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ORIGINAL ARTICLE

INFLUENCE OF BONE QUALITY ON THE PARAMETERS SELECTION FOR A DENTAL IMPLANT DIGITAL SURGICAL GUIDE PLANNING

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Abstract: The integration of digital technologies—from data acquisition to guide fabrication—significantly increases implant placement accuracy and reduces intraoperative risks. This digital integration optimizes workflow, improves communication between specialists, and supports more informed decision making, essential for the long-term success of complex rehabilitations. The aim of this study was to evaluate the influence of bone quality on the selection of parameters such as sleeve type, implant length and diameter selection for a dental implant digital surgical guide planning, with the help of a dedicated software. *Methods*: This study included a sample of 40 clinical situations in which implant rehabilitation was performed using digitally guided surgery techniques. For each clinical case, the three-dimensional diagnostic protocol included intraoral scans (STL files) for accurate reproduction of dental arches and soft tissues, and CBCT examinations (Cone Beam Computed Tomography), with volumetric data exported in standard DICOM format. *Results*: The results of our study across 40 implant sites revealed that D3 bone was the most common classification, and bone density varied widely (ranging from 57 to 1533 HU). Despite this wide variation, we found that bone density did not act as a sole or primary determinant in the 3D digital planning of implant length, diameter, or sleeve type. *Conclusions*: Our study indicates that 3D digital implant planning relies predominantly on anatomical landmarks and prosthetic requirements rather than the raw bone density of the site. Although component selection is not statistically influenced by bone density, this one play a major role in intraoperative stability and the final accuracy of the guide.

Keywords: surgical guide; dental implant; guided surgery; CAD/CAM; CBCT; intraoral scanning; digital planning

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1. Introduction

Digital workflows integrate virtual facial and intraoral models with CBCT imaging, enabling prosthetically driven planning and the development of personalized treatment plans [1]. This approach facilitates guided implant positioning, resulting in superior accuracy and increased predictability of functional and aesthetic outcomes [2,3].

An integrated digital workflow, achieved through the fusion of 3D imaging files and stereolithography files, contributes to the creation of a virtual dental patient, allowing a holistic evaluation of dentofacial anatomy, function, and aesthetics [4]. This integration also enables precise assessment of bone height, density, and volume, along with the identification of critical anatomical structures directly on a personal computer [5].

Furthermore, it allows simultaneous visualization of three-dimensional bone morphology, alveolar ridge soft tissues, and teeth, offering a comprehensive approach to implant planning [2]. This facilitates rigorous preoperative planning, where the ideal implant position is established within the planning software by integrating CT images with the virtual prosthesis [6,7].

This methodology ensures optimal synchronization between surgical and prosthetic components, minimizing errors and optimizing clinical outcomes [4]. The development of precise surgical prototypes and CAD/CAM generated guides using 3D printing transforms virtual plans into tangible tools for surgical execution [8].

This integration of digital technologies—from data acquisition to guide fabrication—significantly increases implant placement accuracy and reduces intraoperative risks [9]. CAD/CAM technologies have also revolutionized prosthetic fabrication, expanding treatment options and significantly improving restoration fit [10,11].

This ensures enhanced predictability of surgical and prosthetic outcomes by optimizing implant placement and reducing complications [12,13]. The development of the virtual patient, through the integration of facial scanning, intraoral digital impressions, and CBCT imaging into a unified virtual coordinate system, enables detailed and personalized prosthetic planning [14].

This digital integration optimizes workflow, improves communication between specialists, and supports more informed decision making, essential for the long-term success of complex rehabilitations.

The aim of this study was to evaluate the influence of bone quality on the selection of parameters such as sleeve type, implant length and diameter selection for a dental implant digital surgical guide planning, with the help of a dedicated software

2. Materials and method

This study included 40 clinical situations in which implant rehabilitation was performed using digitally guided surgery techniques. All patients underwent thorough clinical and paraclinical evaluation. Inclusion criteria targeted adult patients with partial edentulism and with a clinical indication for dental implant treatment.

For each clinical case, the three-dimensional diagnostic protocol included intraoral scans (STL files) for accurate reproduction of dental arches and soft tissues, and CBCT examinations (Cone Beam

Computed Tomography), with volumetric data exported in standard DICOM format.

All files were imported into the specialized digital planning software SKY Pro Guide Plan (Bredent medical GmbH & Co.KG, Senden, Germany). Within the software, surface images (STL) were matched with volumetric images (DICOM).

