CORTICAL BONE THICKNESS OF THE ANTERIOR MAXILLA USING AI SEGMENTATION

Dissertação apresentada à Universidade Católica Portuguesa
para obtenção do grau de Mestre em Medicina Dentária

Por:
Claudia Pizzurro

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“Medicine is a science of uncertainty and an art of probability.”

William Osler

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ABSTRACT

Introduction:

The thickness of the buccal cortical plate in the anterior maxilla is a critical factor in implantology, orthodontics, and aesthetic dentistry. Cone-beam computed tomography CBCT combined with artificial intelligence (AI)–based segmentation and three-dimensional digital workflows, may facilitate three-dimensional assessment of alveolar bone morphology.

Aim:

To evaluate buccal cortical bone thickness in the anterior maxillary region using CBCT imaging associated with AI-based segmentation and three-dimensional digital analysis.

Materials and Methods:

CBCT examinations of patients with anterior maxillary teeth were retrospectively analysed. DICOM files were imported into CoDiagnostiX® software for AI-based segmentation and STL model generation. The obtained models were analysed in Geomagic Control X® through a standardized three-dimensional workflow. Linear measurements of cortical bone thickness were performed at the cervical, middle, and apical thirds of the teeth. Descriptive, inferential, and exploratory statistical analyses were conducted to assess cortical bone distribution and anatomical variability.

Results:

A total of 44 CBCT examinations were analysed. Considerable anatomical variability was observed in buccal cortical bone thickness. Mean thickness values generally decreased from the apical to the cervical level, with the lowest values observed at the cervical third. Mixed linear model analysis demonstrated a significant effect of root level on cortical bone thickness on both the right ($p = 0.003$) and left sides ($p = 0.042$), with significantly greater thickness at the apical level compared with the cervical level (Bonferroni-adjusted $p = 0.002$). No significant effects of age or sex were identified. On the left side, lateral incisors presented significantly greater cortical thickness than central incisors ($p = 0.006$).

Conclusion:

The anterior maxillary region presents a predominance of thin buccal cortical bone associated with considerable anatomical variability. The present study demonstrated the feasibility of a three-dimensional digital workflow that combines CBCT imaging, AI-assisted segmentation, STL model generation, and three-dimensional morphometric analysis to assess alveolar bone morphology. The findings of the present study may support more individualized treatment planning in implantology, orthodontics, and aesthetic dentistry.

Keywords:

cone-beam computed tomography; alveolar bone loss; artificial intelligence; maxilla; dental implants.

RESUMO

Introdução:

A espessura da cortical óssea vestibular na região anterior da maxila constitui um fator crítico na implantologia, ortodontia e dentisteria estética. A tomografia computorizada de feixe cónico (CBCT), combinada com segmentação baseada em inteligência artificial (IA) e fluxos de trabalho digitais tridimensionais, pode facilitar a avaliação tridimensional da morfologia do osso alveolar.

Objetivo:

Avaliar a espessura da cortical óssea vestibular na região anterior da maxila utilizando imagens de CBCT associadas à segmentação baseada em IA e à análise digital tridimensional.

Materiais e Métodos:

Foram analisados retrospetivamente exames de CBCT de pacientes com dentes na região anterior da maxila. Os ficheiros DICOM foram importados para o software CoDiagnostiX® para segmentação baseada em IA e geração de modelos STL. Os modelos obtidos foram analisados no Geomagic Control X® através de um fluxo de trabalho tridimensional padronizado. Foram realizadas medições lineares da espessura da cortical óssea nos terços cervical, médio e apical dos dentes. Foram efetuadas análises estatísticas descritivas, inferenciais e exploratórias para avaliar a distribuição da espessura da cortical óssea e a variabilidade anatómica.

Resultados:

Foram analisados 44 exames de CBCT. Observou-se uma considerável variabilidade anatómica na espessura da cortical óssea vestibular. Os valores médios de espessura apresentaram, de forma geral, uma diminuição do nível apical para o nível cervical, sendo os menores valores observados no terço cervical. A análise através de modelos lineares mistos demonstrou um efeito estatisticamente significativo do nível radicular na espessura da cortical óssea, tanto no lado direito ($p = 0,003$) como no lado esquerdo ($p = 0,042$), verificando-se uma espessura significativamente superior ao nível apical quando comparada com o nível cervical (correção de Bonferroni, $p = 0,002$). Não foram identificados efeitos estatisticamente significativos da idade ou do sexo. No lado esquerdo, os incisivos laterais apresentaram uma espessura cortical significativamente superior à dos incisivos centrais (p = 0,006).

Conclusão:

A região anterior da maxila apresenta uma predominância de cortical óssea vestibular fina associada a uma considerável variabilidade anatómica. O presente estudo demonstrou a viabilidade de um fluxo de trabalho digital tridimensional que combina imagens de CBCT, segmentação assistida por IA, geração de modelos STL e análise morfométrica tridimensional para a avaliação da morfologia do osso alveolar. Os resultados do presente estudo poderão contribuir para um planeamento terapêutico mais individualizado em implantologia, ortodontia e dentisteria estética.

Palavras-chave:

Tomografia computorizada de feixe cónico; osso alveolar; inteligência artificial; maxila; implantes dentários.

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Abbreviations

3D – Three-Dimensional

AI – Artificial Intelligence

CBCT – Cone-Beam Computed Tomography

CCD – Charge-Coupled Device

CMOS – Complementary Metal-Oxide Semiconductor

CNN – Convolutional Neural Network

DICOM – Digital Imaging and Communications in Medicine

DMFR – Dentomaxillofacial Radiology

FOV – Field of View

H0 – Null Hypothesis

H1 – Alternative Hypothesis

PSP – Photostimulable Phosphor

ROI – Region of Interest

STL – Standard Tessellation Language

INTRODUCTION

1. INTRODUCTION

1.1. Importance of Alveolar Bone

Numerous studies over the years have consistently shown a strong link between the shape of the gingival tissue and the underlying bone structure. This connection emphasizes that the form and function of periodontal tissues are interdependent, as both support the teeth and maintain their stability. Although root shape influences the size of both the outer and inner bone plates, there is limited research on how a tooth's position within the alveolar process—including apico-coronal and bucco-lingual directions—affects the thickness of the labial bone plate (1).

The 2017 World Workshop on the Classification of Periodontal and Peri-Implant Diseases and Conditions identified alveolar bone loss as a vital marker for assessing the severity and staging of periodontitis. The maxilla plays a significant role in the oral cavity, given its importance in aesthetics and function, particularly in implantology, orthodontics, and restorative dentistry. The features of the alveolar bone in this region directly affect dental treatment outcomes and patient satisfaction (2).

Different individuals exhibit significant variation in alveolar bone development in this area, influenced by factors such as ethnicity, facial skeletal pattern, dental occlusion, and periodontal biotype. Understanding these variations in alveolar bone structure is essential for accurate diagnosis and personalized treatment planning (2).

1.2. Biology and Characteristics of the Alveolar Bone

The maintenance of oral health is basically dependent on the health of the supporting structures, among which the alveolar bone takes a major part in holding teeth in place and helping them to function properly (Figure 1)(3).

The section of alveolar bone adjacent to the tooth (cementum) is known as the alveolar bone proper, or intrinsic alveolar bone. It forms the outer wall of the tooth socket, tightly surrounding the roots of the teeth and functioning as the attachment site for Sharpey's fibers, the terminal extensions of the periodontal ligament (3).

Following this initial section is the supportive, adaptable alveolar bone, consisting of the outer cortical surfaces—both buccal and inner trabecular bone. This combination provides the alveolar process with strength and flexibility, enabling it to effectively resist the forces produced during chewing and biting (3).

The spongy, or cancellous, bone has a mesh-like structure of trabeculae and contains abundant bone marrow, serving two main roles. It supports blood cell production, especially during youth and early adulthood, and enhances the mechanical strength of the alveolar process by providing a stable and flexible base for chewing. This structure is crucial to the success of dental procedures such as implants and advanced periodontal or regenerative treatments (3).

A diagram of a tooth cut vertically shows that the alveolar bone supports the tooth and connects to the root through the periodontal ligament, which absorbs bite forces. The outer surface consists of dense, hard bone, while the inner surface is composed of softer trabecular bone. This structure, with its outer shell and cushioning inner tissue, provides impact resistance. (3)

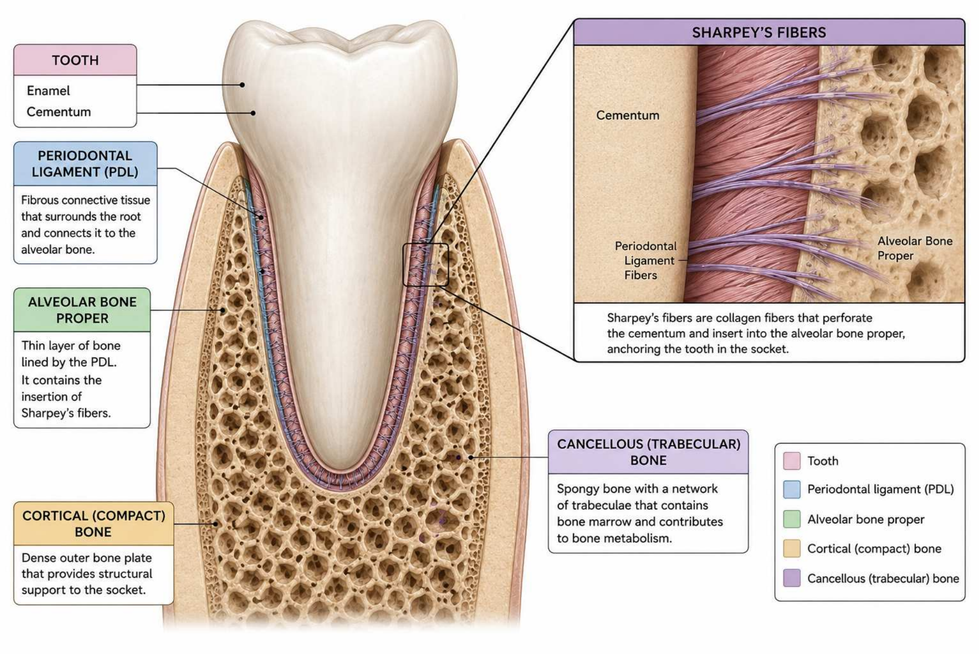


Figure 1 – The alveolar bone

1.3. Structure and Function of the Alveolar Bone

The alveolar bone is the most dynamic component of the periodontium, constantly changing as it reacts strongly to external mechanical stresses. In this context, forces from natural teeth influence both the quantity and quality of the alveolar bone, highlighting the vital relationship between its condition and dental function (4).

The alveolar configuration features a specific zone called the alveolar bone proper, or bundle bone. This area lines the interior of the dental socket and is primarily influenced by the activity of cells within the periodontal ligament. It consists of concentric layers of collagen fiber bundles that connect the periodontal tissues, forming a stable and functional link between the tooth and the adjacent bone (5).

Surrounding this inner layer, the alveolar bone provides additional structural support. It consists of groups of osteons nourished by the Haversian system and bone marrow, which give it both strength and adaptability. This organization maintains a continuous functional connection between the jaws and the alveolar bone through the periodontal ligament and root cementum, allowing the alveolar bone to withstand masticatory forces while also providing a stable foundation for complex dental procedures, including implants and advanced periodontal therapies (5).

1.4. Cellular Composition and Clinical Relevance of Alveolar Bone

The alveolar bone is a mineralized tissue composed mainly of type I collagen, minerals, and water. Its stability depends on key cells like osteoblasts, osteocytes, and osteoclasts, and is also maintained by other cell types such as adipocytes, vascular cells, and immune cells.

Osteoblasts and osteoclasts collaborate to maintain bone health by generating new bone tissue and resorbing old bone. Embedded within the mineralized matrix, osteocytes also play a crucial role in overseeing bone remodeling and maintaining mineral balance (6,7).

In implant dentistry, alveolar bone morphology is crucial for ensuring primary implant stability and long-term osseointegration. This involves not just the volume of available bone but also its shape, structural organization at both macro- and microlevels, and its material properties, such as elasticity and microarchitectural structure (6–8).

The cortical and trabecular components of alveolar bone have distinct structural and biological roles that are highly relevant in implant dentistry. Cortical bone, characterized by greater density and mechanical strength, is essential for primary implant stability, as it provides anchorage during placement. In contrast, trabecular bone has a porous, highly vascularized architecture and contributes mainly to bone remodelling, metabolic activity, and secondary biological stability during osseointegration. Therefore, the interaction between cortical and trabecular bone is fundamental to long-term implant success and to the preservation of the structural integrity of the alveolar process. (6–8).

1.5. Traditional assessment methods

Conventional radiographic techniques, including periapical, bitewing, and panoramic radiographs, have long played a central role in dental diagnosis and treatment planning. These imaging methods enable the assessment of dental and periodontal structures, including alveolar bone levels, root morphology, and periapical conditions. (9).

Despite their widespread clinical use, conventional two-dimensional radiographic techniques have important limitations, including image distortion, anatomical superimposition, and reduced accuracy in assessing complex three-dimensional bone morphology. As a result, cone-beam computed tomography (CBCT) has seen increasing clinical use for the more detailed evaluation of maxillofacial structures. (10,11).

1.5.1. Periapical and Bitewing radiographs

Radiographic evaluation plays an important role in dental diagnosis and treatment planning, with periapical and bitewing radiographs among the most used imaging methods. Periapical radiographs allow for the assessment of periodontal structures, root morphology, and periapical lesions, whereas bitewing radiographs are used mainly to detect interproximal caries and alveolar bone changes. (8,9).

Despite their clinical usefulness, these conventional two-dimensional imaging techniques have important limitations, including image distortion, anatomical superimposition, and the inability to provide an accurate three-dimensional evaluation of alveolar bone morphology. (8–10).

1.5.2. Panoramic radiographs

Panoramic radiographs provide a broad view of the maxillofacial structures and are widely used in dental diagnosis and treatment planning. They are particularly helpful for the general assessment of bone structures and tooth position, especially when intraoral radiographs are difficult to obtain. (8–10).

