Keywords
computed tomography; Hounsfield units; maxillofacial bone density; ageing; dental implants.

Authors
Dr. Spurthi Raikote*
Postgraduate, Department of Oral Medicine and Radiology, Government Dental College and Hospital, RIMS, Kadapa, Andhra Pradesh, India. spurthiraikote555@gmail.com

Dr Narjish Rahman Barbhuiya
Postgraduate, Department of Oral Medicine and Radiology, Government Dental College and Hospital, RIMS, Kadapa, Andhra Pradesh, India. drnarjishrb@gmail.com

Dr. Himabindu
Postgraduate, Department of Oral Medicine and Radiology, Government Dental College and Hospital, RIMS, Kadapa, Andhra Pradesh, India. drshimabindu@gmail.com

Dr Sivan Sathish
Professor and HOD, Department of Oral Medicine and Radiology, Teerthanker Mahaveer Dental College and Research Centre, Teerthanker Mahaveer University, Moradabad, Uttar Pradesh, India. drsivan.dental@tmu.ac.in

Dr Chandrasekhar M Reddy
Professor and HOD, Department of Oral Medicine and Radiology, Government Dental College and Hospital, RIMS, Kadapa, Andhra Pradesh, India. oralmedicine2006@gmail.com

Address for correspondence: Dr. Spurthi
Postgraduate, Department of Oral Medicine and Radiology, Government Dental College and Hospital, RIMS, Kadapa, Andhra Pradesh, India
Email: spurthiraikote555@gmail.com

Received:13-06-2026
Revised: 20-07-2026
Accepted: 25-07-2026
Published: 01-08-2026
Doi:10.1922/ejprd.v34i7s.1656

European Journal of Prosthodontics and Restorative Dentistry (2026) 34 (7s), 410–420

# Age-Related Regional Variations in Maxillofacial Bone Density Using Computed Tomography-Derived Hounsfield Units

**Abstract**

**Background:**
Assessment of maxillofacial bone density is essential for implant placement, orthodontic temporary anchorage device (TAD) stability, and reconstructive surgery. However, evidence regarding age-related regional variations remains limited. Therefore, this study evaluated age-related changes in maxillofacial bone density using computed tomography (CT)-derived Hounsfield Units (HU) and their clinical implications.

**Materials and Methods:**
A prospective cross-sectional study included 80 healthy participants equally distributed into four age groups (10–20, 21–40, 41–60, and >60 years) with equal sex representation. HU values were measured from ten standardized maxillofacial regions on multidetector CT images. Statistical analysis included one-way ANOVA, Tukey's post hoc test, and independent-samples t-test to compare HU values between sexes ($p < 0.05$).

**Results:** Bone density differed significantly among age groups across all regions ($p < 0.001$). Peak HU values occurred in the 21–40-year group and declined progressively with age. The posterior maxilla showed the greatest reduction (Mean HU decrease from 682.2±67.6 to 254.0±77.4), whereas the pterygomaxillary junction, pterygoid process, and zygomatic bone (Mean HU decrease from 1194.5±75.3 to 853.5±84.1) retained comparatively higher HU values.

**Conclusion:**
Maxillofacial bone density declines with age in a region-specific manner. Preservation of bone density within the pterygomaxillary junction, pterygoid process, and zygomatic bone supports their use as favorable anchorage sites for implantology, orthodontic TAD placement, and maxillofacial reconstructive surgery.



 

## 1. INTRODUCTION

Successful rehabilitation of the maxillofacial skeleton relies heavily on an accurate assessment of bone quality. Bone density is one of the principal determinants of primary implant stability, osseointegration, orthodontic temporary anchorage device (TAD) stability, and the long-term success of reconstructive procedures [1,2]. While bone quantity has traditionally received considerable attention during treatment planning, increasing evidence suggests that bone density is equally critical in predicting biomechanical performance and clinical outcomes. Computed tomography (CT) is the commonly used reference imaging modality for quantitative evaluation of bone mineralization because it provides standardized attenuation values expressed as Hounsfield Units (HU) [3]. Unlike subjective intraoperative assessment or conventional radiography, HU measurements offer an objective and reproducible estimate of mineralized tissue density, enabling clinicians to evaluate regional variations in cortical and trabecular bone before surgical intervention [4]. The use of HU-based assessment has therefore become increasingly important in implant dentistry, orthognathic surgery, craniofacial reconstruction, and orthodontic anchorage planning [5].

Bone density within the maxillofacial skeleton is not uniform. Considerable anatomical variations exist between the maxilla and mandible, anterior and posterior regions, and cortical and cancellous compartments. Furthermore, specialized skeletal regions such as the hard palate, zygomatic bone, and pterygoid process exhibit distinct structural characteristics that influence their suitability for implant placement, skeletal anchorage, and bone graft harvesting. These regional differences are primarily governed by functional loading, cortical thickness, trabecular architecture, and patterns of skeletal remodeling [6,7]. Age is another major determinant of bone quality. Progressive alterations in bone remodeling, hormonal status, vascularity, and mineral metabolism lead to changes in cortical thickness and trabecular microarchitecture throughout life. Although generalized skeletal bone loss associated with ageing has been extensively documented, the pattern of age-related density changes within different maxillofacial regions remains incompletely understood [8]. The rate and magnitude of these changes may differ substantially among anatomical sites because of differences in embryological origin, functional loading, masticatory forces, and local remodeling dynamics. In addition, sex-specific variations associated with hormonal changes, particularly following menopause, may further influence regional bone density.

Several studies have investigated bone density at prospective implant recipient sites using CT-derived Hounsfield Units and have demonstrated that denser bone is generally associated with improved primary implant stability and more predictable osseointegration [9,10]. Likewise, orthodontic investigations have highlighted the importance of adequate cortical and trabecular bone density for achieving stable temporary anchorage device fixation [11]. However, most previous studies have focused on isolated anatomical regions, predominantly the alveolar process, or specific implant sites. Comprehensive evaluation of multiple maxillofacial skeletal regions, including the maxilla, mandible, hard palate, zygomatic bone, and pterygomaxillary complex, across different age groups remains scarce. Moreover, comparative analyses incorporating both age- and sex-related variations using standardized CT protocols are limited.

A detailed understanding of age-dependent changes in bone density across these clinically important anatomical regions could substantially improve patient-specific treatment planning. Such information would aid clinicians in selecting optimal implant sites, predicting primary implant stability, determining suitable locations for temporary anchorage devices, identifying alternative anchorage regions such as the zygomatic and pterygoid bones in severely resorbed jaws, and selecting appropriate donor sites for reconstructive procedures. Quantitative bone density mapping may also facilitate risk stratification and individualized surgical planning in elderly patients who exhibit varying degrees of maxillofacial bone remodeling [12,13].