After integration, segmentation of anatomical risk structures (such as the inferior alveolar canal and maxillary sinus) was performed. Bone mineral density was automatically evaluated by the software at the proposed implant sites, expressed in Hounsfield Units (HU). Bone quality was classified into D1–D4 categories based on mean density.

Subsequently, three-dimensional design of the ideal implant position was performed to ensure predictable primary stability, and implant geometric parameters (diameter and length in millimeters) were selected according to available bone volume. Finally, the software enabled the design of the surgical guides used clinically.

The surgical guides were designed following the steps provided by the SKY Pro Guide Plan software:

1. Importing the DICOM file
2. Editing the DICOM file
3. Importing and editing the intraoral scan
4. Determining the region for implant placement
5. Detecting the mandibular nerves
6. Creating a digital wax up simulating the future prosthetic restoration
7. Selecting and positioning the implant
8. Generating a report on implant type and position
9. Generating undercuts of the intraoral scan for the surgical guide insertion
10. Designing the surgical guide
11. Generating the final guide report

A total of 40 digitally planned implant sites were analyzed. Each record included patient demographics, implant site characteristics (arch, morphological position, bone density in Hounsfield Units), Misch bone classification (D1–D4), implant geometry (diameter and length), and the sleeve type used during guided surgery.

The collected data were exported and statistically processed. Descriptive analysis used mean and standard deviation (SD) for continuous variables, and absolute and percentage frequencies for categorical variables. Pearson's correlation coefficient (r) was used to determine correlations between bone density (HU) and implant dimensions (diameter and length). Comparisons between arches (maxilla vs. mandible) regarding density and implant geometry were performed using the independent samples t test. Statistical significance was set at $p < 0.05$.

3. Results

Across all 40 implant sites, the core planning parameters fell within clinically expected ranges, although bone density showed notably high variability compared to the tightly clustered implant dimensions (Table 1).

Table 1. Descriptive statistics of bone density and implant geometry.

Parameter	Min	Max	Mean ± SD
Mean Density (HU)	57	1533	598.15 ± 329.67
Implant Diameter (mm)	3.0	4.5	3.66 ± 0.33
Implant Length (mm)	8.0	14.0	11.55 ± 2.05

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Bone density ranged widely—from 57 HU to 1533 HU—while implant diameters were concentrated in a narrow interval (SD only 0.33 mm). This suggests that diameter selection is relatively standardized regardless of bone quality.

When bone density values were translated into the Misch classification system, nearly half of the sites fell into the D3 category, representing a thinner porous cortical crest and fine trabecular bone.

Table 2. Distribution of bone quality classes (D1–D4) Distribution of bone quality classes (D1–D4).

Class	n	%
D1	1	2.5
D2	12	30.0
D3	17	42.5
D4	10	25.0

D3 bone is the predominant type in this cohort (42.5%), followed by D2 (30.0%) and D4 (25.0%). Only a single site qualified as D1 (very dense cortical bone). A quarter of sites presented with D4 (low-density) bone, which is clinically relevant for primary stability considerations.

Two sleeve sizes were used — Sleeve 4 (24 sites) and Sleeve 6 (16 sites). The average bone density was slightly higher for Sleeve 6, but the difference is not meaningful.

Table 3. Bone density by sleeve type.

Sleeve	n	Mean (HU)	Std	Median
4	24	567.1	292.0	536.0
6	16	644.8	384.7	554.0

With a Pearson correlation was r = 0.12 and ANOVA p-value of 0.47, there is no statistically significant relationship between bone density and sleeve selection.

Pearson correlation tests confirmed that bone density also did not significantly influence implant dimension selection, neither diameter nor length.

Table 4. Bone density by sleeve type.

Correlation	r (Pearson)	p	n
HU vs Diameter	0.198	0.220	40
HU vs Length	−0.099	0.541	40

Significant differences were found when implant sites were divided by arch (Table 5).

Table 5. Comparison between maxilla and mandible.

Parameter	Mandible (N=12)	Maxilla (N=28)	p-value
Mean Density (HU)	795.08 ± 286.69	513.75 ± 314.45	0.011
Mean Diameter (mm)	3.79 ± 0.26	3.61 ± 0.34	0.097
Mean Length (mm)	10.67 ± 1.78	11.93 ± 2.07	0.071

Bone density was significantly higher in the mandible (p = 0.011). However, implant diameter and length did not differ significantly between arches (p > 0.05).

Table 6. Comparison between maxilla and mandible.

Sleeve	Mandible	Maxilla
4	5 (20.8%)	19 (79.2%)
6	7 (43.8%)	9 (56.2%)

Sleeve 4 was predominantly used in the maxilla (79.2%). Sleeve 6 had a more balanced distribution but still favored the maxilla.

