Computed tomographic characterization of mini-implant placement pattern and maximum anchorage force in human cadavers

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Introduction: The purpose of this investigation was to characterize the placement pattern and factors influencing the primary stability of mini-implants in human cadavers. The factors studied were mini-implant length, placement depth, bone density, and bone type. Methods: Sixty standard mini-implants (6, 8, and 10 mm; 20 of each size) were placed into the maxillas and mandibles of 5 fresh human cadavers. Computed tomography imaging was used to measure the placement pattern, bone density, and thickness surrounding each device. The mini-implants were subsequently subjected to increasing tensile forces (pull-out force) until failure, and the maximum mechanical anchorage force of each was recorded with a dynamometer. A statistical model was realized by using MATLAB version 7.5.0 with Statistics Toolbox 7 (MathWorks, Natick, Mass) including the maximum anchorage force, mini-implant length, bone type, placement depth, and density surrounding each section of the mini-implant. Results: Placement depth was strongly dependent on mini-implant length: 15% of the 6-mm implants failed to anchor their parallel sections into cortical bone, but 95% of the 10-mm mini-implant parallel sections penetrated beyond the buccal cortical bone; all 20 tips of the 6-mm mini-implants (100%) reached cancellous bone, whereas 75% of the 10-mm implants penetrated both cortical plates, reaching the lingual cortical bone. Longer mini-implants were associated with greater incidences of sinus and bicortical perforations. The correlation coefficients between the initial maximum mechanical anchorage force and the studied factors were as follows: bone density and placement depth combined (r = 0.65, P < 0.001), mini-implant length (r = 0.45, P = 0.004), bone density (r = 0.42, P = 0.007), and placement depth (r = 0.29, P = 0.06). Conclusions: During mini-implant length selection, the clinician should consider the important trade-off between anchorage and risk of placement complications or damage to the tissues. Longer mini-implants enable more anchorage; however, they are associated with a higher risk of damage to neighboring structures. Placement depth and bone density at the site of mini-implant placement are the best predictors of primary stability. (Am J Orthod Dentofacial Orthop 2011;140:356-65)
compared 17 studies assessing mini-screw failure rates and estimated an average rate of 16.4% by meta-analysis. Other recent studies have analyzed mini-implants in relation to factors such as implant type, cortical bone density, bicortical placement, cortical thickness, and maximum anchorage force. Nevertheless, the strong interdependence among these variables might obfuscate conclusions when analyzed individually. As a result, there are multiple conflicting theories pertaining to the key determinants of mini-implant stability. At present, there is a lack of comprehensive and well-controlled studies examining all of these factors simultaneously. Furthermore, no studies analyzing maximum anchorage force were done with human subjects.

In this study, a multifactorial approach with computed tomography (CT) was used to analyze the placement pattern and initial mechanical anchorage force of mini-implants in human cadavers. This unique approach allowed us to characterize mini-implant placement patterns in relation to relevant bone architecture and establish, for the first time, the correlation between initial mechanical anchorage force and bone density, bone thickness, and implant length.

**MATERIAL AND METHODS**

Five unembalmed human cadavers were obtained by donation to the Virginia State Anatomical Program. Study approval was obtained by the Eastern Virginia Medical School Institutional Review Board, #09-06NH-0146. Only cadavers with posterior teeth and no postmortem processing of the tissues were included in the study. The average age of the cadavers was 87 years old (SD, ± 5 years); 2 were male, and 3 were female. Soft-tissue resections of the orobuccal tissues were performed to facilitate accurate and reproducible placement of the mini-implants. All dental restorative materials on the cadaver teeth that might interfere with the x-ray transmissions used by CT imaging were removed with a dental drill.

Twelve thread-forming 1.8-mm diameter mini-implants (IMTEC, 3M Unitek, Monrovia, Calif) were placed into the buccal alveolar bone of each cadaver by using an IMTEC Ortho LT driver (3M Unitek)28; 6 were placed into maxillary buccal alveolar bone (Fig 1, B), and the other 6 were placed into mandibular buccal alveolar bone (Fig 1, C), for a total of 60 mini-implants placed in the jaws of all 5 cadavers. The mini-implants were divided into 3 identifiable regions, from tip to head, that compose their length: (1) a conical tapered section designed to self-tap and drill the bone, (2) a cylindrically shaped parallel section designed to anchor into the bone, and (3) an unthreaded head region designed as an anchorage point (Fig 1, A). An equal number of 6-, 8-, and 10-mm implants were used (20 of each length) and distributed across the 60 locations as shown in Figure 2.