However, panoramic imaging has important limitations, including image distortion, magnification errors, and reduced accuracy in linear measurements, particularly in the anterior maxillary region. As a result, conventional radiographic techniques may not provide sufficient three-dimensional information for the detailed assessment of the alveolar bone and for implant planning. (8–10).

Overall, conventional radiographic techniques remain vital for diagnosis in dentistry; however, their inherent two-dimensional limitations have led to increased use and development of three-dimensional imaging methods such as CBCT (8–10)

1.6. Digital evaluation methods

Continuous technological progress has led to the adoption of new imaging methods in dentistry, such as digital radiography and cone-beam computed tomography (CBCT). Digital radiography streamlines clinical procedures by reducing radiation doses, eliminating the need for chemical processing, and enabling software-based adjustments such as brightness, contrast, and zoom. Consequently, it offers better diagnostic visibility compared to traditional radiographs (7).

1.6.1. Digital sensors

Digital sensors are divided into photostimulable phosphor (PSP) plates and silicon-based systems like CCD (Charge-Coupled Device) and CMOS (Complementary Metal-Oxide-Semiconductor). These advancements have facilitated quicker image capture and enhanced diagnostic accuracy, leading to the broad adoption of digital imaging in modern dental practices (12).

1.6.2. CBCT

CBCT (Cone-Beam Computed Tomography) represents a major advancement in dental imaging, providing detailed 3D images of dental and maxillofacial structures through high-resolution cross-sectional views. It allows precise linear measurements and provides a thorough evaluation of alveolar bone morphology, making it essential for implantology, orthodontics, and surgical planning (13).

The quality and accuracy of CBCT images are influenced by factors such as voxel size, field of view (FOV), spatial resolution, and reconstruction algorithms. Smaller voxel sizes and reduced FOV protocols generally provide greater precision in anatomical evaluation (13).

More recently, the integration of artificial intelligence (AI) into digital workflows enabled semi-automatic segmentation and three-dimensional reconstruction of anatomical structures. AI-assisted segmentation combined with STL model generation facilitates three-dimensional evaluation of alveolar bone morphology (13).

1.7. AI Technologies

Artificial intelligence (AI) refers to machines' capacity to imitate human behaviors and cognitive functions, enabling them to perform complex tasks such as pattern recognition, problem-solving, and decision-making. As AI becomes increasingly integrated into medicine, it has driven significant advancements in diagnosis, treatment planning, and patient care. In dental and maxillofacial radiology (DMFR), AI demonstrates promising potential for diagnostic assistance and digital image analysis (14,15).

Machine learning, an essential branch of AI, enables computational models to learn from large-scale image datasets and improve their performance over time. Consequently, AI supports radiologists in image interpretation and helps streamline digital diagnostics. Preclinical studies indicate that AI algorithms can detect root canal orifices, identify vertical fractures, and recognize proximal caries on radiographs, showing promising prospects for future clinical use (15–17).

In addition to improving the efficiency of dental professionals, AI can act as an educational tool for patients. By providing images with color overlays or other AI-generated visual outputs, patients can better understand their dental issues, visualize less invasive treatment options, and improve their oral hygiene habits. Studies indicate that highlighting lesions with AI assistance helps patients recognize them more accurately and boosts their confidence in diagnoses and treatment plans (16).

Simultaneously, AI integration has the potential to optimize radiographic image processing and 3D analysis workflows. Convolutional neural networks (CNNs) enable automated segmentation and labeling of teeth, while transfer-learning-based models and transformers advance tooth detection, segmentation, and numbering. These technologies collectively improve image interpretation and assist digital treatment planning, ultimately providing advantages for dental practitioners and patients during diagnostics and treatment planning (17).
Among the commercially available software platforms that integrate AI-assisted image processing, CoDiagnostiX® has been increasingly used in digital implantology and three-dimensional treatment planning. The software supports the semi-automatic segmentation of CBCT datasets and the generation of three-dimensional STL models, facilitating anatomical visualization and morphometric analysis. In the

present study, CoDiagnostiX® was used as part of the digital workflow for AI-assisted segmentation before three-dimensional analysis.

1.7.1. Advances in AI Segmentation Techniques

The use of artificial intelligence (AI) in bone segmentation represents a significant advance in CBCT image interpretation. Deep learning models, especially convolutional neural networks (CNNs), are increasingly employed for automatic detection and segmentation of anatomical structures in CBCT images. This progress supports advanced three-dimensional image processing and the integration of digital workflows in dentomaxillofacial analysis (16).

Additionally, transfer learning enables the adaptation of pre-trained models to dentomaxillofacial datasets, thereby aiding the development of AI-driven segmentation tools for cortical bone analysis. These tools can be integrated into three-dimensional digital workflows to facilitate image processing and morphometric evaluation of alveolar bone structures. (15).

Another important limitation concerns the AI-based segmentation process performed with CoDiagnostiX®. Although the software enabled three-dimensional reconstruction of CBCT datasets and supported the digital workflow adopted in this study, the generated segmentations were not directly validated against manual segmentation, expert annotation, or a reference standard. As a result, the accuracy of the segmentation process could not be independently confirmed within the scope of the present investigation.

Therefore, the potential influence of segmentation-related errors on the measurements obtained cannot be entirely excluded. Although the use of commercially available, clinically established software may support a structured digital workflow, the present study was not designed to assess the accuracy of the AI algorithm itself. Future studies should incorporate validation protocols comparing AI-generated segmentations with manual measurements or reference models to further evaluate the reliability and accuracy of AI-assisted bone analysis workflows.

1.7.2. Challenges and Limitations of Current Imaging Techniques

Despite notable advancements in CBCT imaging and AI-based evaluation, several challenges remain. CBCT scans may be affected by artifacts such as beam hardening, scatter, and patient movement, which can compromise the accuracy of cortical thickness segmentation and measurements (12)

Furthermore, the success of AI models heavily relies on having access to comprehensive, labeled datasets, which are still scarce in dental radiology.

Variability among CBCT machines, imaging parameters, and anatomical features poses additional challenges for model standardization. Another major limitation concerns the integration of AI into clinical practice, as this process requires extensive validation, standardization, and regulatory approval (18).

1.7.3. Future Directions and Research Opportunities

Recent developments in AI and digital imaging are likely to broaden the use of digital workflows in dentistry. Real-time AI systems could soon assist clinicians during surgeries by providing instant data on cortical thickness, proximity to anatomical structures, and the best drilling paths (19). Predictive AI models can evaluate the likelihood of bone healing and forecast implant success by analyzing three-dimensional features of cortical and trabecular bone. Integrating AI with advanced imaging methods, such as micro-CT and MRI, could enable more comprehensive assessments of bone quality, resulting in more personalized and safer treatment plans (19).

1.8. Importance of Cortical Bone

1.8.1. Importance of Bone Density in the Maxillofacial Region

Understanding bone density in the maxillofacial region offers significant advantages for both dental research and clinical practice. Muscular load forces directly influence bone formation and density, and analyzing the three-dimensional distribution of bone allows for the evaluation of the relationship between adaptive skeletal remodeling and its biomechanical environment (18).

Increases in bone density at specific skeletal surfaces indicate active mineral deposition. During growth, such changes may reveal new sites of bone formation. Evaluating these properties is especially useful in implantology, helping to choose the best implant locations and assess osseointegration. In orthodontics, these assessments support tracking tooth movement and the adaptive response of the alveolar bone (18).

1.8.2. Bone Assessment for Implant Dentistry

Alveolar bone plays a vital role in ensuring primary stability and the long-term success of dental implants. (19,20).

The alveolar bone is essential for the initial stability and long-term success of dental implants. Its complex structure necessitates both qualitative and quantitative assessment, as bone density alone does not entirely indicate implant stability or successful osseointegration (20).

The morphology of cortical bone and the microstructure of trabecular bone are crucial because they directly contact the implant surface. A thorough examination of the alveolar bone aids in assessing peri-implant tissues, tracking bone volume after grafts, and detecting peri-implantitis early, enabling more accurate and effective clinical interventions (19,20).

1.8.3. Bone Thickness, Gingival Biotype, and Aesthetics

The anterior maxillary region is essential for aesthetics, smile harmony, and patient self-esteem (19).

The contour of the gums is directly influenced by the thickness of the buccal bone and the surrounding soft tissue around implants. Narrow alveolar bone is usually linked to delicate gingival tissue, while thicker bone offers better support for soft tissue and interdental papillae. Patients with a thick tissue biotype tend to resist gingival recession more effectively, achieve better aesthetic results in implant restorations, and have more reliable coverage of prosthetic components (19,21).

Assessing soft tissue thickness and underlying bone before implant placement is essential to prevent complications such as gingival recession and implant exposure. If deficiencies are identified, bone and/or soft-tissue augmentation procedures may be necessary to achieve ideal gum contours, thereby supporting both functional stability and aesthetic appearance (19).

1.8.4. Bone morphology and clinical factors

The indicators assessed include buccal bone thickness, the position and depth of osteotomy incisions, and apical bone height. Evidence indicates that a buccal bone thickness of ≥2 mm is crucial for maintaining alveolar height and reducing the risk of fenestration, soft-tissue recession, and perforation of cortical defects (21,22).

Moreover, understanding the anatomical relationship between the tooth and the surrounding alveolar bone is essential for effective surgical planning and precise implant placement. (21,22).

1.8.5. Genetic and Functional Factors in Bone Stability

The stability of mini-screws and dental implants depends largely on the density of both cortical and trabecular bone, with trabecular bone playing a particularly important role (22,23).

While genetics largely shape the structure of facial bones and muscles, chewing forces continually influence them. Differences in facial shape affect the structure, density, and mineral makeup of cortical bone, emphasizing the close link between genetic factors and functional adaptations in bone strength. Understanding this relationship is vital for successful orthodontic and implant treatments (22,23).

1.8.6. Clinical Implications of Cortical Bone Thickness

The cortical bone thickness in the anterior maxilla is vital for surgical planning and the long-term success of implant-supported restorations. Regions with a thin cortical layer are more susceptible to fenestration and dehiscence during osteotomy, especially when buccal bone resorption occurs, and the periodontal biotype is thin. These factors can undermine primary stability, increase the risk of gingival recession, and impair aesthetic outcomes, particularly in the anterior region (4).

Cortical bone thickness also affects the success of immediate implant placement and the feasibility of immediate loading, since primary stability largely depends on the mechanical strength of the alveolar cortical plate. Thicker cortical bone generally provides improved initial fixation and reduced micromovement, thereby promoting better osseointegration (5). Furthermore, the integrity of the buccal cortical bone is crucial for supporting soft tissues, preserving the papillary structure, and preventing exposure of prosthetic components (21).

1.8.7. Variability of Cortical Bone Thickness in Different Populations

Cortical bone thickness varies widely among individuals and is influenced by factors such as age, sex, and ethnicity. Research shows that younger people tend to have thicker, denser cortical plates, which reflect higher osteoblastic activity and lower physiological resorption (4). As individuals age, their bone mineral density and cortical thickness gradually decrease, which are important factors to consider when choosing implants and planning the surgical approach (4).

Gender-related differences have been observed, with males typically showing higher bone density and cortical thickness, which may affect primary stability and their response to mechanical stress. (2).

1.8.8. Impact of Systemic Conditions on Cortical Bone Thickness

Systemic conditions directly impact the quality and thickness of cortical bone, thereby affecting the success of implant procedures. Osteoporosis, which involves decreased bone mineral density and changes in microarchitecture, leads to thinner cortical plates and weaker bones. This can undermine primary stability and raise the risk of implant failure (4). Diabetes mellitus is a significant condition because it hampers bone healing, fosters chronic inflammation, and raises the risk of peri-implantitis due to weakened immune response (5). In women after menopause, hormonal fluctuations are linked to significant decreases in bone density and cortical thickness. This underscores the importance of thorough assessment when planning surgeries and choosing implants (5).

1.9. Previous CBCT Studies on Buccal Cortical Bone Thickness

Several CBCT-based studies have examined buccal cortical bone thickness in the anterior maxillary region because of its importance for implant placement, orthodontic movement, and aesthetic outcomes. Previous investigations have consistently shown that the buccal cortical plate of maxillary anterior teeth is generally thin, especially at the cervical and middle thirds of the root. Januário et al. reported that the facial bone wall often measures less than 1 mm, particularly in the anterior maxilla, highlighting the aesthetic and surgical challenges that may arise during implant placement (22,24)

Similarly, Braut et al. reported a reduced buccal bone thickness around maxillary incisors and highlighted the high prevalence of thin facial bone walls in the aesthetic zone. Their findings suggested that this anatomical variability should be carefully considered during treatment planning. Subsequent CBCT studies supported these observations, showing significant differences according to tooth type, root level, age, and individual anatomical characteristics.

Most previous studies have relied on conventional CBCT measurements taken directly from cross-sectional images. By contrast, the use of AI-based segmentation, STL model generation, and three-dimensional digital analysis is still relatively limited. Therefore, the present study aimed not only to assess buccal cortical bone thickness but also to explore the feasibility of a three-dimensional digital workflow that integrates CBCT imaging, AI-assisted segmentation, and three-dimensional morphometric analysis.

However, direct comparisons across studies remain challenging because of substantial methodological heterogeneity in sample selection, anatomical reference points, measurement sites, image acquisition parameters, and statistical approaches. These differences may partly account for the variability reported in the literature.

Taken together, the available literature suggests that the buccal cortical bone in the anterior maxilla is generally thin and shows considerable anatomical variability between individuals. However, further studies employing well-defined methodologies and advanced digital workflows are still needed to deepen our understanding of cortical bone morphology and its clinical implications.

OBJECTIVES

2. OBJECTIVES

This study aimed to assess buccal cortical bone thickness in the anterior maxillary region through cone-beam computed tomography (CBCT) combined with AI-based segmentation and 3D digital analysis.

Specific Objectives

1. To measure the buccal cortical bone thickness at the cervical, middle, and apical thirds of maxillary anterior teeth employing CBCT scans and AI-segmented STL models.

2. To compare buccal cortical bone thickness according to root level, tooth type, and laterality in the anterior maxilla.