Table 7. Sleeve size distribution by region.

Sleeve	Anterior	Posterior
4	3 (12.5%)	21 (87.5%)
6	0 (0.0%)	16 (100.0%)

All Sleeve 6 cases were in the posterior region. Sleeve 4 also appeared mainly posteriorly (87.5%), with only 3 anterior cases.

Table 8. Sleeve size distribution by bone class.

Sleeve	D1	D2	D3	D4
4	0 (0.0%)	4 (16.7%)	15 (62.5%)	5 (20.8%)
6	1 (6.2%)	3 (18.8%)	10 (62.5%)	2 (12.5%)

D3 was the dominant bone class for both sleeves (62.5%). Sleeve 4 was more frequently associated with D4 bone.

Table 9. Sleeve size vs. implant diameter.

Sleeve	3.0	3.5	4.0	4.5
4	1 (4.2%)	15 (62.5%)	7 (29.2%)	1 (4.2%)
6	2 (12.5%)	7 (43.8%)	7 (43.8%)	0 (0.0%)

Sleeve 4 strongly favored 3.5 mm implants. Sleeve 6 showed a balanced distribution between 3.5 mm and 4.0 mm.

Table 10. Mean bone density by sleeve type.

Sleeve Type	Cases	Mean HU	Min HU	Max HU
Sleeve 4	30	431.10	57	976
Sleeve 6	10	612.80	263	976
Overall Mean	40	476.53	57	976

3.1 Representative Case

For site 1.5, the intraoral scan and CBCT were aligned, a digital wax up was created, and the appropriate implant was selected. The final guide included mesial and distal tooth support, a mucosal support area, and an occlusal verification window.

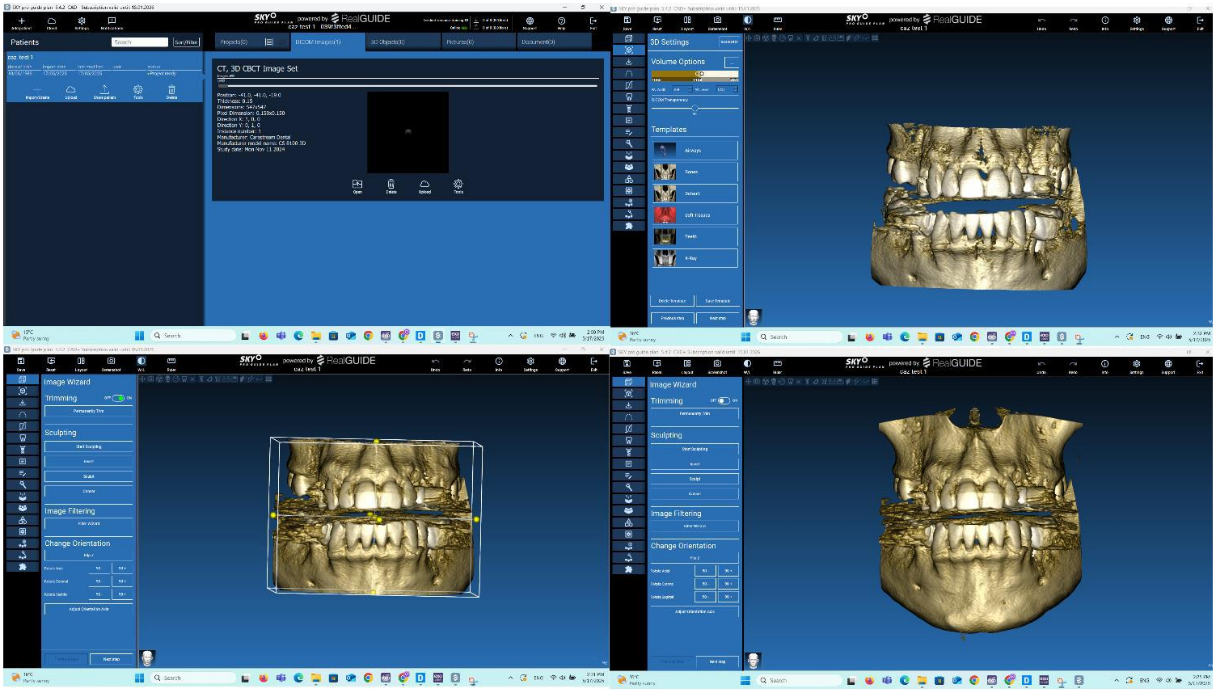


Figure 1. Importing and editing the DICOM files.

