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1.1 Using of skeletal anchorage in modern orthodontic treatment

Orthodontic treatment is, as a rule, a long-term process of tooth movement that occurs through remodeling of bone tissue by alternating processes of resorption and apposition. Bone tissue density plays an important role in this process, which has been demonstrated by a considerable number of scientific studies [1, 2, 3].

However, the parameters of bone tissue density depend on many factors, including the patient's age, intake of calcium supplements, hormonal changes, the presence of harmful habits, and even the intestinal microbiota [4, 5, 6]. In this regard, when conducting clinical studies in patients, there is a need to unify the study groups, in particular according to bone tissue density parameters, in order to ensure homogeneity of the study groups and the statistical reliability of the obtained results.

Usually, bone tissue density is assessed using computed tomography (CT) data, with measurements expressed in Hounsfield units (HU) [7]. However, this research method has a number of limitations. First of all, there is a need to comply with the so-called ALARA principle ("as low as reasonably achievable"), that is, to use the most rational radiation dose possible for the patient. This principle is especially relevant for spiral computed tomography scans. Secondly, there is sometimes a need for dynamic monitoring of changes in bone tissue density over short time intervals. For example, this is required during orthodontic tooth movement, the use of mini-implants, or when studying the dynamics of bone tissue recovery after surgical interventions (tooth extraction, socket preservation, cystectomy, bone augmentation) or after the administration of medications.

In such cases, regular monitoring of bone tissue density in an individual or a group of individuals is necessary. These capabilities are provided by a method for determining the relative bone tissue density using various types of 2D digital radiographic examinations (orthopantomograms, periapical radiographs, etc.) with the aid of specialized software, which was proposed in 2016 by Geiger M. et al. [8].

Treatment duration, in turn, together with the parameters of functional and aesthetic rehabilitation, affects the condition of the tooth crowns and roots as well as the periodontal tissues, and also serves as a criterion of patient satisfaction with the chosen rehabilitation algorithm [9, 10]. Prolonged orthodontic treatment increases the risks of dental caries, root resorption, gingival recession, and the development of periodontal diseases [11, 12].

Orthodontic treatment of dentoalveolar anomalies and deformities is associated with the need to provide reliable anchorage or support relative to which tooth movement is performed [13, 14]. Traditional methods of creating orthodontic anchorage based on the use of teeth cannot ensure absolute anchorage at any point in the oral cavity. An alternative solution is the use of mini-implants, which make it possible to obtain stable intraosseous anchorage [15, 16].

An orthodontic mini-implant is an intraosseous implant with a diameter of less than 3.0 mm, used as anchorage in orthodontic treatment due to its primary mechanical stability [17]. Three parts are distinguished in an orthodontic mini-implant: the intraosseous part (threaded portion), the gingival part (neck), and the supragingival part (head). The diameter of the intraosseous part does not exceed 3.0 mm, and depending on the system, its length ranges from 5.0 to 12.0 mm. The neck of the orthodontic mini-implant should be located within the gingival tissues, and in most mini-implant systems its length also varies. The supragingival part of the mini-implant is specifically designed for the fixation of orthodontic components (ligatures, elastics, springs, archwires) and varies among different systems [18].

According to the thread design of the intraosseous part, miniscrews can be divided into mini-implants that require preparation of a bone bed and mini-implants with a self-tapping thread, or so-called “self-drilling” screws [19]. For the former, preparation of a guiding channel with a pilot drill along the entire length of the implant is required, whereas for mini-implants with a self-tapping thread, pilot drilling is limited to the cortical layer only. Mini-implants perform their anchorage function due to primary mechanical stability and do not require osseointegration [20, 21, 22].

In 1997, Kanomi R. described in detail all stages of mini-implant placement, also pointing out several advantages of mini-implants over conventional dental implants [23]. He used microscrews placed between the central incisors of the maxilla and mandible for incisor intrusion, and on both sides of the alveolar process in the regions of extracted premolars of the upper and lower jaws for subsequent retraction of the anterior segment. R. Kanomi applied orthodontic loading to the mini-implants several months after implantation, waiting for osseointegration between the mini-implant and the bone. According to his data, after four months of treatment, intrusion of the lower incisors reached 6 mm, with no evidence of root resorption or pathological changes in the periodontium.