Therefore, the present prospective cross-sectional study aimed to quantitatively evaluate Hounsfield Unit variations across multiple maxillofacial skeletal regions, including the anterior and posterior maxilla, anterior and posterior mandible, anterior and posterior hard palate, pterygomaxillary junction, pterygoid process, zygomatic body, and zygomatic arch, among adolescents, young adults, middle-aged adults, and elderly adults using multidetector computed tomography. In addition, sex-related differences in regional bone density were investigated to provide clinically relevant evidence for implantology, orthodontic skeletal anchorage, and maxillofacial reconstructive surgery.

## 2. MATERIALS AND METHODS

### 2.1 Study Design and Ethical Considerations

This prospective cross-sectional observational study was conducted in the Department of Oral Medicine and Radiology, Government Dental College and Hospital, Kadapa, Andhra Pradesh, India, over a period of two months from January 2025 to February 2025. The study was designed to quantitatively evaluate age- and sex-related variations in maxillofacial bone density by measuring Hounsfield Unit (HU) values in multiple clinically relevant skeletal regions using multidetector computed tomography (MDCT). The study protocol was reviewed and approved by the Institutional Ethics Committee of Government Dental College and Hospital, Kadapa (Protocol No. Pr. 104/IEC/GDCH/2025-26) following prior scientific approval by the Institutional Scientific Committee (Scientific Committee Ref. No. 504/UA1/GDCH/2025-2026). Ethical clearance was granted under Protocol No. 104/UA1/GDCH/KDP-25. The investigation was conducted in accordance with the ethical principles of the Declaration of Helsinki (2013) and the Indian Council of Medical Research (ICMR) National Ethical Guidelines for Biomedical and Health Research involving Human Participants. Written informed consent was obtained from all adult participants before CT acquisition. For participants younger than 18 years of age, written informed consent was obtained from parents or legal guardians along with assent from the participant whenever appropriate. To maintain confidentiality, all patient identifiers were removed before image analysis, and anonymized datasets were used throughout the study.

**2.2 Study Population**

The study included 80 consecutive patients who underwent maxillofacial CT examination for various diagnostic indications unrelated to osseous pathology affecting the regions of interest. Participants were prospectively recruited after fulfilling the predefined eligibility criteria. To investigate physiological age-related changes in maxillofacial bone density, the study population was equally stratified into four age groups consisting of adolescents (10–20 years), young adults (21–40 years), middle-aged adults (41–60 years), and elderly adults (>60 years). Each group comprised 20 participants with an equal distribution of males and females, thereby maintaining a 1:1 sex ratio and minimizing gender-related sampling bias. This age stratification was selected to represent different stages of skeletal growth, peak bone maturation, age-associated remodeling, and physiological skeletal senescence. By maintaining equal representation across both age and sex categories, the study aimed to generate a comprehensive assessment of regional bone density changes throughout adult life.

Participants were included only if they possessed complete dentition within the region of interest and demonstrated high-quality CT images suitable for quantitative analysis. Individuals undergoing CT imaging for conditions such as sinusitis, headache, trigeminal neuralgia, or benign soft-tissue lesions without osseous involvement were considered eligible because these conditions do not significantly influence the intrinsic density of the maxillofacial skeleton. Patients with uncontrolled systemic diseases affecting bone metabolism, including diabetes mellitus and hypertension, previous facial trauma, orthognathic surgery, bone grafting procedures, metabolic bone disorders, history of head and neck radiotherapy, long-term medications known to influence skeletal remodeling, extensive periodontal destruction, odontogenic cysts, benign or malignant tumors involving the jaws, completely edentulous arches, or CT scans affected by severe motion or metallic artifacts were excluded to eliminate confounding factors that could influence Hounsfield Unit measurements.

**2.3 CT Image Acquisition Protocol**

All examinations were performed using a 64-slice Siemens Multislice Computed Tomography scanner following a standardized imaging protocol for every participant. The scans were acquired using a tube voltage of 120 kVp and a tube current of 200 mA with a slice thickness of 0.5 mm while ensuring complete coverage of the maxillofacial skeleton within the field of view. Participants were positioned according to the manufacturer's recommendations with the Frankfort horizontal plane maintained parallel to the floor and instructed to maintain maximum intercuspation throughout image acquisition. Every effort was made to minimize patient movement to prevent motion artifacts that could influence attenuation measurements. Image reconstruction was performed using identical reconstruction parameters for all scans to ensure consistency in voxel attenuation values and facilitate accurate comparison among participants. All reconstructed images were evaluated on the dedicated Siemens workstation under standardized display settings throughout the study.

**2.4 Image Analysis and Region of Interest Standardization**

Image analysis was performed using the proprietary Siemens image analysis software by calibrated oral and maxillofacial radiologists experienced in CT interpretation. Bone density was quantified by measuring Hounsfield Unit values within standardized square regions of interest (ROI) measuring 3 mm × 3 mm. Careful attention was paid to ROI placement to ensure reproducibility and avoid inclusion of anatomical structures that could artificially influence attenuation values. For trabecular bone assessment, the ROI was positioned centrally within cancellous bone while avoiding adjacent tooth roots, periodontal ligament spaces, cortical boundaries, maxillary sinus cavities, nasal cavities, neurovascular canals, and image artifacts. When cortical bone evaluation was required, the ROI was positioned entirely within the cortical plate without extending into adjacent cancellous bone. The same anatomical landmarks and measurement protocol were applied uniformly to all participants, thereby minimizing observer variability and ensuring standardization across the study population.

Bone density measurements were obtained from ten anatomically important maxillofacial regions that are frequently utilized in implant dentistry, orthodontic skeletal anchorage, and reconstructive surgery. The anterior maxilla was evaluated in the incisor-canine region, whereas the posterior maxilla was assessed in the premolar-molar region. Measurements were obtained from axial images at the mid-root level, while sagittal reconstructions were used to evaluate anteroposterior bone density gradients and coronal sections were examined to assess cortical and trabecular bone characteristics while considering the influence of maxillary sinus pneumatization (Figure 1). The anterior and posterior mandible were evaluated in a similar manner using axial sections at the mid-root level, supplemented by sagittal and coronal reconstructions to comprehensively assess regional density distribution and cortical architecture (Figure 2).