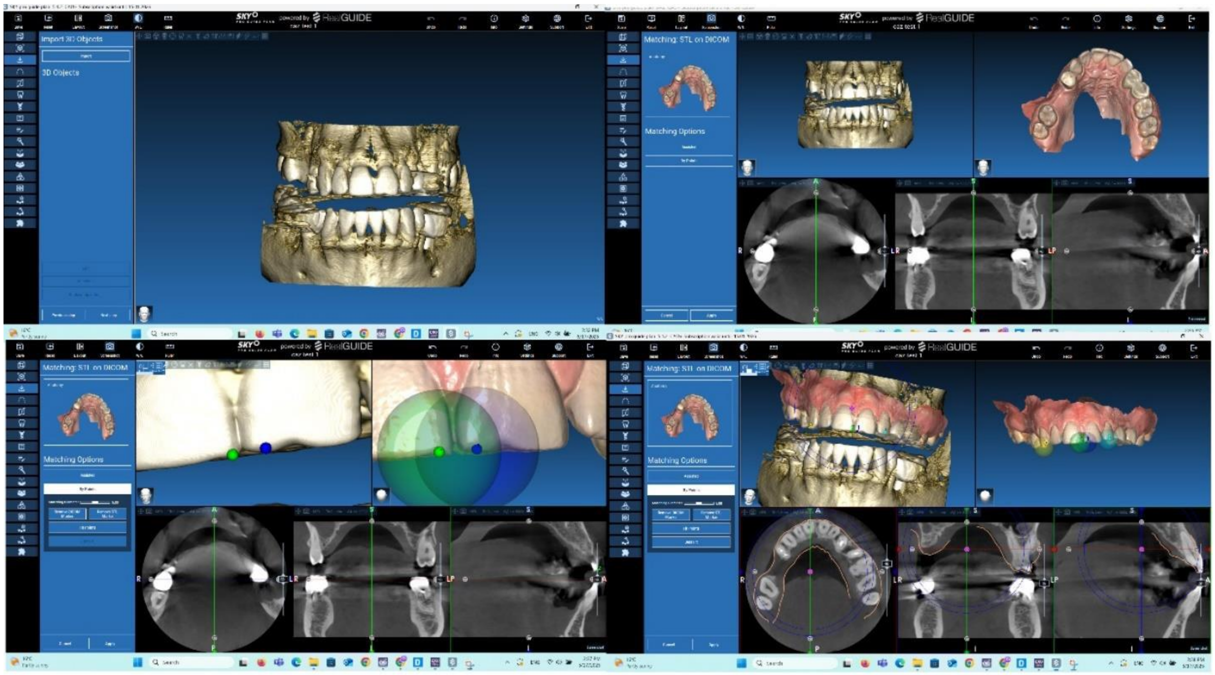
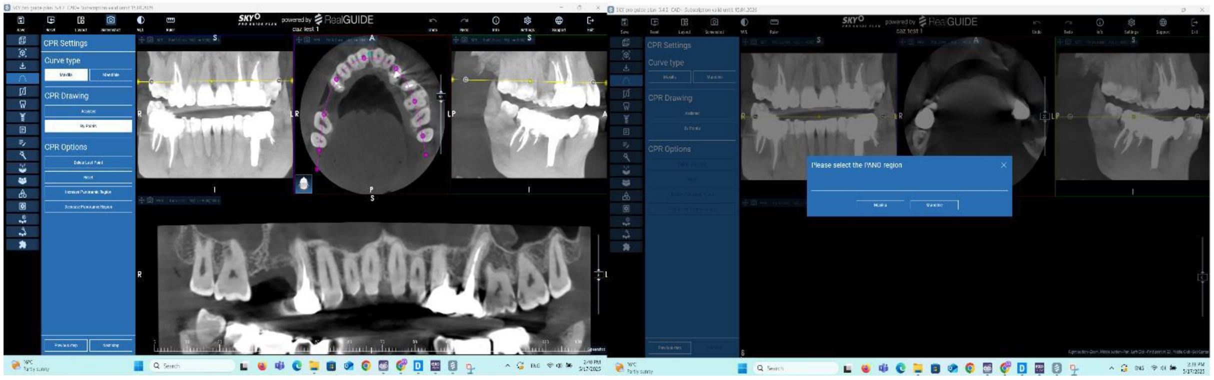


Figure 2. Importing and matching the intraoral scan with the DICOM.



Please select the PANO region

Figure 3. Determining the region for implant placement.