3. To analyse the anatomical distribution and interindividual variability of buccal cortical bone thickness in the anterior maxillary region.

4. To evaluate the influence of root level on buccal cortical bone thickness distribution through descriptive and inferential statistical analyses.

5. To assess differences in buccal cortical bone thickness between central and lateral incisors, as well as between the right and left hemiarches.

6. To explore the clinical implications of buccal cortical bone morphology for implant planning, aesthetic dentistry, and surgical decision-making in the anterior maxilla.

3. RESEARCH HYPOTHESES AND STATISTICAL FRAMEWORK

This study was based on the understanding that buccal cortical bone thickness in the anterior maxilla does not follow a uniform pattern but instead varies considerably across anatomical sites. Because alveolar bone morphology plays a key role in implantology and aesthetic dentistry, a set of research hypotheses was developed to investigate whether these differences could be associated with root level, tooth type, and laterality.

Previous CBCT-based studies have consistently shown that the buccal cortical plate in the anterior maxilla is often thin, particularly in the cervical third, and tends to become thicker toward the apical region. At the same time, its morphology may vary by tooth type and other anatomical characteristics, underscoring the value of three-dimensional evaluation in surgical planning and implant-related procedures.

Given the increasing role of digital technologies in dental diagnostics, this study combined CBCT imaging with artificial intelligence (AI)-based segmentation and three-dimensional digital workflows to enable a more detailed assessment of alveolar bone morphology.

The proposed hypotheses reflected the study's main aims and were tested using descriptive and inferential statistical analyses. This approach enabled assessment of anatomical variability and exploration of potential relationships among the variables under investigation. To provide a clear and structured statistical evaluation, null (H0) and alternative (H1) hypotheses were formulated for each research objective.

The statistical analyses were selected based on the study design and data distribution and included descriptive analysis, mixed linear models, post hoc Bonferroni comparisons, and mixed linear models for hemiarch comparison.

This methodological approach enabled a comprehensive assessment of the distribution of buccal cortical bone thickness in the anterior maxillary region.

3.1. Primary Hypotheses

The present study was based on the hypothesis that buccal cortical bone thickness in the anterior maxillary region varies significantly according to root level, with thinner bone at the cervical third and greater thickness at the apical third.

Table 1 summarizes the research hypotheses and the corresponding statistical analyses.

Research Objective	**Null Hypothesis (H0)**	**Alternative Hypothesis (H1)**	**Statistical Analysis**
Evaluate cortical bone thickness according to root level	No significant differences exist among cervical, middle, and apical root thirds	Significant differences exist among the three root levels	Mixed Linear Model / Post-hoc Bonferroni
Compare cortical thickness between tooth groups	No significant differences exist between central and lateral incisors	Tooth type significantly influences cortical bone thickness	Mixed Linear Model
Assess the interaction between tooth type and root level	Buccal cortical bone thickness distribution follows the same pattern independently of tooth type	Bone thickness variation differs according to tooth type and root level interaction	Mixed Linear Model/interaction Model
Evaluate symmetry between right and left sides	No significant differences exist between right and left hemiarches	Significant differences exist between the right and left hemiarches	Mixed Linear Model for hemiarch comparison

Table 1- Research hypotheses and statistical approach

3.2. Hypotheses and Scientific Rationale

The present hypotheses were formulated based on previous studies showing that buccal cortical bone thickness in the anterior maxilla is generally limited and unevenly distributed along the tooth root. Earlier investigations found thinner values at the cervical third and greater thickness toward the apical region. These anatomical patterns are highly relevant for surgical planning and may directly affect implant treatment planning and aesthetic outcomes.

Previous CBCT-based studies have also highlighted considerable interindividual variability in alveolar bone morphology, suggesting that cortical bone thickness may vary with tooth type, root level, and other anatomical characteristics. Therefore, the present study examined whether these variables significantly influenced the distribution of buccal cortical bone thickness.

In addition to these anatomical considerations, the present investigation employed CBCT imaging, AI-based segmentation, STL model generation, and three-dimensional digital analysis to evaluate alveolar bone morphology. The combination of digital imaging and three-dimensional analysis was considered a useful methodological approach for assessing buccal cortical bone thickness in the anterior maxillary region.

3.3. Secondary Hypotheses

Secondary hypotheses included the potential influence of tooth type and laterality on the distribution of buccal cortical bone thickness in the anterior maxillary region.

Based on the current literature, several anatomical tendencies were reported in previous CBCT-based investigations. These tendencies served as a theoretical reference for interpreting the results obtained.

Table 2 summarizes the anatomical patterns reported in previous CBCT studies.

Variable	**Trends Reported in Previous Literature**
Cervical third	Reduced cortical thickness
Middle third	Intermediate thickness values
Apical third	Greater cortical thickness
Central incisors	Reduced buccal thickness in cervical region
Laterality	Mild asymmetry may occur

The integration of anatomical, radiographic, and statistical variables contributed to a comprehensive methodological framework, reinforcing the scientific and clinical relevance of the present investigation.

Table 2- Anatomical *patterns described in previous CBCT studies*

MATERIALS AND METHODS

4. MATERIALS AND METHODS

4.1. Study Design

This study was an observational, retrospective, cross-sectional analysis aimed at assessing buccal cortical bone thickness in the anterior maxillary region using cone-beam computed tomography (CBCT) images and AI-based bone segmentation. The sample included previously obtained imaging exams from patients treated at a university clinic. A total of 176 anterior maxillary incisors (central and lateral incisors) from 44 patients were evaluated. Since it was retrospective, the sample size depended on the number of CBCT exams that met the predefined inclusion and exclusion criteria during the study period. Although no formal a priori sample size calculation was performed due to the retrospective nature of the study, the final sample consisted of 44 patients and 176 anterior maxillary incisors that met all predefined inclusion criteria. Because the study was based on previously available CBCT examinations, the sample size was determined by the number of eligible cases during the selected study period.

To provide further context regarding sample adequacy, effect sizes for the inferential analyses were calculated and interpreted alongside p-values. The significant differences observed across root levels, together with the corresponding effect sizes (η^2 = 0.025–0.058), suggest that the sample was adequate to detect the main anatomical trends investigated. However, the absence of an a priori sample size calculation should be acknowledged as a methodological limitation, as smaller effects may have gone undetected. Therefore, the findings should be interpreted with caution and confirmed by future studies using larger samples and prospective sample size estimation.

The study combined three-dimensional analytical methods with linear measurements to assess the distribution of buccal cortical bone thickness in the anterior maxillary region. Statistical analyses were conducted to describe the distributions of the variables under investigation and to compare cortical bone dimensions across the cervical, middle, and apical thirds of the root.

4.2. Characterization of the Data to Be Collected

4.2.1. Study Introduction

CBCT scans from patients who had imaging for clinical reasons between July 2024 and July 2025 were initially examined. After applying specific inclusion and exclusion criteria, a final group of 44 patients was selected. These scans provided a detailed three-dimensional view of the anterior maxillary region, with particular attention to variability in buccal cortical bone thickness across the cervical, middle, and apical thirds of the root.

4.2.2. Inclusion Criteria

Table 3 presents the inclusion criteria applied in the present study.

Inclusion Criteria	Description
Previous Imaging	CBCT examinations of the maxilla with adequate diagnostic image quality, obtained between July 2024 and July 2025
Region of Interest	Presence of fully erupted maxillary central and lateral incisors.
Dental Status	Natural teeth without extensive restorations, fractures, or resorptive defects
Periodontal Health	Absence of clinical signs of advanced periodontal disease or severe alveolar bone loss
Surgical History	No history of previous bone grafting or regenerative surgical procedures in the anterior maxillary region
Age	Patients aged 18 years or older

Table 3 - **Inclusion Criteria**

4.2.3. Exclusion criteria

Exclusion Criteria	**Description**
Poor image quality	CBCT examinations with artifacts, motion blur, or insufficient image quality for accurate measurements
Missing teeth	Absence of one or more maxillary central or lateral incisors
Extensive restorations	Teeth with extensive restorations, crowns, or prosthetic rehabilitations affecting anatomical evaluation
Root alterations	Teeth presenting root fractures, severe root resorption, or developmental anomalies
Periodontal disease	Advanced periodontal disease associated with severe alveolar bone loss
Previous surgery	History of bone grafting, regenerative procedures, or implant placement in the anterior maxillary region
Incomplete records	CBCT datasets with incomplete clinical or imaging information

Table 4 - ***Exclusion Criteria***

These exclusion criteria were established to ensure accurate three-dimensional measurements and to minimize potential sources of bias related to anatomical alterations or inadequate image quality.

4.2.4. Data Anonymization

Data Anonymization guaranteed that none of the collected data could be traced back to any individual patient. Each imaging examination was assigned an alphanumeric code to protect participants' identities and maintain the confidentiality of the analyzed data.

4.2.5. Confidentiality and Ethics

Clinical and imaging data were handled with strict confidentiality to protect patient privacy and restrict access to the study's researchers. The collected information was used solely for research purposes, ensuring ethical and responsible management in line with the Declaration of Helsinki.

The Institutional Ethics Committee approved the current project, giving a positive opinion for the study titled "Application of Digital Technologies in Oral Rehabilitation," reference nº 201.

4.3. Data Collection and Analysis Instruments

This study analyzed the buccal cortical bone thickness in the anterior maxillary region, using data from cone-beam computed tomography (CBCT) scans. These scans were accessed through the institution's clinical management software, NewSoft DS® - Version 17 (developed by ImaginaSoft HS, Portugal, 2020).

The CBCT scans, exported in DICOM format, were acquired using the Planmeca ProMax® 3D Mid (Planmeca OY, Helsínquia, Finlândia, 2018), ensuring parameters suitable for three-dimensional bone analysis.

The CBCT examinations were acquired using a voxel size of 0.4 mm and a field of view (FOV) appropriate for evaluation of the anterior maxillary region. Voxel size is considered an important determinant of spatial resolution and measurement precision in CBCT-based analyses.

The DICOM files were imported into CoDiagnostiX® - Version 10.8.1. (Dental Wings GmbH, Chemnitz, Germany, 2024) software, where an artificial intelligence–driven bone segmentation algorithm was used to generate three-dimensional maxillary bone models in STL format.

To help clarify the methodological sequence adopted in this study, a conceptual workflow diagram was developed. The workflow outlines the sequential methodological phases of the investigation, including CBCT acquisition, artificial intelligence–based segmentation, STL model generation, three-dimensional analysis, statistical evaluation, and the clinical interpretation of buccal cortical bone morphology.

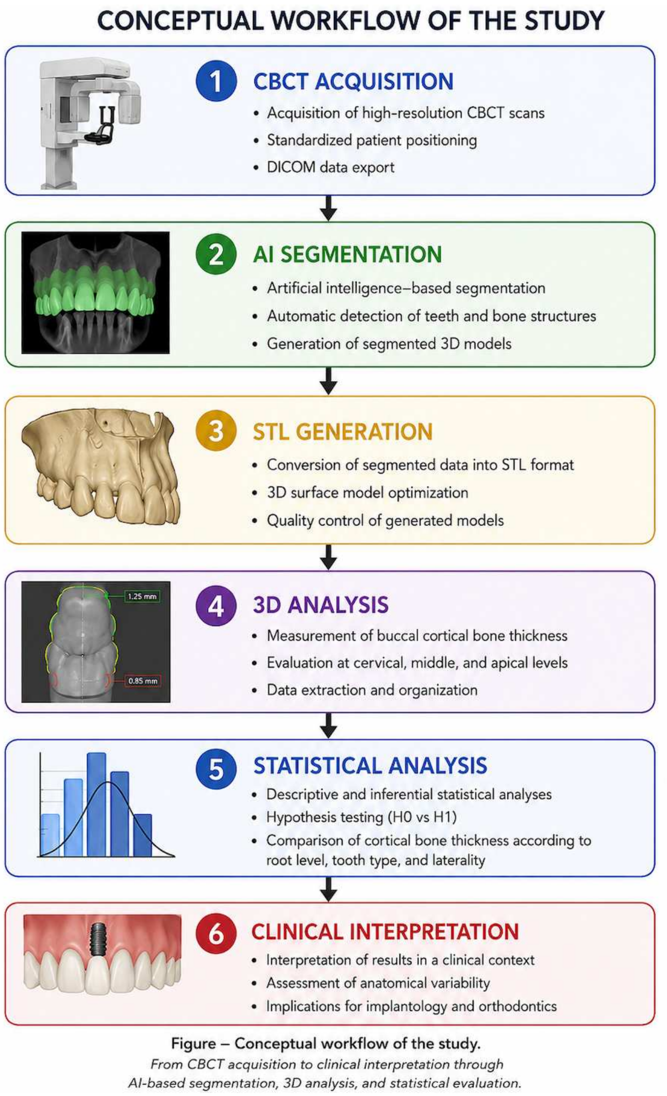


Figure 2- Conceptual workflow of the present study

The implementation of this structured digital workflow facilitates image processing and the organization of three-dimensional data, thereby supporting the evaluation of buccal cortical bone morphology.

Linear measurements of the buccal cortical bone thickness were taken at specific root levels from these segmented models.

- Cervical third
- Middle third
- Apical third

All measurements were performed in a three-dimensional setting, enabling a comprehensive assessment of the distribution of buccal cortical bone thickness. The anterior maxillary region, including the central and lateral incisors, was designated as the region of interest (ROI) for three-dimensional measurements of buccal cortical bone thickness.

The AI-segmented bone models were examined to determine bone thickness at the three root thirds (cervical, middle, and apical) for each tooth within the ROI. Linear measurements enabled the calculation of mean, minimum, and maximum values, along with the standard deviation (SD ±) to indicate variability.

Where applicable, measurements were also shown as three-dimensional colour maps. These maps depict the distribution of bone thickness along the tooth root, allowing for a more intuitive visual interpretation of anatomical variations.

The regions of the dental hemiarches analyzed were chosen based on anatomical reference points on the root surfaces of the maxillary central and lateral incisors. This enabled the evaluation of buccal cortical bone thickness at the cervical, middle, and apical thirds of the root.