**Fig 1. Representative axial, sagittal, and coronal multidetector CT images demonstrating standardized region-of-interest placement for Hounsfield Unit measurements in the anterior and posterior maxillary regions.**

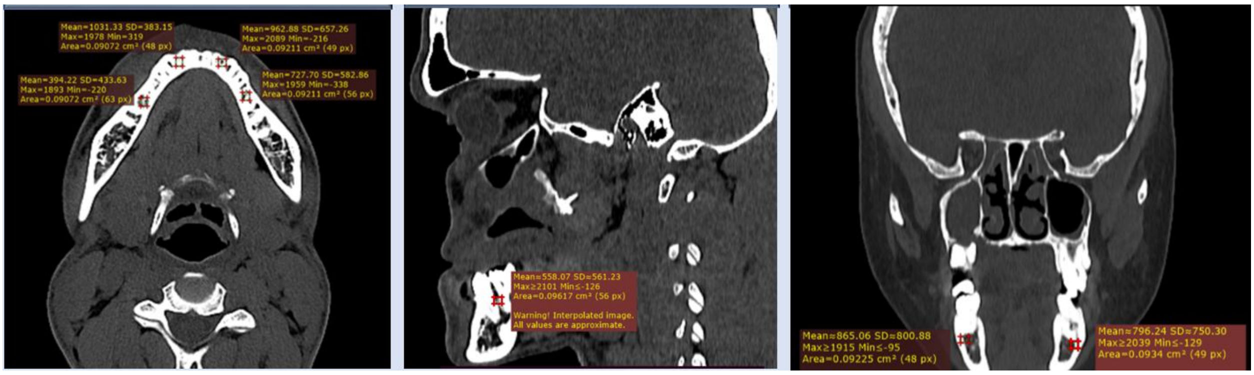

**Fig 2. Representative multidetector CT images demonstrating standardized ROI placement for Hounsfield Unit (HU) measurements in the mandibular anterior and posterior regions.**

The hard palate was evaluated by measuring Hounsfield Unit values within the anterior palatal region adjacent to the incisive foramen and the posterior hard palate adjacent to the molar region (Figure 3).

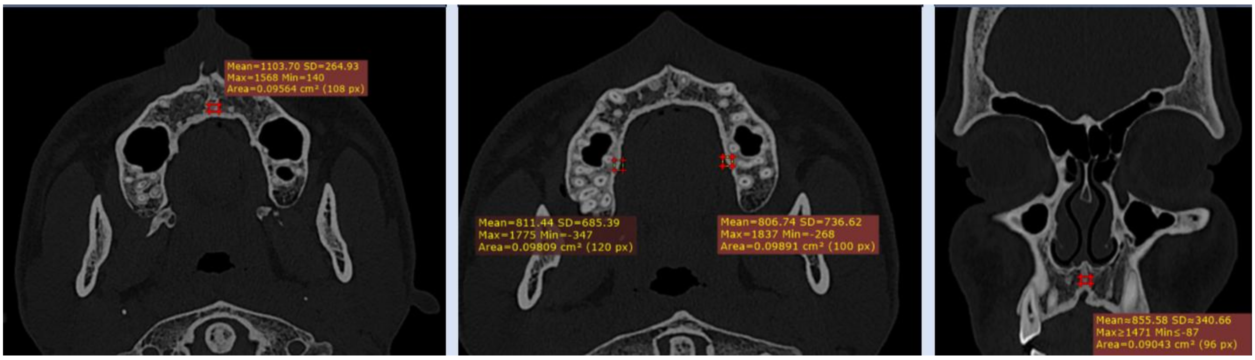

**Fig 3. Representative axial and coronal multidetector CT images illustrating standardized region-of-interest placement for Hounsfield Unit measurements in the anterior and posterior hard palate.**

Coronal images were additionally examined to evaluate palatal cortical thickness and ensure accurate ROI placement. The pterygomaxillary region was assessed by measuring the pterygomaxillary junction and the pterygoid process of the sphenoid bone using both axial and coronal reconstructions because these regions serve as important anchorage sites for pterygoid implants in patients with severe posterior maxillary atrophy (Figure 4).

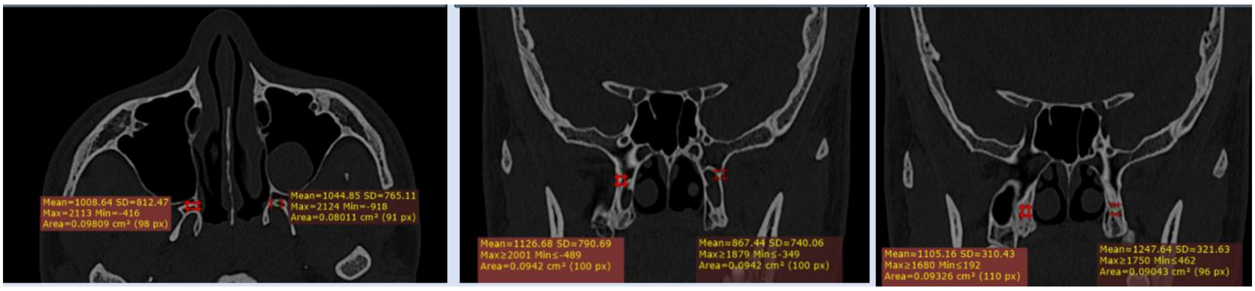

**Fig 4. Representative multidetector CT images demonstrating standardized region-of-interest placement for Hounsfield Unit measurements in the pterygomaxillary junction and pterygoid process.**

Similarly, the zygomatic body and zygomatic arch were evaluated using standardized axial and coronal sections owing to their increasing role as alternative implant anchorage sites in complex maxillofacial rehabilitation (Figure 5).