He also mentioned the possibility of using mini-implants for horizontal traction and molar intrusion, as well as for anchorage in distal molar movement. Subsequent publications were devoted to various applications of mini-implants in orthodontic treatment, which over time significantly expanded the indications for their use.

Different authors, in the course of their studies, have used various implantation sites, the main ones being the palate, the palatal slope of the alveolar process of the maxilla, the retromolar area of the mandible, and the buccal cortical plate of both the maxilla and the mandible [24]. Among the important factors that must be considered when selecting an implant site are the anatomy of the soft tissues, interradicular distance, morphology of the maxillary sinus, localization of nerve trunks, buccolingual depth of the bone tissue, and the buccal and lingual thickness of the cortical plate of the alveolar process [25].

P. Poggio et al. conducted a study of 25 tomograms of the maxillae and mandibles of untreated patients to determine the “safe zones” for mini-implant placement [26]. The authors measured interradicular distances in the mesiodistal direction from the canines to the third molars on both the buccal and oral surfaces, as well as the buccolingual thickness of the alveolar processes in the same regions at distances of 2, 5, 8, and 11 mm from the crest of the alveolar ridge.

As a result of the study, the most favorable zones for mini-implant placement in the maxilla were found to be, on the palatal side, the areas between the second premolar and the first molar, and between the first and second molars; on the buccal side, the areas between the canine and the first premolar, and between the first and second premolars. Overall, for the maxilla, the authors concluded that the more mesial and higher the implantation site is located, the safer it is. In the mandible, the authors identified the areas between the first and second premolars and between the first and second molars as safe zones for mini-implant placement.

Based on their interradicular distance measurements, the researchers also proposed a model of an “ideal” mini-implant for skeletal anchorage in orthodontics: with a diameter of 1.2–1.5 mm, a working length of 6–8 mm, and a conical shape.

Chaimanee P. et al. determined safe interradicular zones for mini-implant placement in 60 patients with different types of orthodontic pathology - skeletal Class I, II, and III - using lateral cephalograms and dental periapical radiographs taken with a parallel technique. In all cases, the greatest interradicular distance was found between the second premolar and the first molar in the maxilla, and between the first and second premolars as well as between the first and second molars in the mandible. In particular, in skeletal Class II pathology, greater interradicular distances were observed in the maxilla, whereas in Class III pathology they were observed in the mandible [27].

Fayed M. et al. determined optimal sites for mini-implant placement using cone-beam computed tomography obtained from 100 patients [28]. The authors assessed the thickness of the alveolar process in the maxilla and mandible at different levels, interradicular distances, and the thickness of the cortical plate. According to their findings, the most optimal site for mini-implant placement in the anterior region of the maxilla is the area between the central and lateral incisors, while in the mandible it is between the lateral incisor and the canine at a level 6 mm from the crest of the alveolar process. In the posterior regions of both jaws, the most favorable conditions for mini-implant placement were found between the second premolar and the first molar on the buccal side, and between the first and second molars on the palatal side.

K. K. Garg and M. Gupta, studying the stability of orthodontic mini-implants using computed tomography in a sample of patients who received intraosseous anchorage in different topographic regions and were subjected to different force magnitudes at various initial loading periods, concluded that the greatest mobility of the mini-implant is observed in the region of the head of the device (ranging from 0.728 to 1.0 mm), whereas in the region of the implant apex this value does not exceed 0.349 mm [29]. Unlike conventional dental implants used as intraosseous supports for prosthetic constructions, mini-implants do not remain completely stationary and exhibit a certain degree of displacement. Greater mobility was recorded on the right side of the jaw compared to the left. The constructions were more stable when placed between the first and second premolars than when positioned between the second premolar and the first molar. Orthodontic loading of 150 g in the maxilla and 100 g in the mandible was identified as optimal, and the timing of loading did not significantly affect the subsequent degree of anchorage mobility. Therefore, immediate loading of the miniscrew is considered one of the possible orthodontic options, provided that a sufficient residual clearance of 1.5 mm from the roots of vital teeth and other anatomically significant structures, such as nerve trunks or blood vessels, is ensured.