Once the three-dimensional maxillary model was correctly aligned in the Geomagic Control X® workspace, measurement lines and reference points were set up.

The “Curves” tool was used to generate reference lines and cross-sectional sections perpendicular to the predefined reference lines. These reference structures facilitated the identification of the regions of interest (ROIs) and the extraction of linear measurements of buccal cortical bone thickness.

The obtained measurements were exported as numerical values and subsequently analysed using descriptive and inferential statistical methods to evaluate cortical bone thickness distribution throughout the anterior maxillary region.

Reference planes were set at the cervical, middle, and apical thirds of the root to define the regions chosen for buccal cortical bone evaluation.

The cervical reference plane was initially set at the level of the cementoenamel junction (CEJ). Later, two more reference planes were defined at the middle and apical thirds of the root.

At each predefined level, anatomical reference points were identified on the buccal cortical bone surfaces, enabling direct linear measurements of cortical bone thickness between the outer surface of the alveolar bone and the adjacent dental root surface.

The spatial distribution of cortical bone thickness and the location of measurement points are illustrated in Figure 3.

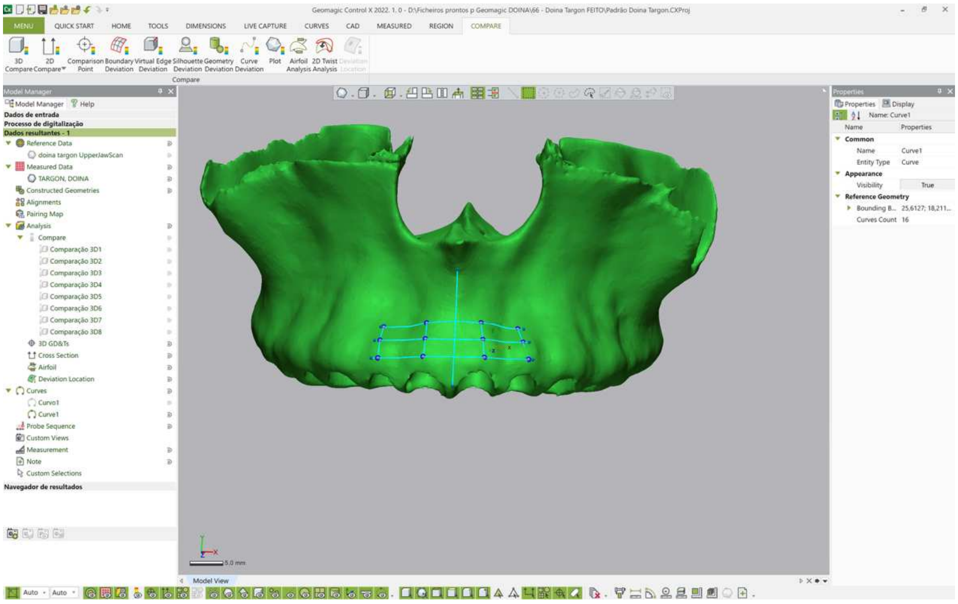


Figure 3- 3D maxillary model positioned in Geomagic Control X, showing the reference grid and measurement points used to define the region of interest (ROI).

Warmer colors (yellow–red) indicate greater thickness, whereas cooler colors (green–blue) indicate lower thickness values. Linear measurements were obtained at predefined reference points across the cervical, middle, and apical thirds of each tooth.

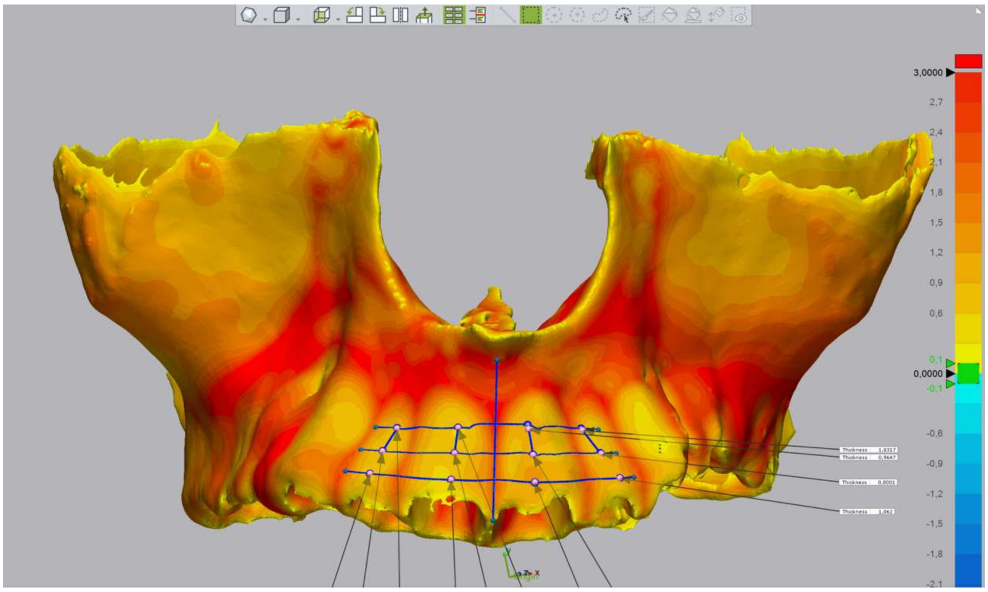


Figure 4- Color-coded map showing the distribution of buccal cortical bone thickness in the anterior maxillary area.

The use of this standardized methodological approach facilitated systematic three-dimensional evaluation of buccal cortical bone thickness and supported three-dimensional assessment of anatomical variations within the anterior maxillary region.

4.4. Statistical Analysis

The collected data were entered and organized in a database created using Microsoft® Excel® – Version 2411 Build 16.0.18227.20082 (Microsoft Corporation, Redmond, WA, 2024), in which the values corresponding to buccal cortical bone thickness measurements were recorded.

Statistical analysis was subsequently performed using the Statistical Package for the Social Sciences (SPSS)® – Version 30.0 (IBM

Corporation, Armonk, NY, 2025) in accordance with the study's predefined objectives.

Descriptive statistics included means, standard deviations, minimum and maximum values, and graphical representations to visualize the distributions of the investigated variables.

Descriptive analyses were initially performed to explore the distribution of the variables. Inferential analyses were subsequently conducted using mixed linear models, in accordance with the study design and the repeated-measures structure of the data.

For inferential analysis, mixed linear models were used to evaluate buccal cortical bone thickness while accounting for the repeated-measures structure of the data. Distinct models were created for the right and left sides of the maxillary arch.

In each model, buccal cortical bone thickness was considered the dependent variable, root level, tooth type, and sex were included as fixed factors, and age was included as a covariate. The interaction between root level and tooth type was also evaluated. Participant identification was modeled as a random effect by specifying a random intercept. This approach was adopted to account for the non-independence among multiple teeth from the same individual and to appropriately model the repeated-measures structure of the data.

Whenever statistically significant effects were identified, Bonferroni-adjusted post-hoc comparisons were performed to determine which groups differed significantly.

To evaluate differences between the right and left sides, an additional mixed linear model was applied to the thickness difference between hemiarches, considering root level, tooth type, and sex as fixed factors and age as a covariate. In all statistical analyses, $p < 0.05$ was considered statistically significant.

4.5. Workflow for 3D Measurement in Geomagic Control X

The three-dimensional analysis of the maxillary models was performed using Geomagic Control X® software, following a structured workflow to evaluate buccal cortical bone thickness.

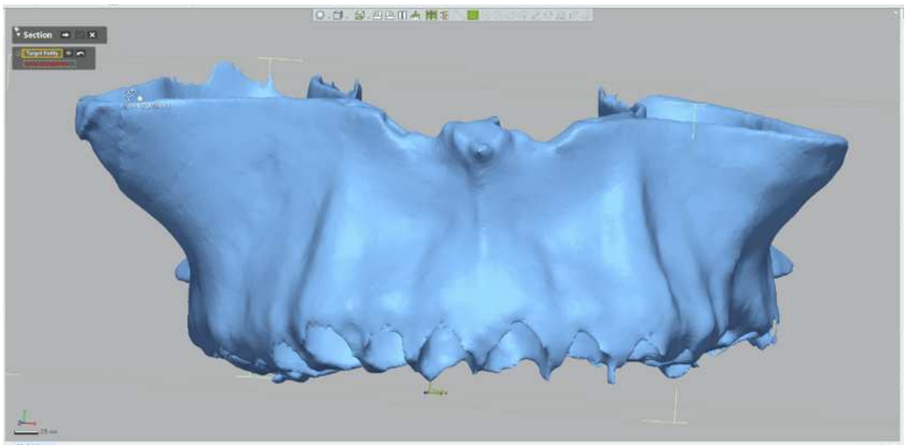


Figure 5- 3D maxillary model imported into Geomagic Control X®. *The STL model of the maxilla is visualized in a three-dimensional environment before orientation and analysis.*

Initially, the STL model of the maxilla was imported into the software and visualized in a three-dimensional environment (Figure 5). The model was oriented according to anatomical reference planes to ensure consistency in subsequent measurements.

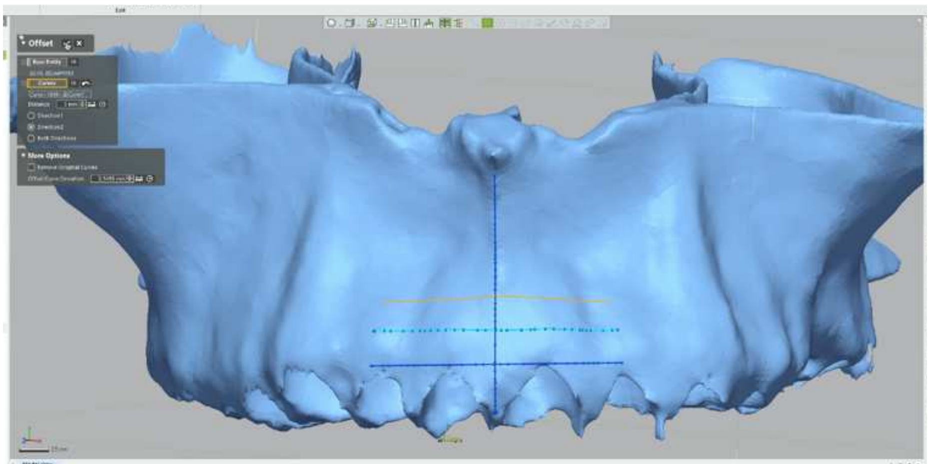


Figure 6- Definition of reference axes and initial curves

Reference lines and horizontal curves were defined to determine the position of the measurement levels along the root.

Subsequently, reference curves were generated using the *"Curves"* tool to identify key anatomical regions across the anterior maxillary segment (Figure 6). Reference lines and horizontal curves were then established to define the positions of the measurement levels along the root.

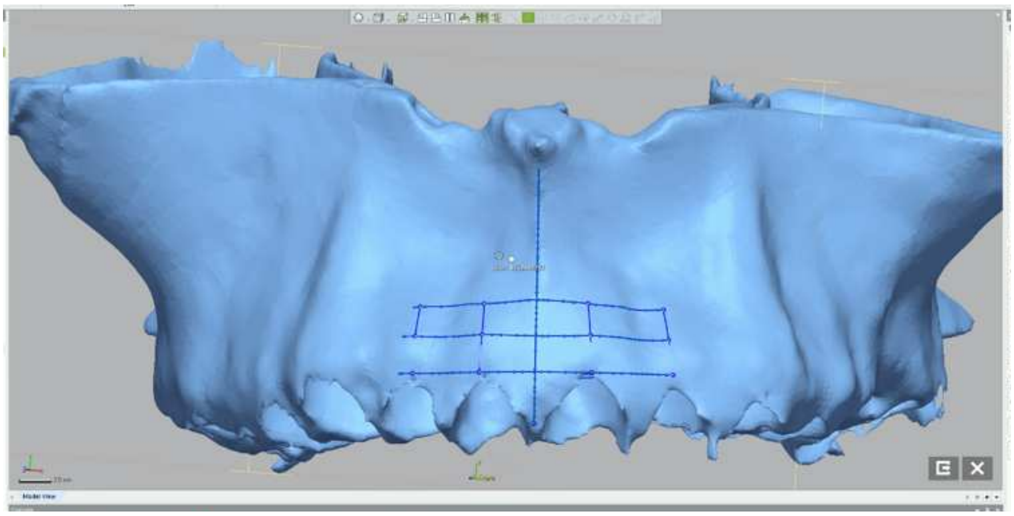


Figure 7- Construction of reference grid for measurement

A structured grid of curves and points was created across the anterior maxillary region to establish standardized locations for assessing cortical bone thickness.

An offset operation was then applied to the reference curves to establish uniform spacing between measurement sections during data acquisition (Figure 7). This made it possible to generate parallel curves at predefined distances, thereby ensuring a more consistent measurement process.

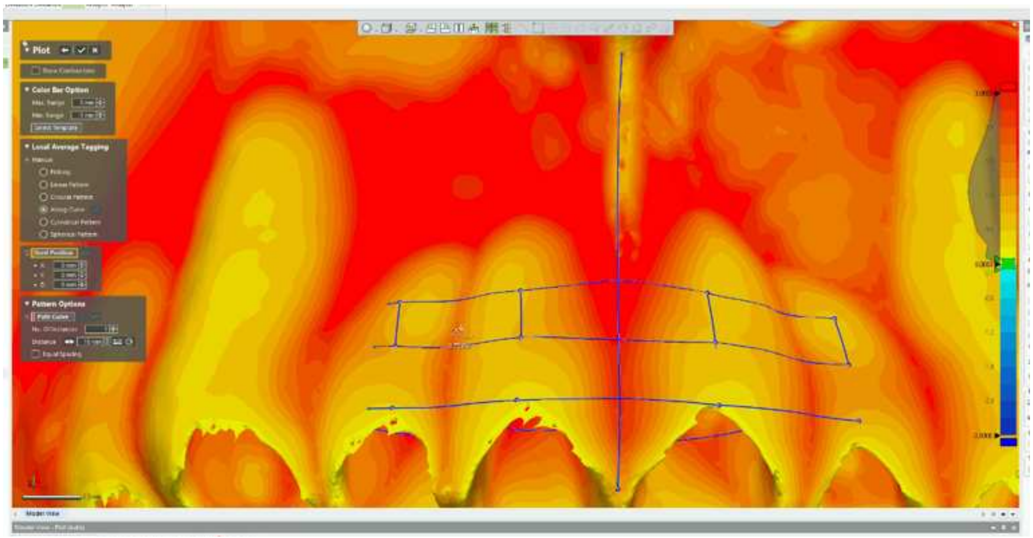


Figure 8- ***Placement of measurement points along reference curves.***

Standardized reference points were distributed along predefined curves.