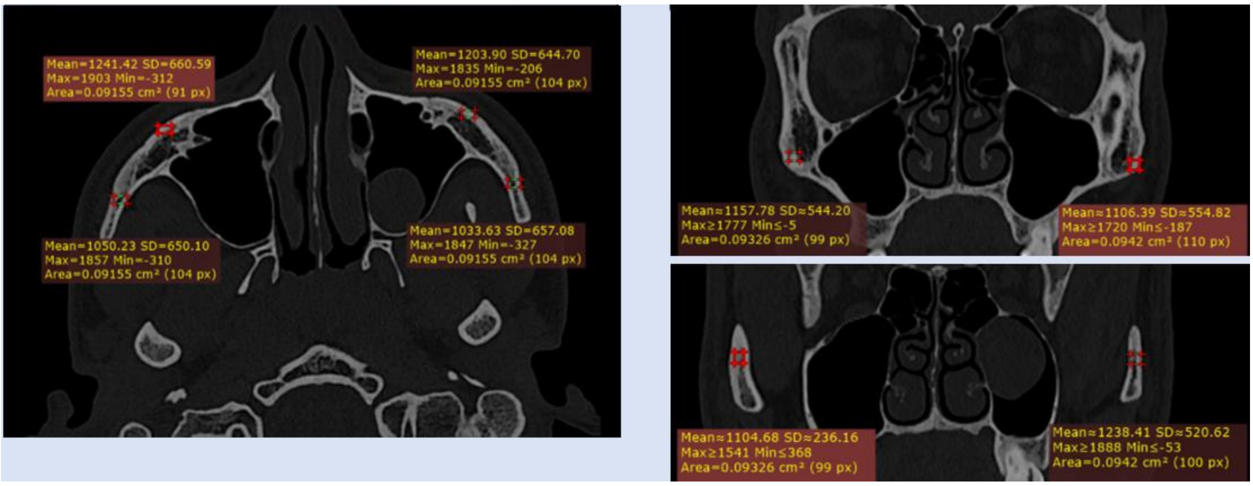


**Fig 5. Representative multidetector CT images demonstrating standardized region-of-interest placement for Hounsfield Unit measurements in the zygomatic body and zygomatic arch.**

### 2.5 Bone Density Classification

The measured Hounsfield Unit values were interpreted according to the Misch bone density classification, which categorizes bone quality into clinically meaningful groups based on CT attenuation values. According to this classification, bone with attenuation values exceeding 1250 HU was categorized as D1 bone, values ranging from 850 to 1250 HU as D2 bone, values between 350 and 850 HU as D3 bone, values between 150 and 350 HU as D4 bone, and values below 150 HU as D5 bone. This widely accepted classification provides a practical framework for predicting primary implant stability, evaluating the suitability of temporary anchorage device placement, and planning reconstructive surgical procedures. Categorization according to Misch classification also enabled comparison of anatomical regions with respect to their expected biomechanical performance and potential clinical applications.

### 2.6 Statistical Analysis

All collected data were entered into Microsoft Excel and subsequently analyzed using IBM Statistical Package for the Social Sciences (SPSS) software version 27.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean ± standard deviation (SD). The normality of data distribution was assessed using the Shapiro–Wilk test before inferential statistical analysis. Differences in mean Hounsfield Unit (HU) values among the four age groups were evaluated using one-way analysis of variance (ANOVA) for each anatomical region. Whenever a statistically significant overall difference was identified, Tukey's Honestly Significant Difference (HSD) post hoc test was performed to determine pairwise differences between age groups. Independent-samples t-test was used to compare mean HU values between male and female participants for each anatomical region. All statistical tests were two-tailed, and a p value of less than 0.05 was considered statistically significant.

## 3. RESULTS

### 3.1 Demographic Characteristics

The study included 80 participants divided equally into four age groups: 10–20 years, 21–40 years, 41–60 years, and ≥61 years. Each age group comprised 20 participants, including 10 males and 10 females. Overall, the sample consisted of 40 males and 40 females, ensuring an equal sex distribution across all age categories.

### 3.2 Assessment of Data Normality

The normality of Hounsfield Unit measurements was assessed using the Shapiro–Wilk test separately for each anatomical region within each age group. Of the 40 age-group–region distributions evaluated, 38 demonstrated no statistically significant departure from normality ($p>0.05$). Significant departures from normality were observed for posterior mandibular HU values in the 10–20-year group ($W=0.883$, $p=0.020$) and the 21–40-year group ($W=0.839$, $p=0.004$). Nevertheless, because the age groups were equal in size and each contained 20 participants, one-way analysis of variance was retained as the primary age-group comparison.

### 3.3 Age-Related Differences in Maxillofacial Bone Density

The mean HU values for the ten anatomical regions according to age group are presented in Table 1. Across all anatomical sites, the highest mean bone-density values were observed in participants aged 21–40 years. A subsequent reduction was evident in the 41–60-year group, followed by a more pronounced decline among participants aged ≥61 years. In the 21–40-year group, the highest mean density was recorded in the anterior palate (1206.2±81.4 HU), followed by the zygomatic body (1194.5±75.3 HU), anterior mandible (1161.0±109.2 HU), pterygomaxillary junction (1119.0±36.3 HU), zygomatic arch (1118.0±100.6 HU), and pterygoid process (1079.0±36.3 HU). The posterior maxilla consistently demonstrated relatively lower bone-density values than most other maxillofacial regions. Among participants aged ≥61 years, the pterygomaxillary junction retained the highest mean density (858.5±64.8 HU), followed by the zygomatic body (853.5±84.1 HU) and pterygoid process (826.0±65.6 HU). The posterior maxilla demonstrated the lowest mean value in this age group (254.0±77.4 HU), indicating a marked age-associated reduction in posterior maxillary bone density. (Table 1)

**Table 1. Mean Hounsfield Unit values according to age group**

| Anatomical region | 10–20 years | 21–40 years | 41–60 years | ≥61 years |
|---|---|---|---|---|
| Anterior maxilla | 657.5±52.7 | 832.2±38.9 | 575.5±42.4 | 394.0±60.4 |
| Posterior maxilla | 541.8±69.2 | 682.2±67.6 | 454.0±66.5 | 254.0±77.4 |
| Anterior mandible | 864.2±97.0 | 1161.0±109.2 | 891.5±100.5 | 624.5±107.4 |
| Posterior mandible | 791.0±129.4 | 1048.0±160.0 | 776.5±133.6 | 542.0±148.9 |
| Anterior palate | 947.8±76.2 | 1206.2±81.4 | 891.5±66.5 | 664.5±91.4 |
| Posterior palate | 761.5±69.4 | 1076.2±123.8 | 731.5±66.5 | 479.5±87.7 |
| Pterygomaxillary junction | 957.8±48.8 | 1119.0±36.3 | 957.5±44.6 | 858.5±64.8 |
| Pterygoid process | 922.5±52.0 | 1079.0±36.3 | 926.0±41.7 | 826.0±65.6 |
| Zygomatic body | 981.0±83.8 | 1194.5±75.3 | 1011.5±59.4 | 853.5±84.1 |
| Zygomatic arch | 921.0±79.3 | 1118.0±100.6 | 921.5±66.5 | 763.5±91.5 |

Values are expressed as mean±standard deviation in HU.