Mini-implants have been used in the treatment of various dentoalveolar anomalies and deformities [30, 31]. Despite the generally positive characteristics of mini-implants, their interaction with bone tissue has not yet been fully elucidated. The stability of a mini-implant during orthodontic treatment depends on many factors, including implant type, size, surface characteristics, insertion angle, insertion torque, magnitude of the applied orthodontic force, topographic location, soft tissue characteristics, and others [32].

The effectiveness of mini-implants in providing reliable anchorage for tooth movement has been demonstrated in numerous studies [33, 34]. However, the question of how the use of mini-implants affects the duration of orthodontic treatment remains insufficiently studied.

For the purpose of orthodontic treatment, 62 individuals with defects in the posterior region of the mandibular dental arch (absence of the first permanent molar on one or both sides of the mandible) were selected. In these patients, mesialization of the second and third permanent molars was planned in order to replace the dental arch defect with the patient's own teeth.

The first group consisted of 32 individuals (18 women, 56.25%, and 14 men, 43.75%) aged 18–25 years (mean age of men: 23.99 years; mean age of women: 22.31 years; mean age of the study group: 23.15 years). Orthodontic treatment in this group was planned using a fixed appliance (bracket system) in combination with mini-implants (Figure 1).

The second group included 30 individuals (19 women, 63.33%, and 11 men, 36.67%) aged 19–25 years (mean age of men: 23.69 years; mean age of women: 22.45 years; mean age of the study group: 23.07 years). Orthodontic treatment was planned using a fixed appliance (bracket system) without additional intraosseous anchorage with mini-implants.

The duration of orthodontic treatment was defined as the period from placement of the fixed appliance to its removal and transition to the retention phase of treatment.

Figure 1. Mini-implant placed in the oral cavity [author's elaboration]

All patients underwent assessment of bone tissue density in the area of molar mesialization using orthopantomograms in order to obtain a homogeneous patient sample and to increase the statistical significance of the results of the subsequent study.

Bone tissue density was determined using ImageJ software (Wayne Rasband, USA) according to the algorithm described by Geiger M. [8]. This research method is based on the principle that shades of gray on radiographic images correspond to the degree of X-ray absorption and determine the radiological density of specific tissues. All grayscale values are stored by the software in an 8-bit range. Each image pixel is assigned a value from 0 to 255 arbitrary units, where 0 arbitrary units correspond to black, indicating low radiological density, and 255 arbitrary units correspond to white, indicating complete absorption of X-ray radiation by the tissues.

In ImageJ, the area of the dental arch defect was delineated using the “Freehand Selection” function in such a way that the selected region did not overlap with other anatomical structures, such as tooth roots or the mandibular canal (Figure 2).