A structured set of reference points was established along these curves to enable cortical bone thickness measurements at predefined anatomical locations (Figure 8).

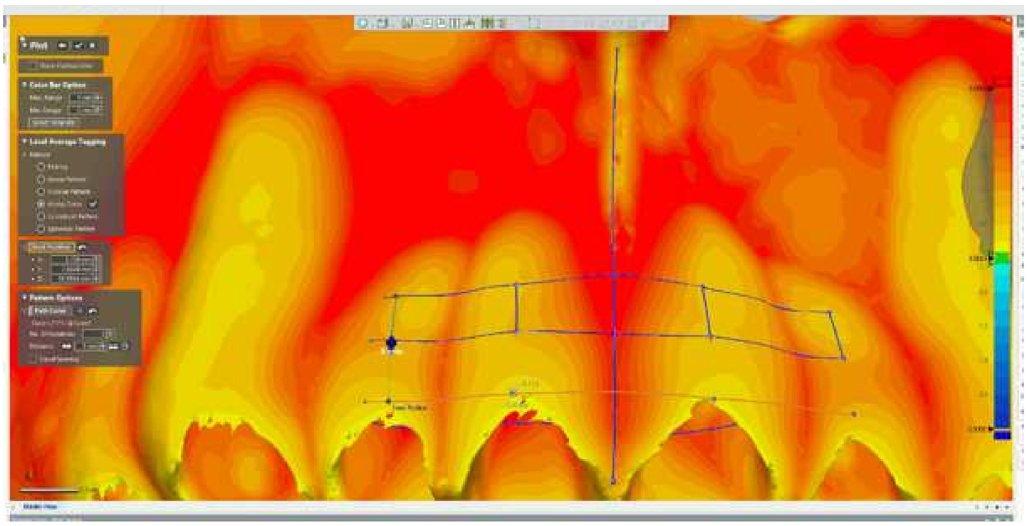


Figure 9- ***Generation of colour-coded deviation map.***

A color map was used to visualize variations in cortical bone thickness.

A three-dimensional deviation map was created using the “3D Compare” and “Deviation Analysis” tools, providing a qualitative visualization of cortical bone thickness distribution. Warmer colours (yellow–red) indicate greater thickness, while cooler colours (green–blue) represent thinner regions (Figure 9).

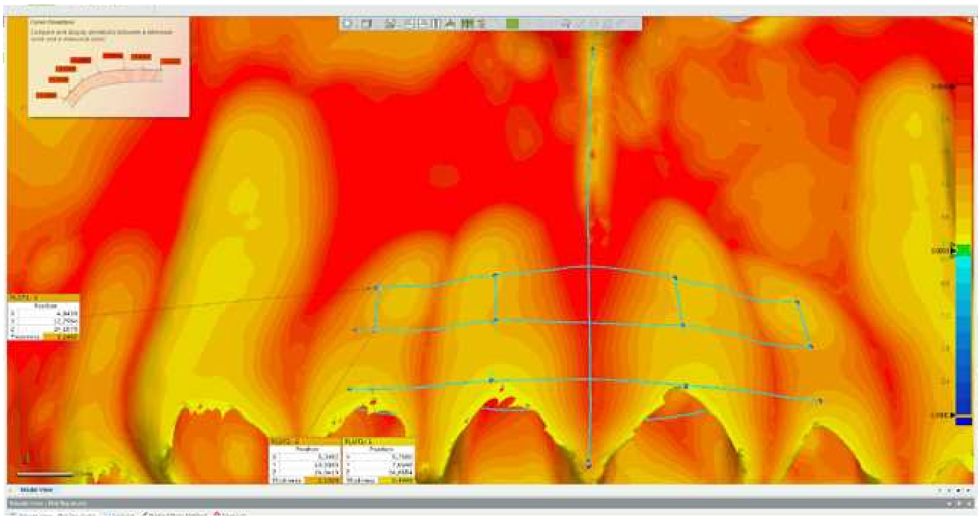


Figure 10- Extraction of local thickness measurements using plot analysis.
The “Plot” function was used to obtain quantitative thickness values at each predefined reference point along the curves.

Linear measurements were then obtained at each predefined reference point using the *“Plot”* function, allowing local thickness values to be calculated along the selected curves (Figure 10). To provide a comprehensive analysis of bone distribution, multiple measurements were recorded across the cervical, middle, and apical thirds.

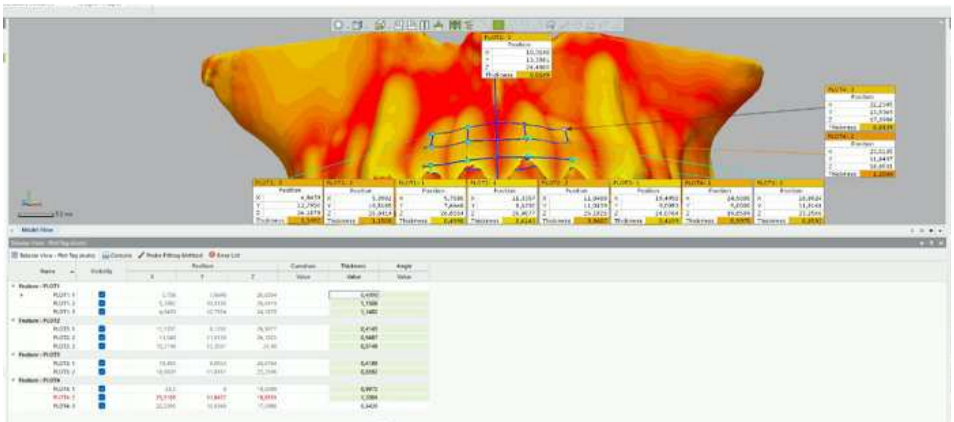


Figure 11- Tabular representation of recorded measurements

The collected data, including positional coordinates and cortical bone thickness values, were then exported and organized for subsequent statistical analysis.

Finally, all recorded measurements, including minimum, maximum, and mean thickness values, were automatically exported and organized into tabular format within the software (Figure 11). These data were subsequently used for statistical analysis.

This methodological workflow facilitated a systematic three-dimensional assessment of buccal cortical bone thickness in the anterior maxillary region and supported the evaluation of anatomical variations.

RESULTS

5. RESULTS

5.1. Statistical Methods

The study was conducted using a sample of 44 individuals and aimed to analyse the thickness of the buccal cortical bone in anterior teeth of the maxillary arch. Bone thickness was evaluated according to three main dimensions: root level, tooth type, and laterality. The root levels considered were apical, middle, and cervical, while the analysed teeth included lateral and central incisors on both the right and left sides.

Initially, the sample was characterized according to sex and age using absolute and relative frequencies, as well as means, standard deviations, and minimum and maximum values. A descriptive analysis of cortical bone thickness was then performed by calculating the mean, standard deviation, and 95% confidence interval for each combination of tooth type, root level, and side of the dental arch.

For the inferential analysis, mixed linear models were used to evaluate buccal cortical bone thickness while accounting for the repeated-measures structure of the data. Distinct models were created for the right and left sides of the maxillary arch.

In each model, buccal cortical bone thickness was defined as the dependent variable, with root level, tooth type, and sex as fixed factors and age as a covariate. The interaction between root level and tooth type was also assessed. Participant identification was modeled as a random effect by specifying a random intercept.

Whenever statistically significant effects were observed, Bonferroni-adjusted post hoc comparisons were performed to identify which groups differed significantly.
To assess differences between the right and left sides, an additional mixed linear model was applied to the thickness difference between hemiarches, with root level, tooth type, and sex included as fixed factors and age as a covariate. Statistical analysis was performed

using IBM SPSS Statistics® version 30.0, with a significance level of 5%.

5.2. Sample characterization

A total of 44 individuals participated in the study, 56.8% of whom were male (n = 25).

Table 4 presents the demographic characteristics of the study sample.

	Frequency		Age			
Sex	n	%	Mean	Standard Deviation	Minimum	Maximum
Female	19	43.2	57.11	12.09	31.00	74.00
Male	25	56.8	38.28	14.66	19.00	68.00
Total	44	100.0	46.41	16.43	19.00	74.00

***Table 5*- Characterization of the sample according to sex and age**

According to Table 4, female participants presented a higher mean age (57.11 ± 12.09 years) compared to male participants (38.28 ± 14.66 years). Overall, the mean age of the sample was 46.41 ± 16.43 years.

5.3. Descriptive Analysis of Buccal Bone Thickness

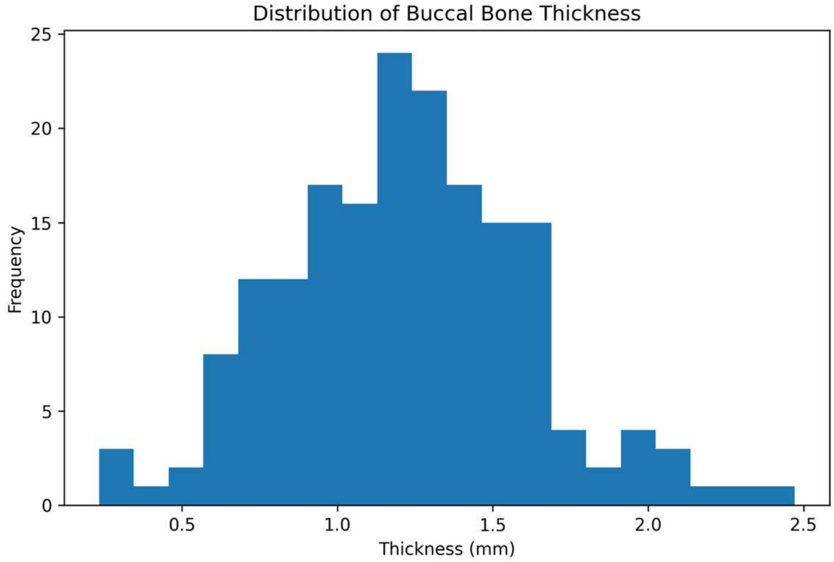


Figure 12- Distribution of Buccal Bone Thickness Values

The histogram illustrates the global distribution of buccal bone thickness measurements obtained in the present study. Most values were concentrated between 0.5 mm and 1.5 mm, confirming the predominance of thin buccal cortical plates in the anterior maxilla. The distribution showed positive asymmetry, with fewer cases exhibiting increased thickness values above 2 mm.

The predominance of reduced thickness values confirms the frequent presence of thin buccal cortical bone in the anterior maxillary region.

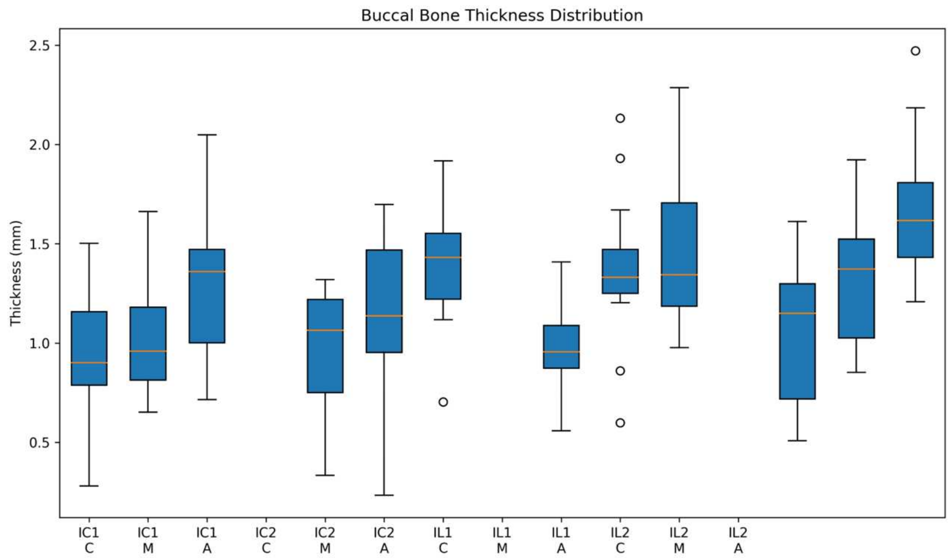


Figure 13- Buccal Bone Thickness Distribution According to Tooth Type and Root Level

The boxplot shows the distribution of buccal bone thickness values by tooth type and root level. Overall, greater thickness values were observed at the apical level, while cervical measurements generally showed lower median values. Lateral incisors exhibited slightly greater thickness than central incisors. In addition, considerable variability was found across all groups, underscoring the anatomical heterogeneity of the anterior maxillary region.

These findings demonstrate variations in buccal cortical thickness according to root level and tooth type.

5.3.1. Descriptive Analysis – Right Side

Table 5 presents the descriptive statistics of buccal cortical bone thickness according to tooth type and root level on the right side.

Root level	Right side - 1º quadrant			
	Lateral		Central	
	$\bar{X} \pm s$	IC 95%	$\bar{X} \pm s$	IC 95%
Apical	1.387±0.790	[1.151-1.659]	1.474±0.816	[1.225-1.722]
Middle	1.255±0.552	[1.084-1.427]	1.179±0.537	[1.015-1.342]
Cervical	1.145±0.531	[0.962-1.283]	0.961±0.453	[0.823-1.099]

$\bar{X} \pm s$ – mean ± standard deviation; 95% CI - 95% confidence interval for the mean

***Table 6* - Characterization of cortical thickness by tooth and root level, right side**

Based on Table 5, the mean buccal cortical thickness values decreased from the apical to the cervical level.