### 3.4 One-Way ANOVA for Age-Group Comparisons

One-way ANOVA demonstrated statistically significant differences among the four age groups for every anatomical region examined (all $p<0.001$). The strongest age-group effect was observed in the anterior maxilla ($F=272.28$), followed by the anterior palate ($F=157.12$), posterior palate ($F=148.38$), and posterior maxilla ($F=130.17$). Statistically significant age-related differences were also demonstrated in the pterygomaxillary junction, anterior mandible, pterygoid process, zygomatic body, zygomatic arch, and posterior mandible (Table 2).

**Table 2. One-way ANOVA comparing Hounsfield Unit values among age groups**

| Anatomical region | F statistic | p value |
|---|---|---|
| Anterior maxilla | 272.28 | <0.001 |
| Posterior maxilla | 130.17 | <0.001 |
| Anterior mandible | 89.66 | <0.001 |
| Posterior mandible | 41.52 | <0.001 |
| Anterior palate | 157.12 | <0.001 |
| Posterior palate | 148.38 | <0.001 |
| Pterygomaxillary junction | 94.09 | <0.001 |
| Pterygoid process | 86.91 | <0.001 |
| Zygomatic body | 67.96 | <0.001 |
| Zygomatic arch | 57.73 | <0.001 |

Degrees of freedom for all analyses were 3 and 76.

### 3.5 Tukey HSD Post Hoc Comparisons

Tukey HSD post hoc analysis demonstrated that the 21–40-year group had significantly higher HU values than the other three age groups across all ten anatomical regions. Participants aged ≥61 years had significantly lower HU values than the 10–20-, 21–40-, and 41–60-year groups at every anatomical site. The comparison between the 10–20-year and 41–60-year groups showed regional variation. Significant differences were observed in the anterior maxilla and posterior maxilla, with the 10–20-year group demonstrating higher density values. In contrast, no significant differences between these two age groups were found in the anterior mandible, posterior mandible, anterior palate, posterior palate, pterygomaxillary junction, pterygoid process, zygomatic body, or zygomatic arch (Table 3).

**Table 3. Summary of Tukey HSD pairwise age-group comparisons (Values represent Tukey-adjusted p values)**

| Anatomical region | 10–20 vs 21–40 | 10–20 vs 41–60 | 10–20 vs ≥61 | 21–40 vs 41–60 | 21–40 vs ≥61 | 41–60 vs ≥61 |
|---|---|---|---|---|---|---|
| Anterior maxilla | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Posterior maxilla | <0.001 | 0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Anterior mandible | <0.001 | 0.839 | <0.001 | <0.001 | <0.001 | <0.001 |
| Posterior mandible | <0.001 | 0.989 | <0.001 | <0.001 | <0.001 | <0.001 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Anterior palate | <0.001 | 0.122 | <0.001 | <0.001 | <0.001 | <0.001 |
| Posterior palate | <0.001 | 0.717 | <0.001 | <0.001 | <0.001 | <0.001 |
| Pterygomaxillary junction | <0.001 | 1.000 | <0.001 | <0.001 | <0.001 | <0.001 |
| Pterygoid process | <0.001 | 0.996 | <0.001 | <0.001 | <0.001 | <0.001 |
| Zygomatic body | <0.001 | 0.589 | <0.001 | <0.001 | <0.001 | <0.001 |
| Zygomatic arch | <0.001 | 1.000 | <0.001 | <0.001 | <0.001 | <0.001 |

### 3.6 Sex-Related Differences in Maxillofacial Bone Density

Male participants demonstrated numerically higher mean HU values than female participants in all ten anatomical regions. Independent-samples t-test analysis showed statistically significant sex-related differences in the posterior maxilla (p=0.003), anterior mandible (p<0.001), posterior mandible (p<0.001), anterior palate (p=0.010), posterior palate (p=0.005), zygomatic body (p<0.001), and zygomatic arch (p<0.001). The largest absolute difference between males and females was observed in the posterior mandible, where males demonstrated a mean value of 920.75±194.51 HU compared with 658.00±180.73 HU in females. No statistically significant sex-related differences were observed in the anterior maxilla (p=0.247), pterygomaxillary junction (p=0.154), or pterygoid process (p=0.069) (Table 4).

**Table 4. Comparison of Hounsfield Unit values between male and female participants**

| Anatomical region | Male, mean±SD | Female, mean±SD | t statistic | p value |
|---|---|---|---|---|
| Anterior maxilla | 636.38±171.91 | 593.25±158.78 | 1.17 | 0.247 |
| Posterior maxilla | 538.38±166.38 | 427.62±158.45 | 3.05 | 0.003 |
| Anterior mandible | 973.25±204.22 | 797.38±193.59 | 3.95 | <0.001 |
| Posterior mandible | 920.75±194.51 | 658.00±180.73 | 6.26 | <0.001 |
| Anterior palate | 987.12±203.03 | 867.88±199.91 | 2.65 | 0.010 |
| Posterior palate | 832.75±239.63 | 691.62±200.32 | 2.86 | 0.005 |
| Pterygomaxillary junction | 990.12±105.08 | 956.25±105.29 | 1.44 | 0.154 |
| Pterygoid process | 959.38±98.72 | 917.38±105.25 | 1.84 | 0.069 |
| Zygomatic body | 1066.62±135.76 | 953.62±129.69 | 3.81 | <0.001 |
| Zygomatic arch | 998.50±145.74 | 863.50±126.73 | 4.42 | <0.001 |

Independent-samples t-tests were conducted with 78 degrees of freedom.

### 3.7 Overall Pattern of Maxillofacial Bone Density

The findings demonstrated a distinct age-dependent pattern of maxillofacial bone density. Bone density increased from adolescence to reach its highest level during young adulthood, followed by a reduction during middle age and a marked decline after 60 years. Although this pattern was observed throughout the maxillofacial skeleton, the magnitude of reduction varied considerably among anatomical regions. The posterior maxilla exhibited comparatively low HU values and a substantial reduction with increasing age. Conversely, the pterygomaxillary junction, pterygoid process, and zygomatic regions retained relatively high HU values even in elderly participants. These regional differences indicate that the pterygoid and zygomatic regions may preserve comparatively favourable bone density during ageing, while the posterior maxilla may be more vulnerable to age-related deterioration. Male participants generally demonstrated greater bone density than female participants, although statistically significant sex differences were not uniformly present across all anatomical sites.