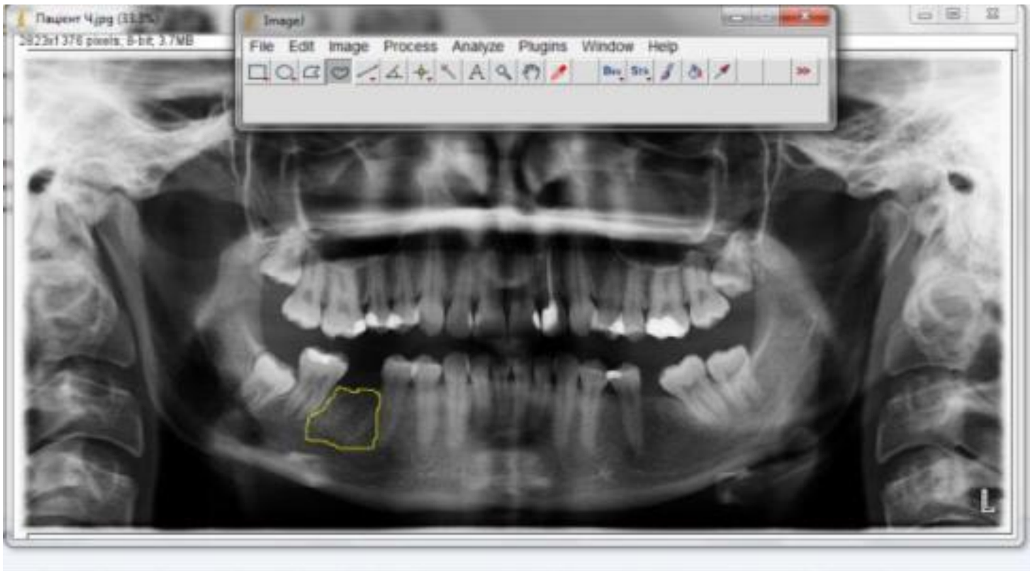

Figure 2. Method for calculating bone tissue density in the molar mesialization area on orthopantomograms according to the method of Geiger M. (2016)
[author’s elaboration]

Using the “Histogram” function, the density range of the selected area was determined in arbitrary units, as shown in Figure 3. The obtained data were recorded in tables for further analysis and standardization of the patient groups.

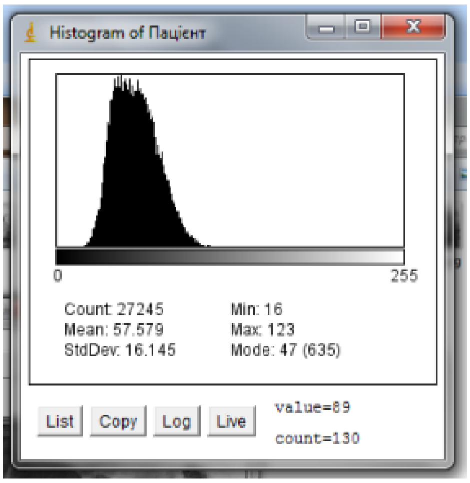

Figure 3. Determination of bone tissue density range in the mesialization area using the “Histogram” function [author’s elaboration]

Considering the fact that bone tissue density directly affects the rate of orthodontic tooth movement, we assessed the relative bone tissue density of the alveolar process in the area of the dental arch defect using densitometric measurements of grayscale values with the applied software program ImageJ (Wayne Rasband, NIH, USA) (Table 1).

Table 1.

Results of bone tissue density assessment in the mesialization area in Study Groups I and II (in arbitrary units)

№	Group I		№ п/п	Group I		№ п/п	Group II		№ п/п	Group II	
	Right	Left		Right	Left		Right	Left		Right	Left
1	22-150	n/a	**17**	n/a	20-149	**1**	17-156	n/a	**17**	n/a	22-150
2	16-151	n/a	**18**	n/a	24-144	**2**	26-145	n/a	**18**	n/a	17-154
3	16-125	n/a	**19**	n/a	22-150	**3**	16-151	n/a	**19**	n/a	26-149
4	33-152	n/a	**20**	n/a	14-151	**4**	14-151	n/a	**20**	n/a	13-151
5	26-135	n/a	**21**	n/a	16-141	**5**	22-150	n/a	**21**	14-151	19-155
6	17-156	n/a	**22**	18-151	25-142	**6**	20-155	n/a	**22**	16-142	13-148
7	18-149	n/a	**23**	14-150	26-141	**7**	17-145	n/a	**23**	22-150	15-152
8	15-145	n/a	**24**	16-143	17-156	**8**	14-151	n/a	**24**	21-151	26-145
9	19-150	n/a	**25**	26-149	19-151	**9**	19-154	n/a	**25**	14-151	15-156
10	n/a	16-149	**26**	17-156	20-154	**10**	18-149	n/a	**26**	19-148	17-156
11	n/a	21-152	**27**	22-150	22-148	**11**	n/a	22-151	**27**	19-148	14-152
12	n/a	16-145	**28**	17-152	21-151	**12**	n/a	19-144	**28**	24-151	17-155
13	n/a	15-152	**29**	14-156	22-150	**13**	n/a	18-151	**29**	19-156	14-150
14	n/a	22-154	**30**	16-149	14-152	**14**	n/a	17-156	**30**	22-150	17-148
15	n/a	19-151	**31**	19-151	17-158	**15**	n/a	25-152	**31**	-	-
16	n/a	17-156	**32**	20-155	17-151	**16**	n/a	14-151	**32**	-	-
M	Right Group I			Left Group I			Right Group II			Left Group II	
	18,55±1,14 – 148,75±1,85*			19,22±0,65 – 149,91±0,92			18,65±0,72 – 150,25±0,84			18,0±0,78 – 151,3±0,72	
p	p>0,05										