All mini-implants were placed by the same certified and experienced orthodontist (J.M.R.) in accordance with the manufacturer’s guidelines. In the case of excessive resistance to manual placement, pilot holes were made with a slow-speed straight handpiece at 800 rpm by using a 1-mm diameter hand piece 35 carbide bur.
The pilot hole should not affect the primary stability of the implant. Soft-tissue thickness was verified with a measuring probe and was found to be less than 1.5 mm at all placement sites. (The manufacturer recommends a soft-tissue thickness of less than 1.5 mm when using the shortest [6 mm] mini-implant; all placement sites met this criterion.) The mini-implants were placed perpendicular to the buccal bone and between the roots of the teeth. A diagram of mini-implant placement into alveolar bone is provided in Figure 3, where the soft tissues, and cortical and cancellous bones are clearly depicted.

High-resolution CT images of each head were taken before and after the mini-implants were placed by using a LightSpeed 64 slide scanner (General Electric, Milwaukee, Wis) with sections spaced 0.625 mm apart. Characterization of the bone and placement pattern of each mini-implant was achieved by using View Personal (version 1.0.10.0; Synedra Information Technologies, Innsbruck, Austria) with the viewing scale set to 2 cm. More specifically, the bone type, thickness, and density surrounding the tip and parallel sections of the mini-implant were measured as illustrated in Figure 4 as a representative example. Damage to the neighboring structures was also assessed: root damage, and sinus and bicortical perforation. All measurements were repeated 3 times by the same person (G.L.) to prevent intraoperator variability.

Maximum anchorage force for each mini-implant was measured by using the custom tensile-strength apparatus shown in Figure 5. The cadaver specimens were
secured with an adjustable vise, and screws were placed at multiple points into the temporal bones to prevent slippage and rotation while an 0.18-in nickel-titanium wire connected the head of the mini-implant to a dynamometer (GS digital force gauge; Dillon, Avery Weigh-Tronix, Montreal, Canada) with a maximum measurable force of 500 N and accuracy of 0.2 N. A slowly increasing tensile force was then applied to each mini-implant until failure, and then it was pulled out of the bone. The maximum initial anchorage force was recorded at this point. To mimic actual clinical procedures as much as possible and to standardize the process across all 60 mini-implants, the force was applied in a direction parallel to the occlusal plane. The entire apparatus was developed and tested on fresh pig heads before the actual human experimentation. (The apparatus that measured the maximum anchorage force of mini-implants was developed at McGill University with the help of Gary Savard from the Department of Mechanical Engineering.) All placement sites met these criteria. Materials, construction, and design were made to minimize elasticity in the setup and ensure a static tensile force between the mini-implant and the dynamometer.

Statistical analysis

The measurement data were used to construct a statistical model in MATLAB version 7.5.0 with Statistics Toolbox 7 (MathWorks, Natick, Mass), including the maximum anchorage force, mini-implant length, bone type, placement depth, and density surrounding each section of the mini-implant. The model was used to determine the correlation coefficients between these variables. The statistical significance level was set at $P < 0.05$.

RESULTS

The results of this study are divided into 2 parts: analysis of the placement pattern (location of the mini-implants as it relates to bone architecture and assessment of damage to neighboring structures) and...
determination of the initial maximum anchorage force and its relationship to implant length, placement depth, and bone density.

CT images were used to localize the tip and parallel section of each mini-implant into 1 of 4 layers (Fig 3): soft tissue (gingiva), buccal cortical bone, cancellous bone, and lingual cortical bone. The distribution of the mini-implant tips and parallel sections in the 4 layers are plotted in Figure 6 for each implant length (6, 8, and 10 mm). The degree of implant penetration strongly depended on implant length: 15% of the 6-mm implants failed to anchor their parallel sections into cortical bone, whereas 95% of the 10-mm mini-implant had tips located in the pneumatized sinus where cancellous bone was previously present. Mini-implant placement into soft tissue (A), buccal cortical bone (B), cancellous bone (C), and lingual cortical bone (D).