## 4. Discussion

The present study quantitatively evaluated age- and sex-related variations in maxillofacial bone density using multidetector computed tomography (MDCT)-derived Hounsfield Unit (HU) measurements across ten anatomically important skeletal regions. The principal findings demonstrated that bone density undergoes a distinct age-dependent pattern, characterized by a progressive increase from adolescence to young adulthood, followed by a gradual decline during middle age and a marked reduction after 60 years of age. More importantly, the reduction in bone density was not uniform throughout the maxillofacial skeleton. While the posterior maxilla exhibited the greatest age-related reduction in HU values, the pterygomaxillary junction, pterygoid process, and zygomatic bone retained comparatively higher bone density even in elderly individuals. These findings highlight the regional heterogeneity of skeletal ageing and provide clinically relevant information for implant dentistry, orthodontics, and maxillofacial reconstructive surgery.

Peak bone density observed in the 21–40-year age group is consistent with the well-established concept that skeletal mineralization reaches its maximum during early adulthood before physiological bone remodeling gradually exceeds bone formation with advancing age. Previous investigations have similarly demonstrated that bone mineral density increases until the third decade of life, after which cortical thinning, trabecular rarefaction, and reduced mineralization contribute to progressive skeletal weakening [14,15]. Although this phenomenon has been extensively investigated in the appendicular skeleton, quantitative information regarding age-related changes within different regions of the maxillofacial skeleton has remained comparatively limited. The present study extends existing knowledge by demonstrating that these physiological changes occur differently among individual maxillofacial bones rather than affecting the craniofacial skeleton uniformly.

Among all evaluated regions, the posterior maxilla demonstrated the lowest HU values and the greatest age-related decline. This observation is biologically plausible because the posterior maxilla predominantly consists of trabecular bone with relatively thin cortical plates and is further influenced by progressive maxillary sinus pneumatization following tooth loss and ageing [16-18]. Reduced functional loading, cortical thinning, and enlargement of the maxillary sinus collectively contribute to diminished bone quantity and quality in this region. Previous implant studies have consistently reported lower primary implant stability and reduced insertion torque within the posterior maxilla, frequently necessitating sinus augmentation or alternative implant strategies [19]. The present findings provide quantitative radiological evidence supporting these clinical observations and further emphasize the challenges associated with implant placement in posterior maxillary bone among elderly individuals.

In contrast, the pterygomaxillary junction, pterygoid process, and zygomatic bone exhibited comparatively preserved bone density despite advancing age. Although a gradual reduction in HU values was observed across all age groups, the magnitude of decline in these regions was substantially less than that observed in the posterior maxilla. These findings likely reflect their unique anatomical and biomechanical characteristics. The pterygoid process and zygomatic bone possess relatively thick cortical bone and dense trabecular architecture and remain subjected to continuous functional loading through masticatory muscle attachments. Consequently, these skeletal regions appear to maintain structural integrity despite physiological skeletal ageing [20,21].

The preservation of bone density within these regions has important clinical implications. Pterygoid and zygomatic implants have become widely accepted treatment options for rehabilitation of severely resorbed maxillae, particularly when conventional posterior implant placement is compromised because of inadequate bone volume or extensive sinus pneumatization [22]. While previous clinical investigations have demonstrated excellent survival rates for both zygomatic and pterygoid implants, the present study provides an anatomical and quantitative radiological explanation for these favorable outcomes. Rather than proving implant success, the findings demonstrate that these regions retain comparatively higher bone density with ageing, thereby supporting their suitability as alternative implant anchorage sites in patients with severe posterior maxillary atrophy. Thus, the present study provides additional biological justification for established implant concepts by demonstrating that preservation of bone density within these regions may contribute to improved biomechanical support.

Another important observation was that male participants generally demonstrated higher HU values than female participants across most anatomical regions, although statistically significant differences were identified only in selected sites. These findings are consistent with the recognized influence of sex hormones on skeletal metabolism. Declining estrogen levels following menopause accelerate cortical bone loss and trabecular deterioration, resulting in lower bone mineral density among females during later decades of life [23,24]. Nevertheless, the relatively limited number of significant sex-related differences observed in the present study suggests that age may exert a greater influence on maxillofacial bone density than sex alone. Consequently, individualized radiological assessment remains essential rather than relying solely on demographic characteristics during treatment planning.

The present findings also have considerable implications for orthodontic skeletal anchorage. Successful placement of temporary anchorage devices (TADs) depends largely upon cortical bone thickness and local bone quality [25]. Regions exhibiting relatively preserved bone density may provide superior primary stability and reduce the likelihood of anchorage failure. Likewise, knowledge of age-related regional bone density variation may assist surgeons in selecting appropriate donor and recipient sites during reconstructive procedures, planning osteotomies, and predicting fixation stability following trauma or orthognathic surgery [26].

One of the major strengths of this investigation is the comprehensive evaluation of ten clinically relevant maxillofacial regions within a standardized MDCT imaging protocol. Unlike previous studies that focused primarily on individual implant sites or isolated jaw regions, the present investigation provides a panoramic quantitative assessment of age-related skeletal variation throughout the maxillofacial complex. Furthermore, equal representation of both sexes and four well-defined age groups enabled systematic evaluation of physiological skeletal ageing while minimizing demographic imbalance. The use of standardized 3 × 3 mm regions of interest and uniform acquisition parameters further enhanced measurement consistency and reproducibility.

Despite these strengths, certain limitations should be acknowledged. The study was conducted at a single institution with a relatively modest sample size, which may limit the generalizability of the findings to broader populations. Because of its cross-sectional design, longitudinal age-related changes could not be directly evaluated. Moreover, although Hounsfield Units provide an objective surrogate measure of bone density, they do not directly assess bone microarchitecture, elasticity, or biomechanical strength, all of which influence implant stability and long-term osseointegration [27,28]. Future multicenter longitudinal investigations incorporating histomorphometric analysis, finite element modeling, and prospective implant outcome assessment would provide further insight into the relationship between regional bone density and clinical performance.

Future advancements in artificial intelligence (AI) and machine learning (ML) are expected to transform Hounsfield Unit-based bone density assessment into a cornerstone of precision dentistry [29]. AI-driven analysis of CT-derived HU values integrated with patient-specific variables such as age, sex, anatomical region, systemic health, and occlusal loading may enable automated prediction of bone quality, primary implant stability, osseointegration potential, orthodontic anchorage success, and long-term treatment outcomes. Integration of quantitative bone-density mapping with CAD/CAM workflows, virtual surgical planning, navigation systems, and three-dimensional (3D) printing technologies may facilitate the fabrication of patient-specific implants, customized bone grafts, and individualized reconstructive solutions optimized according to regional bone density and biomechanical requirements [30]. Such advances have the potential to improve surgical precision, reduce complications, shorten treatment duration, and advance the concept of personalized maxillofacial rehabilitation.