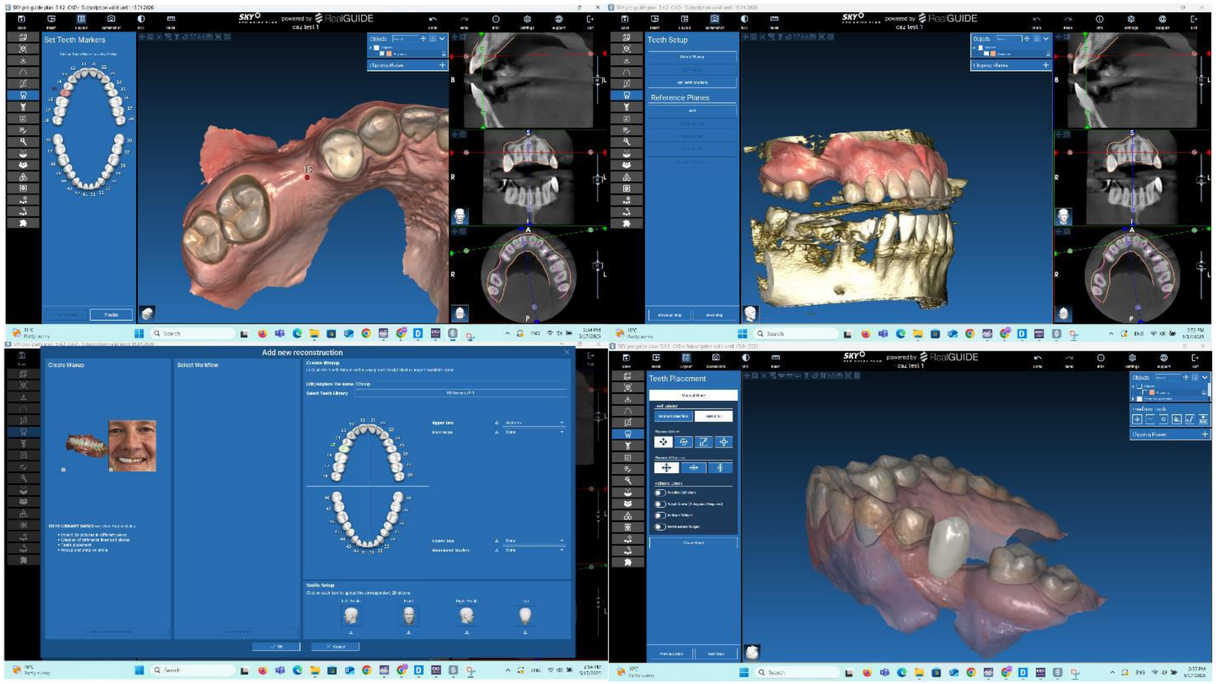


Figure 4. Creating a digital wax up simulating the future prosthetic restoration.