The CT images were also used to identify damage caused by the mini-implant to adjacent anatomic structures including (1) perforation into tooth root structures (Fig 7, A), (2) bicortical placement and perforation (Fig 7, B), and (3) penetration into sinuses (Fig 7, C). The incidence of each is reported in Table 1 by group of implant length. Of the 60 mini-implants, 32 (53%) were placed less than 1 mm from an adjacent tooth root structure. Moreover, 25% of the 6-mm mini-implants, 30% of the 8-mm mini-implants, and 15% of the 10-mm mini-implants perforated directly into root structures. As for damage to adjacent anatomic spaces, none of the 6-mm implants, 10% of the 8-mm implants, and 15% of the 10-mm implants penetrated the maxillary sinus, and 30% of the 8-mm implants and 75% of the 10-mm implants reached the lingual cortical bone (bicortical placement). Of those bicortically situated, 1 of the 8-mm mini-implants and 6 of the 10-mm mini-implants perforated entirely through the lingual cortical plate, either in the palatal region, the nasal cavity, or the lingual area.

The static tensile force at which each mini-implant failed, hereinafter called the maximum anchorage force,
was measured by a dynamometer. Several confounding factors were encountered during the experiment: 7 mini-implant heads were damaged or broken during the pull-out tests, and cord slippage or instrumentation failure was encountered in 13 pull-out tests. Since the primary end point of the experiment was maximum anchorage force, these events were disqualified by definition and were not analyzed.

A boxplot of the maximum anchorage force is shown in Figure 8 for each mini-implant length. The median force increased from 128 N to 160 N and to 211 N for the 6-, 8-, and 10-mm mini-implants, respectively. Therefore, there was a significant difference between the anchorage force of the 6-mm and the 10-mm implants (P < 0.05). Although mini-implant length is a logical determinant of anchorage (especially since the placement pattern analysis showed that longer implants tended to penetrate deeper into the bone), the roles of bone density and thickness might be just as important. The correlation coefficients between maximum anchorage force and bone thickness improved when both the cortical and the cancellous bones were considered. Furthermore, inclusion of both the parallel and the tapered sections of the mini-implant increased the correlation. Although the implant length provides a correlation to maximum anchorage force of r = 0.45 (P = 0.004), a much stronger relationship was found with bone density and thickness. The strongest correlation (r = 0.65, P < 0.001) was when the bone density and thickness of the parallel and tapered sections were considered simultaneously.

DISCUSSION

An unavoidable limitation of any mini-implant pull-out study is that it precludes the use of living subjects. Thus far, dogs have been used as an alternative; however, extrapolation of these findings to humans is limited because of differences in anatomy, bone

**Table I.** Mini-implant placement pattern with respect to average distance between implant and root structures, incidence of penetration into the root and sinus, and incidence of bicortical placement

<table>
<thead>
<tr>
<th></th>
<th>6-mm implant (n = 20)</th>
<th>8-mm implant (n = 20)</th>
<th>10-mm implant (n = 20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distance to adjacent root structure</td>
<td>528 μm</td>
<td>441 μm</td>
<td>414 μm</td>
</tr>
<tr>
<td>Incidence of penetration into root structure</td>
<td>5 (25%)</td>
<td>6 (30%)</td>
<td>3 (15%)</td>
</tr>
<tr>
<td>Incidence of bicortical placement</td>
<td>0 (0%)</td>
<td>6 (30%)</td>
<td>15 (75%)</td>
</tr>
<tr>
<td>Incidence of sinus perforation</td>
<td>0 (0%)</td>
<td>2 (10%)</td>
<td>3 (15%)</td>
</tr>
</tbody>
</table>