For the lateral incisor, the mean thickness was greater at the apical level (1.387 ± 0.790 mm), decreasing to 1.255 ± 0.552 mm at the middle level and to 1.145 ± 0.531 mm at the cervical level.

A similar trend was observed for the central incisor, with mean values of 1.474 ± 0.816 mm at the apical level, 1.179 ± 0.537 mm at the middle level, and 0.961 ± 0.453 mm at the cervical level.

These findings suggest that, on the right side, the apical region presents greater cortical thickness than the cervical region.

5.3.2. Descriptive Analysis – Left Side

Table 6 presents the descriptive statistics of buccal cortical bone thickness according to tooth type and root level on the left side.

Root Level	Left Side – 2nd Quadrant			
	Lateral Incisor		Central Incisor	
	Mean ± SD	95% CI	Mean ± SD	95% CI
Apical	1.340 ± 0.671	[1.108–1.528]	1.261 ± 0.726	[1.040–1.481]
Middle	1.318 ± 0.685	[1.085–1.517]	1.002 ± 0.463	[0.861–1.143]
Cervical	1.191 ± 0.563	[1.001–1.352]	0.955 ± 0.416	[0.828–1.081]

Mean ± SD – mean ± standard deviation; 95% CI – 95% confidence interval for the mean.

***Table 7*- Characterization of thickness according to tooth and root level, left side**

According to Table 6, a similar trend was observed on the left side, with higher mean cortical thickness values at the apical level and progressively lower values toward the cervical level.

For the left lateral incisor, the mean values were 1.340 ± 0.671 mm at the apical level, 1.318 ± 0.685 mm at the middle level, and 1.191 ± 0.563 mm at the cervical level.

For the left central incisor, the reduction in thickness was more pronounced, decreasing from 1.261 ± 0.726 mm at the apical level to 1.002 ± 0.463 mm at the middle level and 0.955 ± 0.416 mm at the cervical level.

Similarly to the right side, the results indicate reduced cortical thickness at the cervical level.

5.4. Exploratory Graphical Analysis

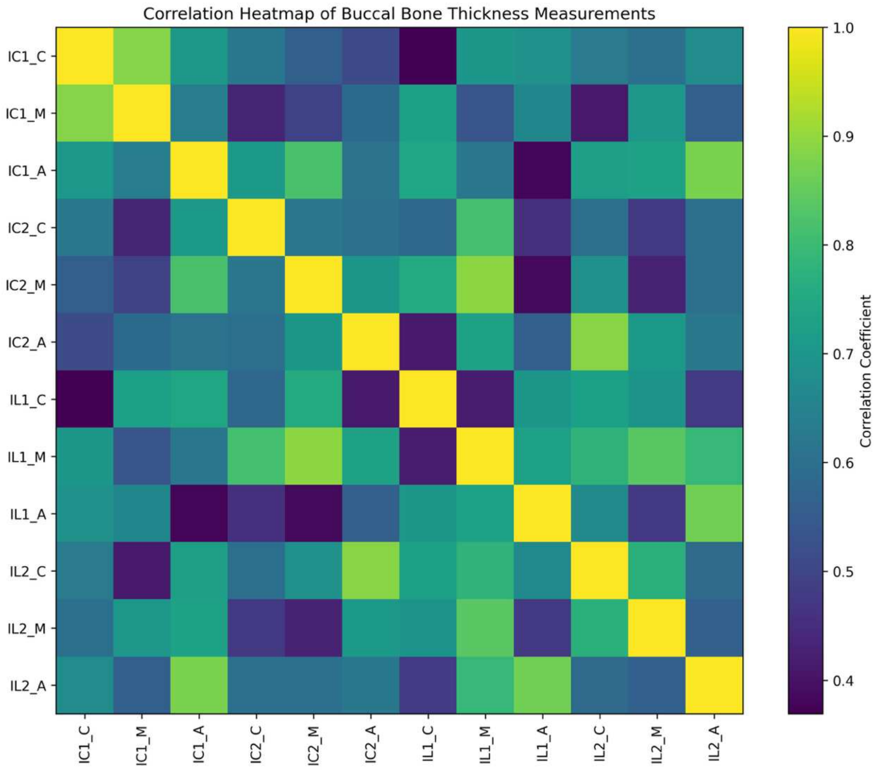


Figure 14- Correlation Heatmap

The correlation heatmap shows the relationships between thickness measurements recorded at different root levels and across tooth groups. Moderate-to-strong positive correlations were observed between adjacent root levels, suggesting anatomical continuity in the distribution of cortical bone.

Stronger correlations were observed between adjacent root levels within the same tooth group, whereas weaker correlations were found between anatomically more distant regions. These findings support the concept of structural continuity in alveolar bone morphology and reinforce the consistency of the three-dimensional measurement workflow.

5.5. Inferential Analysis – Right Side

Analysis	Test Statistic (F)	p-value	Interpretation
Root Level	6.103	0.003	Significant differences between root levels
Tooth Type	1.035	0.310	No significant differences between lateral and central incisors
Sex	0.849	0.358	No significant effect of sex
Age	3.173	0.079	No significant effect of age
Root Level × Tooth Type	1.483	0.229	Interaction not significant
Bonferroni Post Hoc Comparison	Apical vs. Cervical	0.002	Significant difference, greater thickness at the apical level

Table 8 **- Result of the mixed linear model evaluating buccal cortical bone thickness on the right side of the maxillary arch**

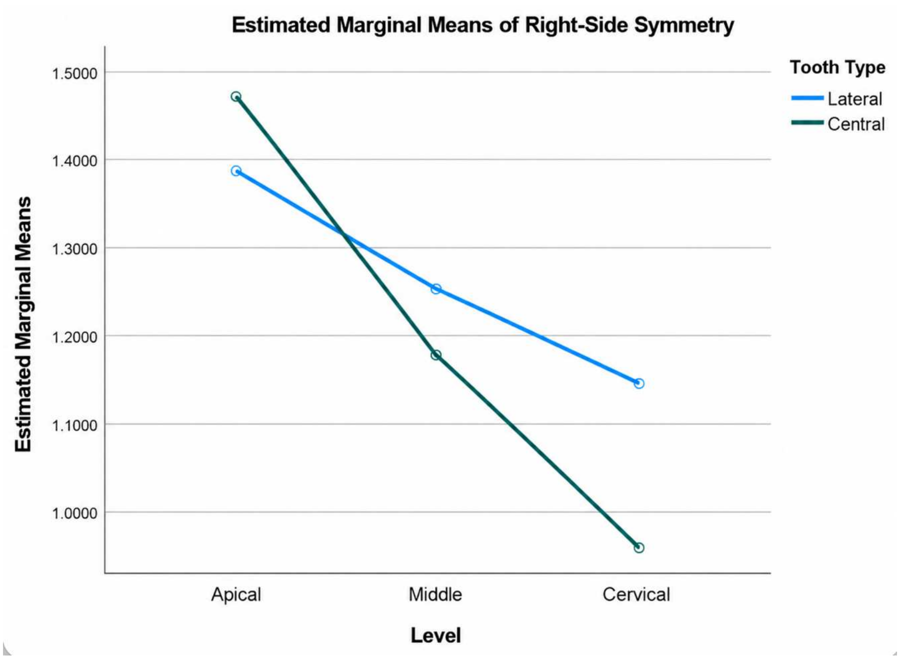
Table 7 presents the results of the mixed linear model applied to buccal cortical bone thickness on the right side of the maxillary arch.

The mixed linear model revealed a statistically significant effect of root level ($F = 6.103$, $p = 0.003$), indicating that buccal cortical bone thickness varied significantly among the apical, middle, and cervical levels. Post hoc comparisons with Bonferroni correction identified a significant difference between the apical and cervical levels (p = 0.002), with greater thickness observed at the apical level.

No statistically significant effect of tooth type was identified (F = 1.035, p = 0.310), suggesting that, on the right side, buccal cortical bone thickness did not differ significantly between lateral and central incisors.

The effect of sex was not statistically significant (F = 0.849, p = 0.358), and age also did not demonstrate a statistically significant independent effect on cortical bone thickness (F = 3.173, p = 0.079).

Furthermore, the interaction between root level and tooth type was not statistically significant (F = 1.483, p = 0.229), indicating that the pattern of thickness variation among root levels was similar for both tooth types analysed.



Graph 1- Mean Buccal Cortical Bone Thickness According to Root Level and Tooth Type on the Right Side

Graph 1 graphically confirms the trend identified in the previous analysis. In both tooth types, a progressive decrease in cortical thickness from the apical to the cervical level can be observed.

The lines corresponding to the lateral and central incisors show a relatively similar pattern, which is consistent with the absence of a statistically significant interaction between root level and tooth type. Therefore, the graph suggests that the variation in thickness along the root levels occurred similarly in both tooth types analysed.

5.6. Inferential Analysis – Left Side

The results of the mixed linear model evaluating buccal cortical bone thickness on the left side of the maxillary arch are presented in Table 8.

Analysis	Test Statistic (F)	p-value	Interpretation
Root Level	3.212	0.042	Significant differences between root levels
Tooth Type	7.810	0.006	Significant differences between lateral and central incisors, with greater thickness in lateral incisors
Sex	0.286	0.593	No significant effect of sex
Age	3.012	0.084	No significant effect of age
Root Level × Tooth Type	0.906	0.405	Interaction not significant
Bonferroni Post Hoc Comparison	Apical vs. Cervical	0.002	Significant difference, greater thickness at the apical level

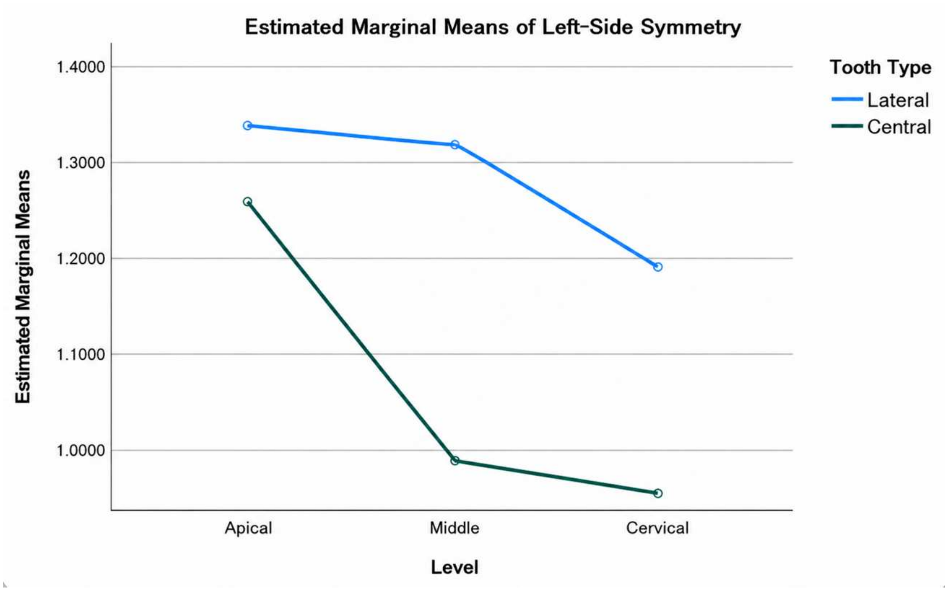
Table 9 **- Results of the mixed linear model evaluating buccal cortical bone thickness on the left side of the maxillary arch.**

The mixed linear model revealed a statistically significant effect of root level (F = 3.212, p = 0.042), indicating that buccal cortical bone thickness varied significantly among the apical, middle, and cervical levels. Post hoc comparisons with Bonferroni correction identified a significant difference between the apical and cervical levels (p = 0.002), with greater thickness observed at the apical level.

A statistically significant effect of tooth type was also identified (F = 7.810, p = 0.006), indicating that, on the left side, lateral incisors presented greater buccal cortical bone thickness than central incisors.

No statistically significant effect of sex was observed (F = 0.286, p = 0.593), and age also did not demonstrate a statistically significant independent effect on cortical bone thickness (F = 3.012, p = 0.084).

Furthermore, the interaction between root level and tooth type was not statistically significant (F = 0.906, p = 0.405), indicating that the pattern of thickness variation among root levels was similar for both tooth types analysed.



Graph 2- Mean Buccal Cortical Bone Thickness According to Root Level and Tooth Type on the Left Side

The graph of estimated means for the left side demonstrates that the lateral incisor generally presented higher mean values than the central incisor, particularly at the middle and cervical levels.

A decreasing trend in cortical thickness from the apical to the cervical level was also observed in both teeth. Although the reduction appeared more pronounced in the central incisor, the interaction between root level and tooth type was not statistically significant. Therefore, this visual difference should be interpreted only as a descriptive trend, not as statistical evidence of distinct variation patterns between tooth types.

5.7. Comparison between right and left sides

To evaluate potential differences in buccal cortical bone thickness between the right and left sides, a mixed linear model was applied to the thickness difference between hemiarches. Root level, tooth type, and sex were included as fixed factors, age was included as a covariate, and participant identification was considered as a random effect.

The results of the mixed linear model evaluating differences in buccal cortical bone thickness between the right and left sides are presented in Table 9.

Analysis	**Test Statistic (F)**	**p-value**	**Interpretation**
Root Level	0.806	0.351	No significant differences between root levels
Tooth Type	1.052	0.171	No significant differences between tooth types
Sex	1.889	0.137	No significant effect of sex
Age	2.223	0.715	No significant effect of age
Root Level × Tooth Type	0.133	0.554	Interaction not significant
Analysis	**Test Statistic (F)**	**p-value**	**Interpretation**

Table 10 **- Results of the mixed linear model evaluating differences in buccal cortical bone thickness between the right and left sides.**

To evaluate potential differences in buccal cortical bone thickness between the right and left sides, a mixed linear model was applied to the difference in thickness between hemiarches, with root level, tooth type, and sex as fixed factors and age as a covariate.