Although multidetector CT-derived Hounsfield Units remain the current reference standard for quantitative assessment of bone density, their routine application in dental practice is limited because cone-beam computed tomography (CBCT) has become the preferred imaging modality owing to its lower radiation dose, lower cost, and superior spatial resolution [31]. However, conventional Hounsfield Unit measurements cannot be reliably applied to CBCT because voxel intensity values vary considerably among different scanners, acquisition parameters, reconstruction algorithms, and fields of view. Consequently, quantitative assessment of bone density using CBCT has remained a longstanding challenge in dentomaxillofacial radiology. Emerging voxel-intensity normalization methods, such as the recently introduced Sivan Unit (SU), offer a promising solution by standardizing CBCT voxel values using biologically defined reference tissues, thereby enabling reproducible quantitative assessment across different CBCT systems [32,33]. Future investigations should validate the relationship between SU-derived bone density, CT-derived Hounsfield Units, implant primary stability, and long-term clinical outcomes. Successful validation of standardized CBCT-based quantitative bone-density assessment could substantially expand the role of CBCT from a predominantly qualitative imaging modality to a reliable quantitative tool, thereby supporting precision implant dentistry, AI-assisted surgical planning, and individualized patient care.

## 5. CONCLUSION

This study demonstrated that maxillofacial bone density undergoes significant age-related changes, with a progressive decline after early adulthood; however, the extent of bone loss varies considerably among different anatomical regions. The pterygomaxillary junction, pterygoid process, and zygomatic bone exhibited comparatively preserved bone density, whereas the posterior maxilla showed the greatest age-related reduction. These findings provide quantitative evidence for site-specific treatment planning and support the selection of anatomically favorable regions for implantology, orthodontic temporary anchorage device (TAD) placement, and maxillofacial reconstructive surgery, thereby contributing to more predictable and personalized clinical outcomes.

**Declarations:**

**Funding:** None

**Competing Interests:** None

**Ethical approval**: This study was conducted in accordance with the ethical principles of the Declaration of Helsinki and the Indian Council of Medical Research (ICMR) National Ethical Guidelines for Biomedical and Health Research Involving Human Participants. Ethical approval was obtained from the Institutional Ethics Committee, Government Dental College and Hospital, Kadapa, under Protocol No. Pr. 97/IEC/GDCH/2025–26, with Scientific Committee Reference No. 498/UA1/GDCH/2025–2026 and Protocol No. 97/UA1/GDCH/KDP-25, prior to the commencement of the study.

**Patient Consent:** Written informed consent was obtained from all participants prior to enrollment in the study. For participants younger than 18 years of age, written informed consent was obtained from their parent(s) or legal guardian(s), and assent was obtained from the participants whenever appropriate. All patient information was anonymized to ensure confidentiality and privacy throughout the study.

**Data Availability Statement:** All data supporting the findings of this study are available within the paper and require no supplementary materials.

**Author Contribution Statement:**
All authors reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work. SR, NB, HS, and CR contributed to the study concept and design; SR, CR, HS, and SS contributed to data acquisition, analysis, and interpretation; SR, NB, CR, and HS drafted the manuscript; CR and SS critically reviewed the manuscript for important intellectual content and supervised the study.

## REFERENCES

1. Wang, SH., Fuh, LJ., Chen, M.Y.C. et al. Preoperative assessment of bone density for dental implantation: a comparative study of three different ROI methods. Head Face Med 20, 33 (2024). https://doi.org/10.1186/s13005-024-00434-0
2. Javed F, Ahmed HB, Crespi R, Romanos GE. Role of primary stability for successful osseointegration of dental implants: Factors of influence and evaluation. Interv Med Appl Sci. 2013 Dec;5(4):162-7. doi: 10.1556/IMAS.5.2013.4.3.
3. Yang TJ, Wen PP, Ye X, Wu XF, Zhang C, Sun SY, Wu ZX, Zhang GY, Sun YF, Ye R, Zhou CK, He HJ. CT Hounsfield units in assessing bone and soft tissue quality in the proximal femur: A systematic review focusing on osteonecrosis and total hip arthroplasty.