**Fig 7.** Mini-implant placement into: A, adjacent root structure; B, bicortically; and C, maxillary sinus.

**Fig 8.** Boxplot of maximum anchorage force for 6-, 8-, and 10-mm mini-implants. Note that the 95% CIs between the 6-mm and 10-mm implants do not overlap.
by securing its threads along the bone.\textsuperscript{28} In this study, is designed to provide most of the mechanical anchorage of the mini-implant were considered (Fig 6). In general, the bone depth of both the parallel section and the tip placement) and (2) the age of available cadavers is usually advanced (average age in this study, 87 years), and bone remodeling limits the analysis exclusively to primary cadavers and living patients. The use of cadavers entails maximum anchorage will be exactly the same in plants.\textsuperscript{32,33} Nevertheless, it is not clear whether the most realistic medium for mini-implant pull-out analysis human cadavers were used to mitigate those concerns. Human bone, dentition, and soft tissue provide the most realistic medium for mini-implant pull-out analysis and have been used in similar studies of dental implants.\textsuperscript{32,33} Nevertheless, it is not clear whether the maximum anchorage will be exactly the same in cadavers and living patients. The use of cadavers entails several important restrictions: (1) the absence of bone remodeling limits the analysis exclusively to primary stability (initial mini-implant stability immediately after placement) and (2) the age of available cadavers is usually advanced (average age in this study, 87 years), and bone composition and other anatomic changes might be important.\textsuperscript{34} Kingsmill and Boyd\textsuperscript{35} found that apparent mandibular bone density increases significantly with age, especially for dentate people. Furthermore, in this study, pneumatization of the maxillary sinus was observed in all 5 cadavers, leading to sinus perforation in 5 of the 60 mini-implant placements. Despite this, recently dead cadavers provided an excellent medium for the study of mini-implants, notwithstanding their limitations.

The threaded part of the mini-implant consists of a tapered section and a parallel section (Fig 1, A), which fulfill 2 specific roles: the tapered section facilitates the entry of the mini-implant by self-threading the bone (self-drilling and self-tapping), and the parallel section is designed to provide most of the mechanical anchorage by securing its threads along the bone.\textsuperscript{28} In this study, the bone depth of both the parallel section and the tip of the mini-implant were considered (Fig 6). In general, longer implants had a greater amount of the parallel section embedded into bone. The parallel sections in 15\% of the 6-mm mini-implants had no penetration of the buccal cortical bone, and 40\% had incomplete penetration. A similar observation was made by Tseng et al,\textsuperscript{14} who suggested that the depth of mini-implant placement is more important than its location or length, and recommended a minimum placement depth of 6 mm. On the other hand, 95\% of the 10-mm implants fully penetrated the buccal cortical bone. Since the amount of parallel section embedded into bone directly correlates to the mechanical anchorage (discussed in detail below), longer implants afford more mechanical anchorage. Unfortunately, the increased penetration of longer implants is also associated with a higher risk of damage to neighboring structures (Table I). Lim et al\textsuperscript{8} aptly noted that some clinicians use long miniscrews for stability at the expense of an increased risk of damage. In this study, the average distance of the mini-implants, regardless of their length, was less than 1 mm from a root structure; a distance in con areas should have a safety clearance of at least 2 mm between the miniscrew and the dental root to prevent damage to the dentition, especially in the case of mini-implant migration on application of orthodontic forces. The distance between the mini-implant and the root structure decreases as the mini-implant length increases. Longer mini-implants had a higher incidence of sinus damage and perforation of the lingual cortical plate. No association was found between the incidence

### Table II. Correlation coefficients between maximum anchorage force and various combinations of placement depth, bone density, and implant length