Note:

1. The table presents data for each patient in Groups I and II.
2. M – mean bone tissue density values in the mesialization area (right and left).
3. p – statistical significance of the mean values.
4. n/a – density value was not determined because the patient's own tooth was present.

According to the obtained data, the average bone tissue density values in the dental arch defect area ranged from 14 to 158 arbitrary units in the first study group and from 13 to 156 arbitrary units in the second group. At the same time, the mean bone quality values in patients of Groups I and II did not differ significantly ($18.55 \pm 1.14 – 149.91 \pm 0.92$ and $18.0 \pm 0.78 – 151.3 \pm 0.72$ arbitrary units, respectively; $p > 0.05$).

Thus, it can be concluded that the patient sample selected for the study was homogeneous in terms of bone tissue quality, which in turn significantly increases the statistical reliability of subsequent study results, particularly in analyzing changes in quantitative parameters of the alveolar ridge and the duration of orthodontic treatment. This also allowed for the exclusion of patients whose examination data did not correlate with those of others.

It is important to consider that bone tissue density values may be significantly affected by the presence of areas of osteosclerosis, calcium-containing tumors, remnants of radiopaque endodontic filling materials, bone grafting materials, or autotransplants. Therefore, patients with these factors were excluded from the study.

It should also be noted that performing such measurements in the maxilla is more challenging due to the need to exclude the influence of the maxillary sinus on the results.

The duration of comprehensive dental treatment involving molar mesialization differed between the two comparative study groups. In Group I, where orthodontic mini-implants were used as anchorage supports, the average treatment duration was 2.19 ± 0.05 years (Figure 4).

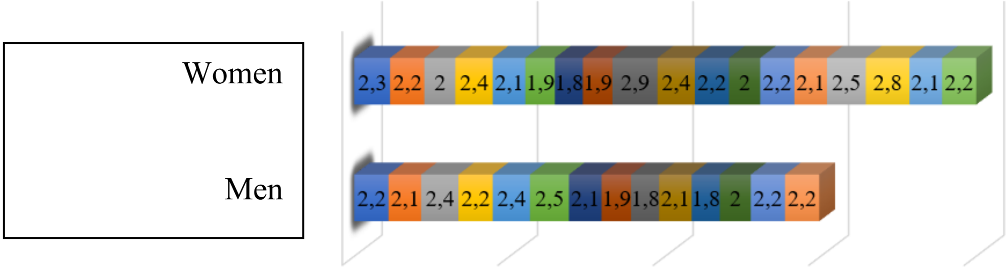

Figure 4. Duration of comprehensive treatment in Group I patients (years) [author's elaboration]

In the second study group, where tooth mesialization was performed without the use of intraosseous anchorage, the average treatment duration was 2.92 ± 0.04 years (Figure 5). Thus, the treatment duration in the first study group using bone anchorage with mini-implants was reduced by 8.8 ± 0.12 months compared to the second group ($p < 0.001$).