PLoS One. 2025 Mar 26;20(3):e0319907. doi: 10.1371/journal.pone.0319907.
4. Seth I, Lim B, Marcaccini G, Novo J, Tso R, Bruechert G, Fogg Q, Rozen WM. Enhancing Preoperative Decision-Making in Trapeziometacarpal Joint Replacement: CT Hounsfield Units as a Reliable Predictor of Bone Quality. Hand (N Y). 2025 Dec 10:15589447251391377. doi: 10.1177/15589447251391377.
5. Pauwels R, Jacobs R, Singer SR, Mupparapu M. CBCT-based bone quality assessment: are Hounsfield units applicable? Dentomaxillofac Radiol. 2015;44(1):20140238. doi: 10.1259/dmfr.20140238.
6. Chugh T, Jain AK, Jaiswal RK, Mehrotra P, Mehrotra R. Bone density and its importance in orthodontics. J Oral Biol Craniofac Res. 2013 May-Aug;3(2):92-7. doi: 10.1016/j.jobcr.2013.01.001.
7. Ocak I, Kemer B, Aksoz Oner G. Comparison of mandibular bone density and morphology in patients with Angle Class I, II, and III malocclusion using panoramic radiography: a cross-sectional study. BMC Oral Health. 2026 Jan 21;26(1):323. doi: 10.1186/s12903-026-07719-7.
8. Demontiero O, Vidal C, Duque G. Aging and bone loss: new insights for the clinician. Ther Adv Musculoskelet Dis. 2012 Apr;4(2):61-76. doi: 10.1177/1759720X11430858.
9. Mehta S, Rohinikumar S, Rajendra Prabhu A, Nesappan T, Veeraraghavan VP, Eswaramoorthy R. Correlation between CT - derived bone density and optimal bone densities acquired from CBCT scans. Bioinformation. 2023 Apr 30;19(4):495-498. doi: 10.6026/97320630019495.
10. Stoilov M, Shafaghi R, Stoilov L, Stark H, Marder M, Enkling N, Kraus D. Influence of Drilling Protocol on Primary Implant Stability Depending on Different Bone Qualities and Implant Macro-Designs, Lengths, and Diameters. J Funct Biomater. 2025 Aug 16;16(8):296. doi: 10.3390/jfb16080296.
11. Petrey JS, Saunders MM, Kluemper GT, Cunningham LL, Beeman CS. Temporary anchorage device insertion variables: effects on retention. Angle Orthod. 2010 Jul;80(4):446-53. doi: 10.2319/070309-376.1.
12. Turkyilmaz I, McGlumphy EA. Influence of bone density on implant stability parameters and implant success: a retrospective clinical study. BMC Oral Health. 2008 Nov 24;8:32. doi: 10.1186/1472-6831-8-32.
13. Turkyilmaz I, Tumer C, Ozbek EN, Tözüm TF. Relations between the bone density values from computerized tomography, and implant stability parameters: a clinical study of 230 regular platform implants. J Clin Periodontol. 2007 Aug;34(8):716-22. doi: 10.1111/j.1600-051X.2007.01112.x.
14. Chen H, Zhou X, Fujita H, Onozuka M, Kubo KY. Age-related changes in trabecular and cortical bone microstructure. Int J Endocrinol. 2013;2013:213234. doi: 10.1155/2013/213234.
15. Farr JN, Khosla S. Skeletal changes through the lifespan--from growth to senescence. Nat Rev Endocrinol. 2015 Sep;11(9):513-21. doi: 10.1038/nrendo.2015.89.
16. M King E, Schofield J. Restoratively driven planning for implants in the posterior maxilla - Part 1: alveolar bone healing, bone assessment and clinical classifications. Br Dent J. 2023 Oct;235(8):585-592. doi: 10.1038/s41415-023-6391-7.
17. Zhou W, Fan S, Cafferata EA, Shen Y, Wu Y. Bone Quality in Resorbed Posterior Maxilla Affects Osteogenesis After Sinus Floor Augmentation: A Retrospective Analysis. Int Dent J. 2026 Apr;76(2):109397. doi: 10.1016/j.identj.2025.109397.
18. Lee, D., Kim, J., Kim, H. et al. Clinical outcomes of maxillary sinus augmentation in atrophied posterior maxilla based on residual bone height. Maxillofac Plast Reconstr Surg 47, 26 (2025). https://doi.org/10.1186/s40902-025-00484-7
19. Shah KL, Alanazi FE, Alkhaldi SH, Ghanem N, Alderaan DA, Issrani R. Implant Stability and Elevation Outcomes of Crestal Sinus Floor Elevation with Densah Burs in Sites with Limited Residual Bone Height: A Prospective Clinical Study. J Pharm Bioallied Sci. 2026 Feb;18(Suppl 1):S150-S152. doi: 10.4103/jpbs.jpbs_1572_25.
20. Daniel D, Pande D, Bakshi JHI, Jose J. Biomechanical Evaluation of Zygomatic Implant Versus Pterygoid Implant in Atrophic Maxilla: An In vitro Finite Element Study. J Maxillofac Oral Surg. 2024 Jun;23(3):734-744. doi: 10.1007/s12663-024-02128-1.
21. Agrawal A, Kumar V, Pillai AR. Contribution of masticatory muscle pattern to craniofacial morphology in normal adults: A cross-sectional MRI study. Natl J Maxillofac Surg. 2023 May-Aug;14(2):213-220. doi: 10.4103/njms.njms_473_21.
22. Almohefer SA. Rehabilitating Patients with Atrophic Maxillae via Zygomatic Implants. Clin Cosmet Investig Dent. 2025 Dec 24;17:681-689. doi: 10.2147/CCIDE.S565674.
23. Charde SH, Joshi A, Raut J. A Comprehensive Review on Postmenopausal Osteoporosis in Women. Cureus. 2023 Nov 9;15(11):e48582. doi: 10.7759/cureus.48582.
24. Ena G, Soyfoo M. Postmenopausal Osteoporosis: From Molecular Pathways to Therapeutic Targets-A Mechanism-to-Practice Framework Integrating Pharmacotherapy, Fall Prevention, and Adherence into Patient-Centered Care. J Clin Med. 2025 Dec 23;15(1):102. doi: 10.3390/jcm15010102.
25. Patel KS, Parmar I, Digumarthi UK, Parmar J, Quraishi A, Patel K, Shah A, Shah K, Jani B, Arora MA. Temporary Anchorage Device: A Narrative Review. Cureus. 2025 Apr 2;17(4):e81617. doi: 10.7759/cureus.81617.
26. Sathish, S. (2026). Advances in CBCT for Dental Implantology: Trends in Assessment, Planning, and Monitoring. In: Advanced Imaging and Diagnostic Trends in Oral and Maxillofacial Radiology. Springer, Singapore. https://doi.org/10.1007/978-981-92-0489-2_15
27. Razi T, Niknami M, Alavi Ghazani F. Relationship between Hounsfield Unit in CT Scan and Gray Scale in CBCT. J Dent Res Dent Clin Dent Prospects. 2014 Spring;8(2):107-10. doi: 10.5681/joddd.2014.019.

28. Sathish, S. Sivan classification system for diagnosis of jaw lesions based on visual volumetric analysis of 3-dimensional cone-beam computed tomographic images. Sci Rep 14, 32138 (2024). https://doi.org/10.1038/s41598-024-83974-4
29. Samaranayake L, Tuygunov N, Schwendicke F, Osathanon T, Khurshid Z, Boymuradov SA, Cahyanto A. The Transformative Role of Artificial Intelligence in Dentistry: A Comprehensive Overview. Part 1: Fundamentals of AI, and its Contemporary Applications in Dentistry. Int Dent J. 2025 Apr;75(2):383-396. doi: 10.1016/j.identj.2025.02.005.
30. Zoabi A, Redenski I, Oren D, Kasem A, Zigron A, Daoud S, Moskovich L, Kablan F, Srouji S. 3D Printing and Virtual Surgical Planning in Oral and Maxillofacial Surgery. J Clin Med. 2022 Apr 24;11(9):2385. doi: 10.3390/jcm11092385.
31. Sathish, S. (2026). Cone-Beam Computed Tomography in Dental Diagnostics. In: Advanced Imaging and Diagnostic Trends in Oral and Maxillofacial Radiology. Springer, Singapore. https://doi.org/10.1007/978-981-92-0489-2_6
32. Sivan Sathish, Sivan Unit (SU) for standardization of voxel intensity in CBCT: A multi-vendor, multi-centric validation study, Physica Medica, Volume 148, 2026, 105868, ISSN 1120-1797, https://doi.org/10.1016/j.ejmp.2026.105868.
33. Cao Z, Gao X, Chang Y, Liu G, Pei Y. Improving synthetic CT accuracy by combining the benefits of multiple normalized preprocesses. J Appl Clin Med Phys. 2023 Aug;24(8):e14004. doi: 10.1002/acm2.14004.