chemicals.

By systematically comparing our methodology with literature studies, this work offers a novel perspective on the success criteria of 3D models and is foreseen to bring a modern approach to medical and industrial fields.

For future work, expanding the study's scope by increasing the number and sample size of medical programs is suggested to yield more precise results.

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