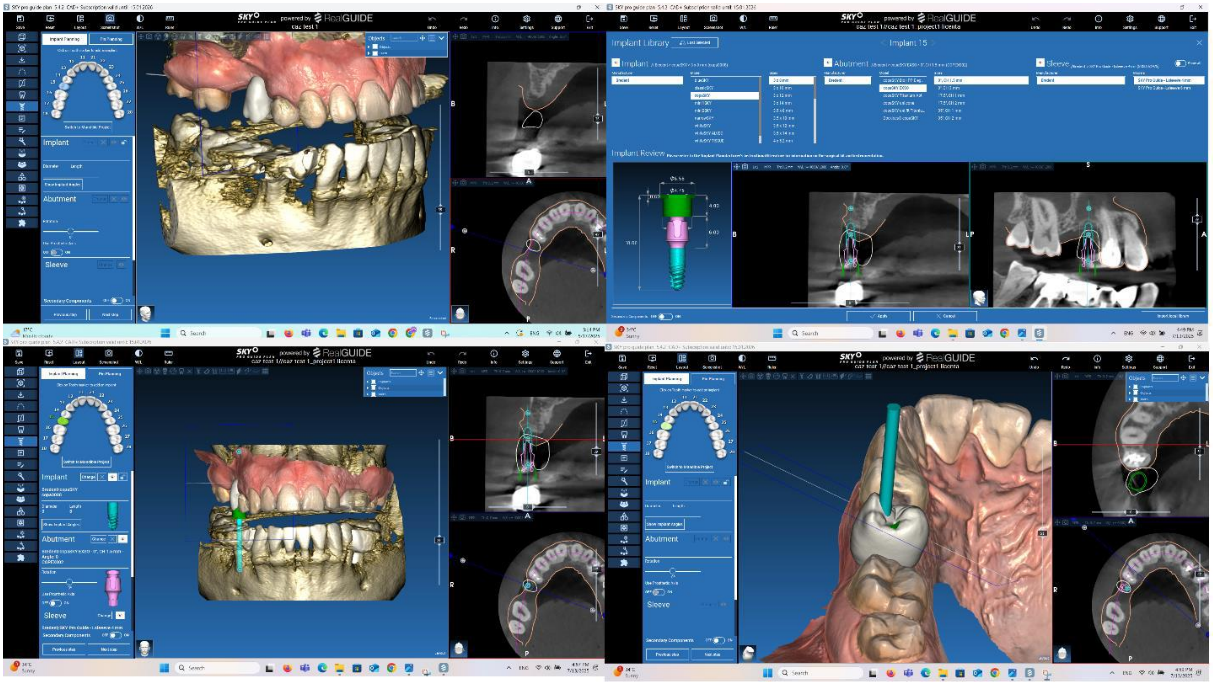


Figure 5. Selecting and positioning the implant.

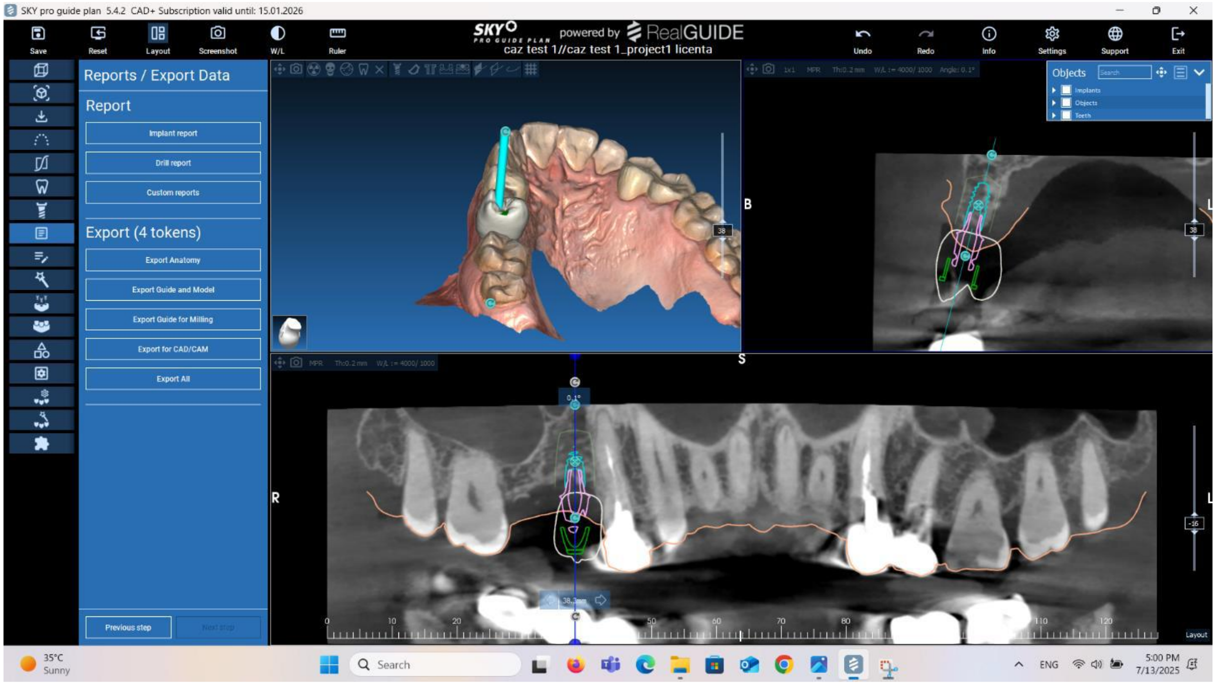


Figure 6. Generating a report on implant type and position.

Figure 7. Generating undercuts of the intraoral scan for the surgical guide insertion.