The mixed linear model did not reveal statistically significant effects of root level ($F = 0.806$, $p = 0.351$), tooth type ($F = 1.052$, $p = 0.171$), sex ($F = 1.889$, $p = 0.137$), or age ($F = 2.223$, $p = 0.715$). Furthermore, the interaction between root level and tooth type was not statistically significant ($F = 0.133$, $p = 0.554$).

These findings indicate that differences in buccal cortical bone thickness between the right and left sides were not statistically significant and did not vary according to root level, tooth type, age, or sex.

5.8. Summary of Findings

Across the evaluated root levels, buccal cortical bone thickness was generally greater at the apical level and lower at the cervical level. This pattern was observed on both the right and left sides for central and lateral incisors and was particularly evident in the middle and apical root thirds.

Inferential analysis demonstrated that the root level had a statistically significant influence on cortical bone thickness on both sides. Although tooth type did not significantly affect cortical thickness on the right side, significant effects were observed for both root level and tooth type on the left side. These findings should be interpreted with caution.

The differences observed between sides may reflect the considerable anatomical variability known to exist within the anterior maxillary region. In addition, the relatively limited sample size and methodological factors, including CBCT image resolution, segmentation accuracy, and landmark identification, may have contributed to the observed variability. Given the thinness of the buccal cortical plate and the limitations of voxel size, small variations in measurements are expected.

Therefore, the apparent asymmetry identified in some analyses should not necessarily be interpreted as a true anatomical difference but may instead reflect biological variability and methodological limitations. Further studies, including larger sample sizes and standardized measurement protocols, are required to clarify whether these differences reflect genuine anatomical characteristics or sample-related variability.

The laterality analysis did not reveal statistically significant differences in buccal cortical bone thickness between the right and left hemiarches. Similarly, the mixed linear model used to evaluate side-related effects found no significant influence of root level, tooth type, age, or sex. Overall, these findings suggest that buccal cortical bone thickness was generally symmetrical between hemiarches within the studied population.

Taken together, the results indicate that the asymmetry observed in specific analyses was localized rather than representative of a generalized anatomical pattern throughout the anterior maxillary region. From a clinical perspective, the predominance of reduced buccal cortical bone thickness at the cervical level may represent an important anatomical limitation for implant placement and aesthetic rehabilitation, particularly in the anterior maxilla, where soft-tissue stability and gingival architecture play a critical role in treatment outcomes.

DISUSSION

6. DISCUSSION

6.1. Research Method

Assessing alveolar bone thickness in the anterior maxillary region has become increasingly important in clinical practice, especially in implantology and orthodontics, because it directly affects peri-implant tissue stability and the final aesthetic outcome. In particular, the thickness of the buccal cortical plate is considered a key factor in treatment planning, as it is closely linked to the risk of bone resorption and gingival recession after implant placement.

Current evidence suggests that the buccal bone in the anterior maxilla is often thin and frequently does not reach the 2 mm threshold considered necessary for optimal aesthetic and functional outcomes. Several CBCT-based studies have shown that, in most cases, buccal bone thickness remains below this value and may be as little as 1 mm at different root levels (25). These anatomical features may increase the risk of complications such as fenestration, dehiscence, and postoperative soft-tissue recession.

In this context, cone-beam computed tomography (CBCT) has emerged as the gold-standard imaging modality for the three-dimensional evaluation of alveolar bone structures. It allows a detailed assessment of bone morphology at different levels along the tooth root, including the cervical, middle, and apical thirds, thereby enabling a more accurate characterization of anatomical variations among individuals (25). Although CBCT-based measurements offer important advantages, they also present some limitations, particularly those related to image resolution and operator-dependent variability. Assessing buccal bone thickness remains a considerable clinical challenge, since this structure is often extremely thin and may be represented by only a few pixels on CBCT images. As a result, even slight inaccuracies in its identification or measurement may lead to substantial variations in the recorded values, ultimately affecting the reliability of the analysis (26).

Furthermore, differences in operator experience may lead to inconsistencies in image interpretation and measurement accuracy. To overcome these limitations, recent advances have introduced artificial intelligence–based approaches, particularly deep learning models, to improve the precision and reproducibility of radiographic measurements. Bilinear convolutional neural networks (BCNNs) have shown performance comparable to, and in some cases even better than, that of experienced clinicians in assessing buccal bone thickness, with high diagnostic accuracy (26). These systems enable automated, standardized analysis, thereby reducing variability among observers.

Considering these developments, this study employed three-dimensional CBCT analysis and advanced digital processing methods.

Bone thickness was measured at standardized reference levels corresponding to the cervical, middle, and apical thirds of the tooth root, allowing for a comprehensive assessment of the spatial distribution of alveolar bone thickness.

The choice of these measurement levels is supported by previous studies, which have shown that bone thickness varies significantly along the root, with lower values generally found at the mid-root level and higher values at the apical region (25).

This anatomical variability is clinically important, as areas of reduced thickness may represent critical zones during surgical procedures. Finally, statistical analysis was performed to describe the distribution of the variables studied and to explore potential differences between groups. The integration of three-dimensional imaging with advanced digital and analytical methods lends this study a modern, innovative character, aligning with current trends in evidence-based dental research.

6.2. Three-dimensional digital evaluation

Three-dimensional digital evaluation represents a significant advancement in assessing alveolar bone morphology, enabling a more precise and standardized analysis than conventional two-dimensional methods. In the present study, this approach was applied using STL models derived from CBCT data, enabling a detailed spatial analysis of cortical bone thickness in the anterior maxillary region (27).

A similar methodological approach has been reported in CBCT-based studies, in which measurements are taken on sagittal sections using standardized reference points along the tooth root. Bone thickness is typically assessed at three predefined levels corresponding to the cervical, middle, and apical thirds of the root, which allows for a consistent and reproducible evaluation of anatomical variations. Dividing the root into thirds provides a structured framework for data collection and facilitates comparisons across different studies (27).

In the present investigation, this concept was further developed through a fully digital three-dimensional workflow. Unlike traditional CBCT measurements taken directly from two-dimensional slices using digital calipers, the use of 3D models allowed the creation of reference curves, grids, and measurement points distributed across the entire surface of the alveolar bone. This approach provided a more comprehensive evaluation of bone thickness, overcoming the limitations associated with single-slice measurements (27).

Moreover, standardized reference points were established using previously described CBCT-based methodologies, thereby facilitating consistent three-dimensional measurements. In the referenced study, measurements were taken directly from CBCT images using a digital caliper, and high intra- and inter-examiner reliability was reported (ICC values > 0.99), supporting the robustness of this methodological approach. The present study builds on this validated framework by incorporating it into a digital 3D analysis system (27).

Another important aspect emphasized in the literature is the clinical relevance of assessing bone thickness at different root levels. Previous studies have shown that facial bone thickness varies significantly along the root, with thinner values often found at the mid-root level and greater thickness at the apical third. These variations are particularly important in implant planning, as areas with reduced thickness may represent zones at greater risk of dehiscence or resorption (27).

Moving from two-dimensional CBCT measurements to three-dimensional digital analysis represents an important methodological advance. Digital tools such as curve generation, grid construction, and point-based measurements allow a more detailed assessment of bone thickness distribution. In addition, the use of color-coded maps improves the visualization of anatomical variability, offering both quantitative data and a more intuitive qualitative interpretation (27).

Despite these advantages, it should be acknowledged that the accuracy of three-dimensional digital analysis still depends on the quality of the CBCT data and the segmentation process. Errors during image acquisition or segmentation may affect the accuracy of the generated models and, consequently, the reliability of the measurements. Nevertheless, when a standardized workflow is applied, as in the present study, three-dimensional digital evaluation remains a highly reliable and reproducible method for assessing alveolar bone thickness (27).

6.3. Radiographic evaluation (CBCT + AI)

Radiographic evaluation is fundamental to assessing alveolar bone morphology, particularly in the anterior maxillary region, where anatomical variability and limited bone thickness can significantly affect treatment outcomes. In this context, cone-beam computed tomography (CBCT) has become the imaging modality of choice, as it allows three-dimensional, highly detailed visualization of hard tissues (27,28).

Compared with conventional two-dimensional radiographic techniques, such as periapical and panoramic radiographs, CBCT offers greater diagnostic accuracy by eliminating image superimposition and distortion. This allows a more reliable assessment of bone dimensions, root positioning, and anatomical relationships, which are essential for accurate diagnosis and treatment planning in implantology and orthodontics (28).

Previous studies have shown that CBCT enables accurate linear measurements of alveolar bone thickness at different points along the tooth root, typically divided into the cervical, middle, and apical thirds. This standardized method improves reproducibility and supports more consistent comparisons between studies. CBCT-based analyses have also demonstrated that buccal cortical bone thickness varies significantly according to root level, with thinner bone commonly found in the cervical and middle thirds and greater thickness in the apical third. These findings highlight the importance of site-specific evaluation in clinical decision-making (28).

Furthermore, CBCT provides a detailed three-dimensional evaluation of the buccal cortical plates, as well as root angulation and spatial positioning within the alveolar process. This type of multidirectional analysis is especially relevant in the anterior maxilla, where the buccal cortical plate is often very thin and, therefore, more vulnerable to resorption and peri-implant complications. In this context, CBCT is strongly recommended for preoperative planning, as it enables clinicians to identify potential risk factors, including bone dehiscence, fenestration, and insufficient bone volume (28).

Despite its advantages, the accuracy of CBCT measurements can be affected by several factors, including voxel size, image resolution, and operator variability. Because the buccal cortical plate may be thinner than 1 mm, even small measurement errors can result in clinically meaningful inaccuracies. For this reason, careful image analysis and standardized measurement protocols are essential to ensure reliable results (28).

To address these limitations, recent advances in digital imaging have led to the integration of artificial intelligence (AI)-based algorithms for automated image segmentation and analysis. These technologies have shown considerable potential to improve measurement accuracy, reduce observer-dependent variability, and enhance the overall reproducibility of radiographic assessments. AI-based segmentation enables the generation of accurate three-dimensional models from CBCT data, allowing for a more detailed evaluation of bone morphology (28).

Consistent with these developments, the present study combined CBCT imaging with advanced digital processing techniques, including AI-based bone segmentation and three-dimensional analysis. This approach allowed for a more standardized and reproducible assessment of alveolar bone thickness by integrating the benefits of radiographic imaging with those of digital modeling. As a result, the methodology adopted in this study reflects current trends in dental research, particularly the shift toward more precise, automated, and data-driven diagnostic approaches (28).

6.4. Alveolar Bone Thickness Findings

The evaluation of alveolar bone thickness in the anterior maxillary region revealed substantial variability among the analyzed teeth and across root levels. This variability was observed both between individuals and within the same tooth, further highlighting the complex anatomical characteristics of the anterior maxilla, as previously reported in the literature (4,14).

The findings of the present study are broadly consistent with previous CBCT-based investigations of buccal cortical bone thickness in the anterior maxilla. Studies by Januário et al. and Braut et al. reported that the buccal cortical plate is often thin, frequently measuring less than 1 mm, particularly in the cervical region of maxillary anterior teeth. In line with these observations, the present study also found reduced buccal cortical bone thickness in the cervical and middle thirds, with greater thickness at the apical level(22,24).

Previous CBCT studies have likewise described a progressive increase in buccal bone thickness from the cervical to the apical region, a pattern evident in the present sample. Taken together, these findings support the view that the anterior maxilla is characterized by thin buccal cortical bone and considerable anatomical variability.

However, differences in measurement protocols, anatomical landmarks, sample characteristics, image acquisition parameters, and image processing methodologies should be considered when comparing absolute thickness values across studies.

However, unlike most previous investigations, which relied primarily on direct measurements obtained from CBCT cross-sectional images, the present study incorporated AI-based segmentation, STL model generation, and three-dimensional analysis using Geomagic Control X®.

It should be emphasized that the primary contribution of the present study was not the evaluation of the AI algorithm itself, but rather the application of a three-dimensional digital workflow that integrates CBCT-derived models, AI-assisted segmentation, STL processing, and morphometric analysis to assess buccal cortical bone thickness.

Therefore, although the anatomical trends observed were consistent with the existing literature, the methodological approach adopted in the present study represents an alternative three-dimensional digital workflow for evaluating alveolar bone morphology.

Overall, the buccal cortical bone exhibited reduced thickness, particularly in the cervical and middle thirds. These findings are consistent with previous CBCT-based studies, which have shown that the buccal bone plate in the anterior maxilla is frequently thin, measuring less than 1 mm (1,14).

This anatomical feature is clinically important because reduced buccal bone thickness has been associated with a higher risk of bone resorption, gingival recession, and less favorable aesthetic outcomes, particularly in implant therapy (4,5).

When bone thickness was evaluated along the root, a clear and consistent pattern emerged. The cervical third generally showed the lowest thickness values, followed by the middle third, whereas the apical third tended to present greater thickness. This finding is consistent with previous studies, which have also reported a progressive increase in bone thickness from the cervical to the apical region (2,14).

Although statistically significant differences were observed between root levels, the corresponding effect sizes were small (η^2 = 0.025–0.058), suggesting that the analyzed factors accounted for only a limited proportion of the overall variability in cortical bone thickness. Therefore, these statistically significant findings should be interpreted in light of their effect sizes and clinical relevance.

Additional analyses adjusted for age and sex yielded similar results, indicating that the observed differences in root levels were not substantially affected by the study population's demographic characteristics.

The reduced thickness at the cervical level is particularly important, as this region is more vulnerable to surgical trauma and post-extraction remodelling processes (5). Central and lateral incisors also showed distinct patterns of bone thickness distribution. Overall, both tooth groups tended to present thinner buccal cortical plates, especially in the cervical region.

These findings are consistent with anatomical studies indicating that bone morphology varies according to tooth type and root anatomy (14).

An unexpected finding of the present study was the asymmetric influence of tooth type between the right and left hemiarches. While tooth type was not statistically significant on the right side, it was significant on the left side ($p = 0.003$; $\eta^2 = 0.031$). The study was not specifically designed to investigate biological laterality patterns, and no direct assessment of anatomical, developmental, or functional factors potentially associated with side-related differences was performed.