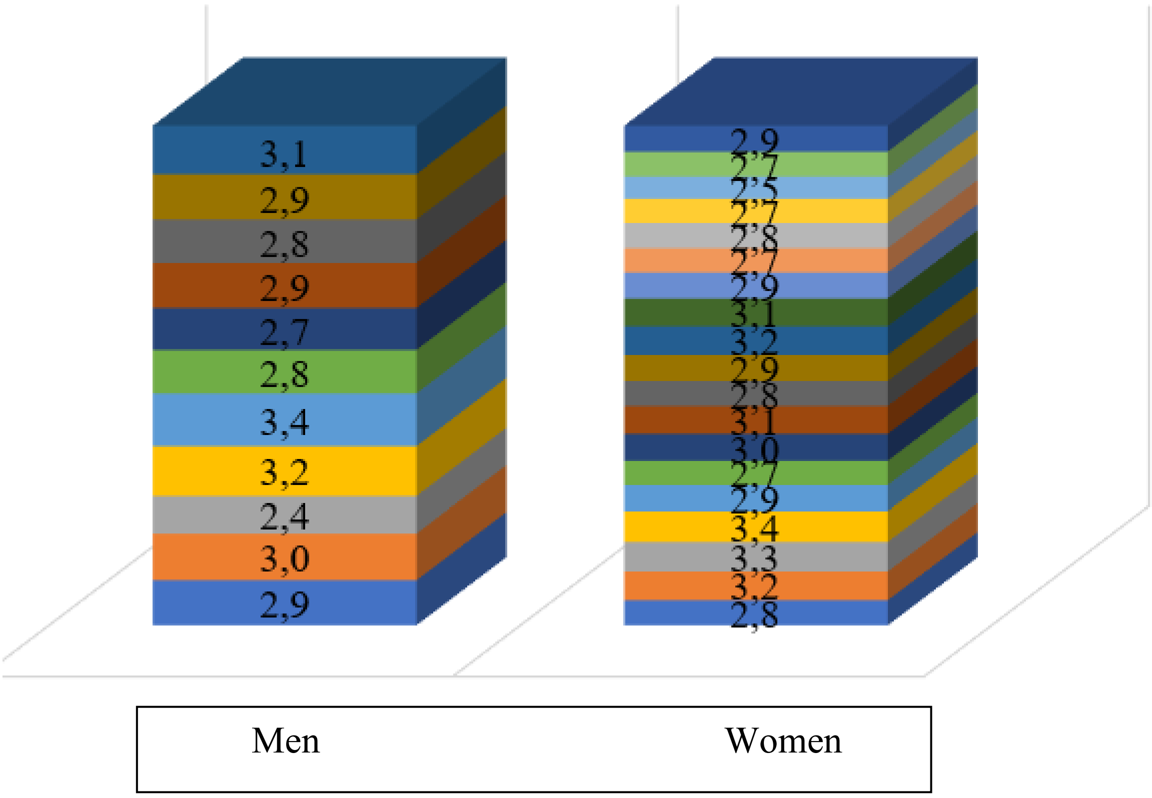

Figure 5. Duration of comprehensive treatment in Group II patients (years) [author's elaboration]

The reduction in treatment duration in the first study group, in our opinion, is associated with the fact that during molar mesialization there is almost no undesirable movement of the anchor segments, such as distal tipping, premolar rotation, or loss of torque by the anterior teeth, since mini-implants placed in the alveolar process provide reliable skeletal anchorage and counteract these displacements.

In the second study group, under the influence of orthodontic force, we observed loss of lower incisor torque in 5 patients (16.7%), distal tipping of the second premolars in 4 patients (13.3%), distal rotation of the second premolars in 2 patients (6.7%), and a combination of several complications in 2 patients (6.7%).

The occurrence of these undesirable movements required additional orthodontic corrective measures to reposition the affected teeth, which prolonged the overall duration of orthodontic treatment compared to the first study group.

Measurements of bone tissue density in the molar mesialization area of the mandible showed no significant differences between the two clinical study groups, allowing for further analysis of the effectiveness of different orthodontic treatment methods in these patients.

The obtained treatment duration results indicate that the use of orthodontic mini-implants as anchorage supports contributes to a reduction in the overall duration of orthodontic treatment.