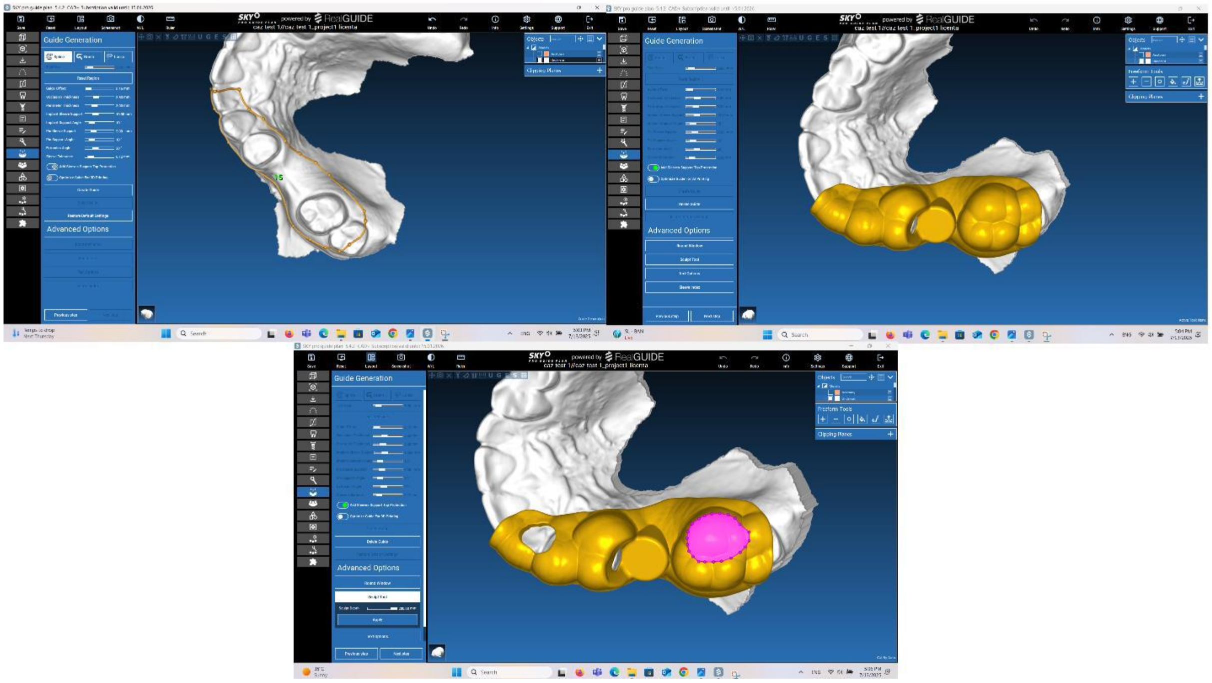


Figure 8. Designing the surgical guide.

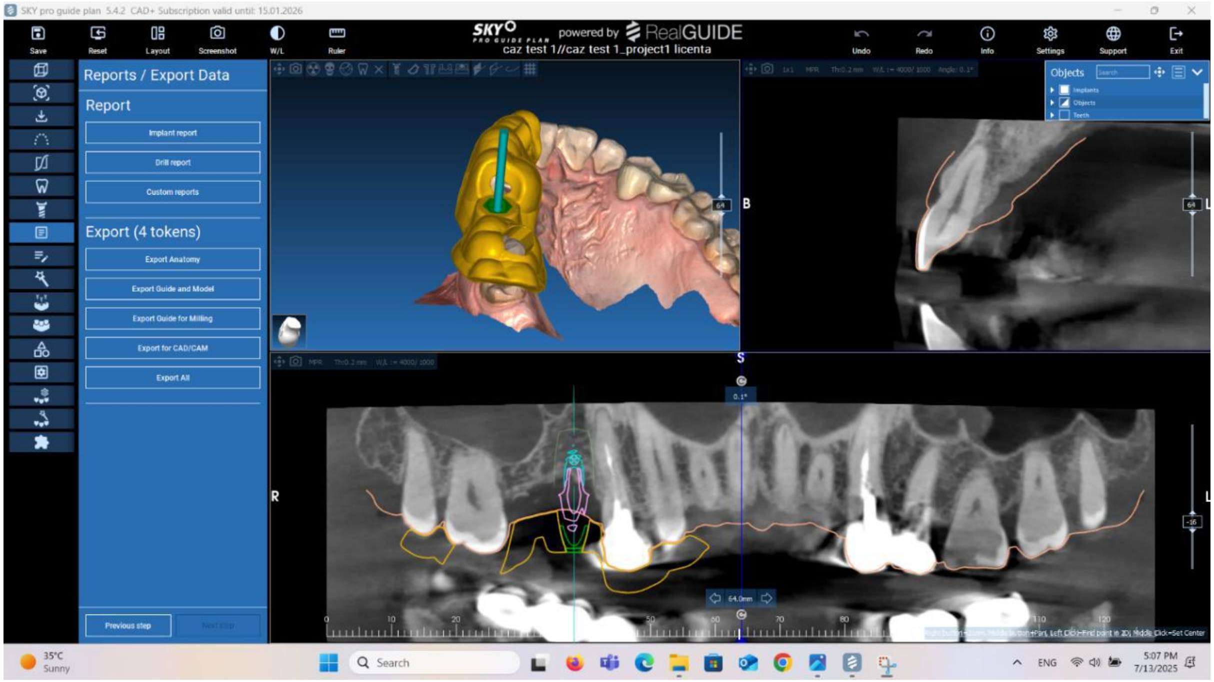


Figure 9. Generating the final guide report.