However, additional mixed linear model analyses evaluating differences between the right and left sides did not identify statistically significant effects of root level, tooth type, age, or sex. Therefore, the observed side-related differences should be interpreted cautiously and may reflect sample-specific variability rather than a consistent anatomical asymmetry.

Therefore, the observed asymmetry should be interpreted with caution. Despite reaching statistical significance, the observed effect size was small ($\eta^2 = 0.031$), suggesting limited practical relevance. Considering the exploratory nature of the analysis, the finding may reflect natural interindividual variability within the sample rather than a consistent biological phenomenon. Consequently, the influence of tooth type on buccal cortical bone thickness should not be generalized beyond the studied sample without further confirmation. In addition, sample-specific characteristics and statistical variability may have contributed to the detection of side-dependent differences.

Future studies involving larger, more diverse populations are needed to further explore the potential influence of laterality on buccal cortical bone thickness and to clarify whether the observed asymmetry reflects a consistent anatomical pattern or is simply a sample-specific finding.

In addition, considerable inter-individual variability was found in the measured values, reinforcing the importance of patient-specific assessment. Similar variability has been reported in previous studies, highlighting that alveolar bone thickness is influenced by multiple factors, including anatomical characteristics, periodontal conditions, and individual biological variability (4,6).

The relatively large standard deviations observed in several measurements suggest marked heterogeneity in buccal cortical bone thickness among individuals. In some anatomical regions, this variability represented a substantial proportion of the corresponding mean values, indicating that cortical bone morphology is highly individualized.

Some of this variability may be associated with demographic factors such as age and sex, which previous studies have linked to differences in cortical bone morphology. To explore this possibility further, additional mixed linear models adjusted for age and sex were fitted. These analyses did not reveal a statistically significant independent effect of either variable on buccal cortical bone thickness. Therefore, the main findings of the present study appear to be largely independent of the sample’s age and sex distribution. Nevertheless, given the limited sample size and the study population's demographic characteristics, residual confounding cannot be entirely excluded.

Accordingly, the mean values reported in the present study should be interpreted as population-level anatomical references rather than as predictive values for individual patients. These findings further underscore the importance of patient-specific radiographic assessment and individualized treatment planning in the anterior maxillary region.

These measurements also helped clarify root positioning within the alveolar bone. Teeth located closer to the buccal cortical plate generally showed reduced buccal bone thickness, which may represent a potential risk factor in both surgical and orthodontic procedures. These findings are consistent with previous studies reporting an association between root position and the morphology of the surrounding bone (1,21).

From a clinical perspective, these findings further highlight the importance of an accurate preoperative evaluation of alveolar bone anatomy. The frequent presence of a thin buccal bone plate in the anterior maxilla indicates that clinicians should carefully plan implant placement and consider the potential need for bone augmentation to reduce the risk of complications and achieve better aesthetic outcomes (5).

Finally, the findings of the present study are in line with the existing literature, confirming that the anterior maxillary region is characterized by a predominance of thin buccal cortical bone and considerable anatomical variability. The use of a three-dimensional digital workflow enabled a more comprehensive and precise evaluation of these patterns, contributing to a deeper understanding of alveolar bone morphology and its clinical implications.

Although several statistically significant differences were identified, the corresponding effect sizes were generally small (η^2 = 0.025–0.058). Therefore, these differences should be interpreted with caution, as statistical significance does not necessarily indicate clinical relevance. Future studies should investigate whether the observed differences exceed clinically meaningful thresholds and affect treatment outcomes.

Overall, the integration of CBCT imaging with three-dimensional digital workflows and AI-assisted segmentation represents a valuable approach for evaluating alveolar bone morphology, offering important insights for both clinical practice and future research.

6.5. Clinical Implications

The findings of the present study carry important clinical implications, particularly for implantology, orthodontics, and aesthetic dentistry. The consistent observation of reduced buccal bone thickness in the anterior maxillary region underscores the importance of careful treatment planning and individualized patient assessment (4,14).

From an implantology perspective, a thin buccal cortical plate represents a major risk factor for post-extraction bone resorption and soft-tissue instability. Previous studies have consistently shown that reduced buccal bone thickness may lead to aesthetic complications, such as gingival recession and loss of peri-implant tissue support, particularly in the anterior maxilla, where aesthetic demands are particularly high. Therefore, preoperative assessment of bone thickness using CBCT is essential for determining the feasibility of immediate implant placement and evaluating the potential need for guided bone regeneration (4,5).

Furthermore, the reduced bone thickness observed in the cervical and middle thirds indicates that buccal implant positioning must be carefully controlled. Implants placed too close to the buccal cortical plate may increase the risk of dehiscence and long-term bone loss. In this context, prosthetically driven implant planning, supported by three-dimensional imaging, is essential for achieving optimal functional and aesthetic outcomes (5,14).

Although statistically significant differences were observed between root levels, the corresponding effect sizes were relatively small (η^2 = 0.025–0.058), suggesting that root level accounted for only a limited proportion of the overall variability in cortical bone thickness. Therefore, statistical significance should not automatically be interpreted as indicating a large clinical effect.

Nevertheless, even relatively small differences in buccal cortical bone thickness may still be clinically relevant in the anterior maxillary region, where the buccal cortical plate is often thin.

Previous studies have suggested that a buccal bone thickness of at least 2 mm may be desirable for maintaining peri-implant tissue stability and minimizing biological and aesthetic complications. (21). In this context, differences of approximately 0.5 mm may represent a clinically relevant proportion of the available buccal bone thickness.

However, the present study was not designed to establish a minimum clinically important difference (MCID) for buccal cortical bone thickness. Consequently, the precise clinical impact of the observed differences cannot be determined and warrants further investigation in future studies evaluating implant outcomes and long-term tissue stability.

In orthodontics, the thickness of the alveolar bone plays a key role in determining the limits of safe tooth movement. The presence of a thin buccal cortical plate may increase the risk of bone dehiscence and gingival recession during orthodontic treatment, particularly when excessive buccal movement of the teeth is performed. Therefore, the evaluation of alveolar bone thickness through CBCT should be considered in cases where significant tooth movement is planned, to minimize biological risks and improve treatment predictability (6,19).

Additionally, the differences in bone thickness observed among individuals further highlight the need for personalized treatment approaches. Standardized protocols may not be suitable for every patient, and clinical decisions should rely on a careful anatomical assessment rather than on generalized assumptions. Incorporating three-dimensional imaging into routine clinical practice allows for a more accurate evaluation of each patient's anatomical characteristics, thereby supporting more precise and predictable treatment planning (4,14).

The use of artificial intelligence–based segmentation and three-dimensional digital workflows in the present study may further improve clinical decision-making. These technologies enable more precise and consistent assessment of bone morphology, reducing operator-dependent variability and enhancing diagnostic reliability. As digital tools continue to advance, their integration into clinical practice is likely to play an increasingly important role in modern dentistry (16,17).

Overall, the findings of this study highlight the value of a comprehensive, technology-assisted diagnostic approach in the anterior maxillary region. A precise assessment of alveolar bone thickness, together with individualized treatment planning, is fundamental to reducing complications, enhancing aesthetic outcomes, and supporting the long-term success of dental treatments. (4,5,14).

6.6. Limitations

Although the present study has several strengths, some limitations should be acknowledged. First, the retrospective design may have introduced bias, since the data were collected from CBCT examinations originally acquired for clinical purposes. As a result, it was not possible to standardize all acquisition parameters or control for all patient-related variables, both of which may have influenced the measurements obtained.

Another important limitation concerns the intrinsic characteristics of CBCT imaging. Although CBCT is widely considered a reliable tool for three-dimensional assessment of alveolar bone structures, its accuracy may be affected by factors such as voxel size, image resolution, and imaging artefacts. In the present study, the CBCT examinations were acquired with a voxel size of 0.4 mm. Considering that buccal cortical bone thickness in the anterior maxilla frequently measures less than 1 mm, some anatomical structures may be represented by only a limited number of voxels. Consequently, measurement precision may be reduced, particularly in regions presenting very thin cortical bone. Therefore, small differences in cortical bone thickness should be interpreted with caution, and the reported values should be considered anatomical estimates rather than absolute representations of the true cortical bone dimensions (8,11,20).

Furthermore, the segmentation process, although supported by artificial intelligence, may introduce additional variability. While AI-based segmentation may facilitate a more structured image-processing workflow, it remains influenced by the quality of the original CBCT data and the algorithm's performance.

Additionally, the CoDiagnostiX® artificial intelligence algorithm was primarily developed using datasets from general populations. Therefore, specific anatomical variations may not always be edfully identified during automatic segmentation procedures, potentially affecting STL model generation and linear measurements (16,17)

The present study did not include direct validation of the AI-based segmentation against manual measurements, phantom models, or gold-standard references. Therefore, the accuracy of the segmentation process could not be independently verified within the scope of the present investigation, and the measurements obtained should be interpreted with consideration of the methodological limitations associated with AI-assisted segmentation workflows (16,17)

It is important to note that the aim of this study was not to evaluate the performance or accuracy of the AI algorithm itself, but rather to assess buccal cortical bone thickness using CBCT-derived three-dimensional models generated through a structured digital workflow. Nevertheless, the possibility that segmentation-related inaccuracies may have affected STL model generation and, consequently, the resulting measurements cannot be entirely excluded. Future studies should therefore incorporate validation protocols that compare AI-generated segmentations with manual measurements or reference models to further assess the reliability and accuracy of AI-assisted bone analysis workflows.

The sample size and the characteristics of the study population should also be considered when interpreting the findings. Although a substantial number of teeth were analyzed, the population was drawn from a single clinical center, which may limit the generalisability of the results. In addition, anatomical variations related to ethnicity, age distribution, and specific clinical conditions were not explored in depth and may also influence alveolar bone morphology.

An additional limitation concerns the sample's demographic composition.

Although both male and female participants were included, a substantial age difference was observed between the two groups, with female participants having a considerably higher mean age than male participants. This imbalance may represent a potential confounding factor, as age- and sex-related differences in cortical bone morphology have been reported in the literature.

To address this issue, additional mixed linear model analyses adjusted for age and sex were performed. These analyses did not identify a statistically significant independent effect of either variable on buccal cortical bone thickness. Therefore, the main findings of the present study appear to be largely independent of the sample’s age and sex distribution.

Nevertheless, given the limited sample size and the demographic characteristics of the study population, residual confounding cannot be entirely excluded. Consequently, the reported values should be interpreted with caution, as part of the observed variability may still be attributable to unmeasured demographic or biological factors. The substantial interindividual variability observed in the measurements may also limit the applicability of average cortical thickness values to individual clinical cases. Future studies involving larger and more demographically balanced populations should further investigate the influence of age and sex on buccal cortical bone thickness and confirm the present findings.

In addition, no formal a priori sample size calculation or statistical power analysis was conducted before data collection. As this was a retrospective study based on previously acquired CBCT examinations, the final sample size was determined by the availability of eligible cases meeting the predefined inclusion and exclusion criteria rather than by statistical estimation. Although significant differences were identified in several comparisons and effect sizes were interpreted alongside p-values, the possibility of insufficient statistical power to detect smaller effects cannot be entirely ruled out. These findings should therefore be interpreted with caution, especially in relation to the non-significant comparisons, and future studies should include prospective sample size calculations to improve the robustness and generalizability of the results. In addition, the inclusion of further CBCT datasets was partly limited by software compatibility issues related to the three-dimensional analysis workflow.

Additionally, the present study focused only on linear measurements of buccal cortical bone thickness and did not assess other relevant parameters, such as bone density or volumetric changes. Including these variables could offer a more comprehensive understanding of alveolar bone characteristics and their clinical implications.

Finally, although the structured three-dimensional digital workflow represents a strength of the study, the methodology still requires technical expertise and access to specialized software, which may limit its use in routine clinical practice.

Despite these limitations, the methodology adopted in this study enabled a detailed and reproducible assessment of alveolar bone thickness, providing valuable insights into the anatomical characteristics of the anterior maxillary region.

6.7. Future Perspectives

Future research should build on these findings by including larger and more diverse populations, which would improve the generalizability of the results and help clarify how demographic and anatomical factors influence alveolar bone thickness.

Multicenter studies involving diverse populations could provide a broader, more representative view of anatomical variability in the anterior maxillary region.
Prospective study designs would also provide greater control over imaging parameters and clinical variables, thereby reducing potential sources of bias inherent in retrospective analyses. In addition, longitudinal studies could offer valuable insight into how alveolar bone changes over time, particularly in the context of tooth extraction, implant placement, and orthodontic treatment.

Future investigations should also consider incorporating additional parameters, such as bone density and volumetric analysis, to complement linear measurements of cortical bone thickness. Taken together, these variables may contribute to a more complete understanding of alveolar bone characteristics and their clinical relevance.

The ongoing development of digital technologies, particularly artificial intelligence–based tools, represents a promising avenue for future research. Advances in automated segmentation algorithms and image-processing techniques may further improve the accuracy, efficiency, and reproducibility of three-dimensional analyses. Integrating artificial intelligence into routine clinical workflows may also support more precise and individualized treatment planning.

Finally, future studies should examine the clinical application of three-dimensional digital workflows in real-time decision-making, especially in implantology and orthodontics. Validating these technologies in clinical settings could help establish standardized protocols and improve the predictability of treatment outcomes.

CONCLUSION

7. CONCLUSION

The present study enabled a detailed three-dimensional evaluation of buccal cortical bone thickness in the anterior maxillary region by integrating cone-beam computed tomography (CBCT), artificial intelligence–based bone segmentation, and digital three-dimensional analysis workflows.

The findings showed that the anterior maxillary region exhibits considerable anatomical variability, with the buccal cortical plate often reduced in thickness, particularly at the cervical and middle thirds of the tooth root. In contrast, greater thickness values were generally found at the apical level.

The study also highlighted the influence of tooth position and root inclination on cortical bone distribution, underlining the importance of an individualized anatomical assessment.

From a clinical perspective, the findings of this study reinforce the importance of an accurate preoperative assessment of alveolar bone anatomy, particularly in implantology, orthodontics, and aesthetic dentistry.

The methodology applied in the present study provides valuable anatomical information and may contribute to more predictable, individualized, and biologically guided dental treatments in the future.

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