<table>
<thead>
<tr>
<th>Parallel section</th>
<th>Tapered section</th>
<th>Correlation (R)</th>
<th>95% CI</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-implant</td>
<td>x</td>
<td>0.45</td>
<td>0.16–0.67</td>
<td>0.004</td>
</tr>
<tr>
<td>$\rho_{\text{cortical}}$</td>
<td>NA</td>
<td>0.42</td>
<td>0.13–0.65</td>
<td>0.007</td>
</tr>
<tr>
<td>$\rho_{\text{cancellous}}$</td>
<td>NA</td>
<td>0.36</td>
<td>0.06–0.61</td>
<td>0.021</td>
</tr>
<tr>
<td>$\text{ID}_{\text{cortical}}$</td>
<td>x</td>
<td>0.26</td>
<td>−0.06–0.53</td>
<td>0.110</td>
</tr>
<tr>
<td>$\text{ID}_{\text{cancellous}}$</td>
<td>x</td>
<td>0.24</td>
<td>−0.08–0.51</td>
<td>0.137</td>
</tr>
<tr>
<td>$\text{ID}<em>{\text{cortical}} + \text{ID}</em>{\text{cancellous}}$</td>
<td>x</td>
<td>0.27</td>
<td>−0.04–0.54</td>
<td>0.087</td>
</tr>
<tr>
<td>$\text{ID}_{\text{cortical}}$</td>
<td>x</td>
<td>0.23</td>
<td>−0.09–0.50</td>
<td>0.161</td>
</tr>
<tr>
<td>$\text{ID}_{\text{cancellous}}$</td>
<td>x</td>
<td>0.21</td>
<td>0.01–0.37</td>
<td>0.177</td>
</tr>
<tr>
<td>$\text{ID}<em>{\text{cortical}} + \text{ID}</em>{\text{cancellous}}$</td>
<td>x</td>
<td>0.29</td>
<td>−0.02–0.55</td>
<td>0.066</td>
</tr>
<tr>
<td>$\text{ID}<em>{\text{cortical}} + \rho</em>{\text{cortical}}$</td>
<td>x</td>
<td>0.49</td>
<td>0.21–0.69</td>
<td>0.002</td>
</tr>
<tr>
<td>$\text{ID}<em>{\text{cortical}} + \rho</em>{\text{cancellous}}$</td>
<td>x</td>
<td>0.38</td>
<td>0.07–0.61</td>
<td>0.017</td>
</tr>
<tr>
<td>$\text{ID}<em>{\text{cortical}} + \text{ID}</em>{\text{cancellous}} + \rho_{\text{cortical}}$</td>
<td>x</td>
<td>0.55</td>
<td>0.29–0.74</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$\text{ID}<em>{\text{cortical}} + \rho</em>{\text{cortical}}$</td>
<td>x</td>
<td>0.41</td>
<td>0.11–0.64</td>
<td>0.008</td>
</tr>
<tr>
<td>$\text{ID}<em>{\text{cortical}} + \rho</em>{\text{cancellous}}$</td>
<td>x</td>
<td>0.44</td>
<td>0.15–0.66</td>
<td>0.004</td>
</tr>
<tr>
<td>$\text{ID}<em>{\text{cortical}} + \rho</em>{\text{cortical}} + \rho_{\text{cancellous}}$</td>
<td>x</td>
<td>0.65</td>
<td>0.42–0.80</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Inclusion of data for the parallel and tapered sections of the mini-implants is indicated for each analysis (r, included). Note that ID only includes bone surrounding the mini-implant (if the mini-implant did not completely penetrate a section of bone, only the portion of bone containing the implant was considered). The correlation coefficient values range from 0 (no correlation) to 1 (perfect direct correlation).

*ID*, Insertion depth; $\rho$, bone density; $L$, implant length; NA, not applicable.
of direct perforation into root structure and the implant length. Minimal sinus perforation might not be harmful; Ardekian et al\textsuperscript{37} found that small perforations (<2 mm) into the maxillary sinus healed by themselves without complication. Moreover, dental root damage induced by mini-implants has demonstrated almost complete repair of tooth and periodontium in 12 weeks after removal of the mini-implant.\textsuperscript{38} Clinicians must therefore be aware of the important trade-off between anchorage into bone and the potential risk of damage when selecting mini-implant length.

In this study, the placement of the mini-implants was based on clinical examination alone. Recent studies with preplacement CT and cone-beam CT imaging have shown improved success and safety of mini-implant placement.\textsuperscript{39,40} Future work should take advantage of these technologies to improve the placement protocol.

Numerous factors have been identified to play important roles in the anchorage of mini-implants\textsuperscript{11-27}; however, the relative importance of each is unclear. In this study, we quantified the relationship between maximum anchorage force and these variables (Table II): implant length (6, 8, or 10 mm), placement depth, bone density and type (cancellous or cortical), and section of the mini-implant (parallel or tapered). The details of this are discussed below. Standardizing to 1.8-mm diameter implants is an important limitation; however, introducing a second variable of width would have unnecessarily complicated the analysis. Nonetheless, future studies should expand the analysis to include various implant diameters.