4. Discussion

The results of our study across 40 implant sites revealed that D3 bone was the most common classification, and bone density varied widely (ranging from 57 to 1533 HU). Despite this wide variation, we found that bone density did not act as a sole or primary determinant in the 3D digital planning of implant length, diameter, or sleeve type.

In contrast, the literature emphasizes that while planning may rely on anatomical and prosthetic criteria, clinical success is heavily dependent on how the surgical guide interacts with this variable bone substrate. The stability of the guide within the oral cavity is directly influenced by the local bone quality and quantity, as well as the surgeon's handling of the device [15]. Furthermore, in cases of low density—such as the predominant D3 bone in our cohort—the intraoral stability of the guide can be compromised by the tissue's low resistance to initial drilling forces [16]. This suggests that even if the clinician does not strictly base dimensional planning on HU density, they must anticipate an increased risk of intraoperative micromovements in less dense bone.

Another key finding in our study was that sleeve type selection was not dictated by bone density but appeared more closely tied to anatomical location—particularly the arch and anterior/posterior position.

This anatomy-driven approach is highly relevant when correlated with literature data regarding accuracy. Shi et al. [17] demonstrated that the distance between the guide sleeve and the bone, as well as the sleeve material, significantly influenced the final accuracy of implant positioning. Therefore, our clinical decision to adapt the sleeve based on the anatomical zone (which often dictates available space and gingival height) is supported by the need to reduce leverage and deviations during drill insertion.

In our study cohort, we observed a notable trend toward standardization regarding implant diameter, with most cases clustering around 3.5 mm, regardless of the underlying bone density.

While this standardization simplifies the surgical protocol, the literature warns that actual surgical execution can introduce inaccuracies that cannot be controlled by design alone. Apical deviations are generally more pronounced than cervical ones, and implants often tend to be positioned too superficially [18]. This aggravation of errors at the apical level requires heightened caution near critical anatomical structures [19]. Additionally, because standardized diameters were predominantly used, attention must be paid to the macro-design of the chosen implant: implants with a rounded apical design can be more easily deflected by dense bone or cortical walls, unlike those with a more aggressive apical thread [20].

Our finding that 3D digital planning in this cohort relies on a combination of anatomical and prosthetic factors rather than bone density alone must be integrated into the broader context of "cumulative errors" described in the literature.

The final accuracy of implant insertion does not depend solely on this smooth digital planning and guide design, but also on a multitude of external factors:

- Data and Software Errors: Limited CBCT resolution or patient movement[21] , metal artifacts, DICOM-to-STL overlapping errors [22], and segmentation errors [23] can all distort the initial design.

- Manufacturing Errors: 3D printing technology (SLA vs. DLP) [24], the printing build angle [25], printing materials, and slicing methods [26; 27] can cause guide deformation.
- Clinical and Human Errors: Patient mouth-opening limitations [28], lack of stability in tooth-supported guides [29], or debris in the implant osteotomy [30] can all generate clinical deviations.

All these weak links can propagate throughout the entire process [31, 32, 33], potentially leading to deviations exceeding 2 mm. Such deviations are considered clinically significant and capable of compromising prosthetic success or the integrity of anatomical structures [34,35]. Thus, the operator's skill level remains decisive in monitoring and verifying each step to counteract these technological limitations [36, 37].

5. Conclusions

Our study indicates that 3D digital implant planning relies predominantly on anatomical landmarks and prosthetic requirements rather than the raw bone density of the site.

Although component selection is not statistically influenced by bone density (predominantly D3 in our study), it plays a major role in intraoperative stability and the final accuracy of the guide.

To ensure full clinical success and avoid critical deviations, the surgeon must be aware of and control the chain of cumulative errors inherent in digital technologies.

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Author contributions

Authors read and approved the final manuscript. All authors have equally contributed to this work.

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Conflict of interest statement

The authors declare no conflicts of interest concerning this study.

Data availability statement

Will be provided on request.

Ethics statement

Approved by the Scientific Ethics and Deontology Commission of the University of Medicine and Pharmacy of Craiova (approval data no. 83 / 19.02.2024).

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