In contrast to the studies of Lim et al\textsuperscript{8} and Park et al,\textsuperscript{12} the correlation between implant length and maximum anchorage force was found to be statistically significant (r = 0.45, P = 0.004). Intuitively, this result was expected, since longer implants tend to penetrate deeper into the bone, achieving a greater amount of mechanical anchorage.\textsuperscript{14} In a retrospective clinical review, Tseng et al\textsuperscript{14} identified implant length as an important risk factor for stability, although this finding was not statistically demonstrated. A similar study by Chen et al\textsuperscript{15} found a significant difference (P <0.05) between the success rates of 6-mm and 8-mm miniscrews (72.2% and 90.2%, respectively). Mini-implant length therefore appears to be an important factor influencing primary mechanical stability.

Bone placement depth included only bone penetrated by the mini-implant. If a section of bone was partially penetrated, only the depth of placement was considered. This distinction is particularly important, since the degree of mini-implant penetration into the cortical and cancellous bone layers is frequently incomplete (Fig 6).

Although there is a correlation between mini-implant placement depth and maximum anchorage force, the relationship was not strong enough to be statistically significant in our study (P = 0.06–0.18). Penetration into cortical bone showed a slightly higher correlation to anchorage force than did cancellous bone. Considering the placement depth into both cortical and cancellous bone types, and including both sections of the mini-implant, provided the best correlation to high anchorage strength (r = 0.29, P = 0.06). Two similar studies with dogs found regular correlations of r = 0.39, P = 0.02,\textsuperscript{25} and r = 0.44, P = 0.05,\textsuperscript{26} between maximal axial anchorage force and cortical bone thickness. Motoyoshi et al\textsuperscript{41} found that cortical bone thickness was directly proportional to the success rate of mini-implants in a study of 65 orthodontic patients. Wilmes and Drescher\textsuperscript{42} reported that greater placement depth resulted in higher placement torque and thus primary stability. Miyawaki et al\textsuperscript{43} linked a high mandibular plane angle (ie, thin cortical bone) to greater mini-implant mobility and failure rate. Clinically, bicortical placement maximizes bone depth and was found to provide superior anchorage resistance and stability compared with monocortical screws.\textsuperscript{11,20} Qualitatively, and not surprisingly, bone provides a dense medium to anchor mini-implants; the more bone surrounding the implant, the greater the mechanical anchorage.

Considerable variation in bone density was found within and between cadavers (Fig 2). For example, the average cortical bone density of the 5 maxillas was 1084 Hounsfield units with mean intracadaver and intercadaver standard deviations of 213 and 232 Hounsfield units, respectively. There were similar variations in the mandibles.

The current literature contains insufficient information about the effect of bone density on mini-implant stability\textsuperscript{16,17}; however, the great variations in maxillary and mandibular bone densities require further investigation. The correlation between bone density and anchorage force was found to be significant for both cortical (r = 0.42, P = 0.007) and cancellous (r = 0.36, P = 0.02) bone types. This finding identifies the important role of both bone types in mini-implant stability.

Although bone density and placement depth have been analyzed independently, it is their combined effect that determines mini-implant anchorage strength. To include both of these factors into the correlation analysis, the bone density and the placement depth were multiplied along each mini-implant section and bone type. Among all the factors analyzed in this study (Table II), the simultaneous consideration of bone density and placement depth, including both the parallel...
and tapered sections of the mini-implant as well as the cortical and cancellous bone types, provided the highest correlation to maximum anchorage force ($r = 0.65$, $P < 0.001$). Clinically, information about bone thickness and density might provide the strongest predictor of implant stability for any site.

CONCLUSIONS

In this study, we characterized the placement pattern and factors influencing the primary mechanical stability of mini-implants in the buccal bones of mandibles and maxillas of recently dead cadavers. The findings are summarized as follows.

1. Shorter mini-implants (6 mm) tended to have incomplete penetration of the buccal cortical bone.
2. Longer mini-implants tended to penetrate farther into the bone (offering more mechanical anchorage) but were also associated with greater incidences of sinus and bicortical perforations.
3. The most important factors determining maximum mechanical anchorage were found to be (in decreasing order) bone density and placement depth combined, mini-implant length, bone density, and placement depth.

This study helps to demystify the important factors determining primary stability. Proper case selection and planning are fundamental to a successful treatment. The availability of 3-dimensional imaging with CT or cone-beam CT can be used to improve mini-implant placement, stability, and safety.

REFERENCES