# Three-Dimensional Evaluation on Cortical Bone During Orthodontic Surgical Treatment

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**Abstract:** Adult patients' severe malocclusions, especially the skeletal ones, cannot be exclusively solved by the orthodontic treatment and therefore a combined orthodontic-surgical treatment is necessary. Today, numerous software allows to plane and to visualize the final treatment results simulating the best therapeutic option. This is a retrospective experimental study that aims to analyze the changes in the buccal cortical bone in patients undergoing orthodontics surgeries and to evaluate the correlation between the dental movement and the changes in the relative bone cortex. The study sample consists of 32 subjects. By applying the CBCT radiographic examinations, the measurements were made in well-defined points of reference. The 3D study of the dental changes of position and the cortical buccal bone related variation, suggests how the determined orthodontic movement of the dental element does not achieve an easily predictable bone variation. Therefore, it also suggests that there is no direct proportionality relationship between the extent of bone apposition/reabsorption and dental movement.

**Key Words:** 3D software surgical, orthodontic treatment, surgical treatment

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Until a few years ago, orthodontic treatment in adults was unusual, in fact, in 1970 less than 5% of all orthodontic patients were 18 or more years old. Epidemiological data reflects that since 1990 this category has reached 25% and, in the eighties, the greatest increase in orthodontic treatments refers to the group of "adult patients.''" In the nineties the number of children treated in orthodontic studies grew again. Although the number of adults who underwent an overall treatment remained almost constant after the peak reached in 1990, around the end of this decade, adults accounted for 15% of all orthodontic patients. The most recent trend seems to see an increase in the group of older adults (aged 40 and over), who for the most part are currently candidates for an overall orthodontic treatment, rather than a partial one. Adults who undergo orthodontic treatment are increasing considerably and this phenomenon is attributable to the ever-increasing aesthetic demands of modern society.[1,2] Although 2D cephalometry is still considered the "gold standard" for the diagnosis and planning of orthodontic treatment, in the pre-surgical orthodontics the 3D cephalometry has made its way, allowing the orthodontist and the surgeon to analyze the asymmetries in accurate way before starting the treatment. Numerous studies have been carried out to verify the accuracy of the 3D cephalometric examination; in particular, it has been demonstrated how CBCT offers a real picture of the clinical situation and how 3D cephalometry can be considered a predictable and reproducible procedure.[3] In presurgical orthodontics one of the main problems is to understand if the correct transverse dimension of the maxilla and mandible could be obtained through an orthodontic expansion or a surgical assisted one may be needed. Some authors report the difficulty in measuring some anatomical features such as the bone thickness or the alveolar bone and root cement[4,5] and to understand if their orthodontic movements could cause alveolar fenestration and/or periodontal resorption. Aim of the presented study is to retrospectively evaluate the effectiveness of the 3D evaluation comparing the radiological data with the clinical results in adult orthodontic patients which underwent presurgical orthodontic treatment and orthognatic surgery procedures.[6–9]

It has proved to be the most effective method for orthodontic diagnosis and today it is still considered the "gold standard." Over time, many cephalometric traces have been developed to be used depending on the complexity of the treatment or the "school of thought" of the orthodontist. However, the using of the "traditional" 2D cephalometric traces based on the latero-lateral tele radiography of the skull is still the bases of the orthodontic measurement. In the 3D models, the DICOM files can be processed in a VOR (virtual operating room) software allowing orthodontists and surgeons to plan the case accurately not more in the two-dimensional view.[10,11]

However, some limits have been underlined in the orthodontics and CBCT. Although CBCT is a very precise method of investigation, the presence of metal brackets orthodontic can reflect artifact during the conversion of the image. To overcome this problem, additional images can be acquired through the extraoral scanning of the plaster models or through the intraoral patient scan of the dentition and then superimposed on the 3D model obtained from the CBCT.[12–17] In surgical cases where CBCT is indicated for a correct diagnosis and therapeutic planning, it is possible to perform a 3D cephalometry that, in addition to soft tissue, skeletal bases and teeth, also takes into account the volume of bone surrounding the teeth (fundamental to be evaluated in adult patients or with periodontal problems) and allows

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to accurately estimate the reabsorption of the dental roots. In the alveolar bone thickness, it would possible to record intra-alveolar thickening of various sizes (from 2 mm to 2 cm), located in 88% to 100% of cases in the jaw in the lateral-posterior region, and that preclude some orthodontics movements such as torque or sagittal displacement of the tooth. These changes are visible only through CBCT.[18] Given the numerous advantages that CBCT offers in terms of precision and visualization of anatomical structures, 3D cephalometric traces have been proposed. The presented investigation is aimed to compare the CBCT 3D cephalometric with 2D latero-lateral tele radiography, the current "gold standard." The studies in the literature focused on evaluating the precision in the identification of the main cephalometric points on tele radiography and on CBCT, respectively. It has emerged that the localization of some cephalometric points (Condylion, Gonion, and Orbital) is more precise in CBCT since, being bilateral points, with this technique they are not subject to overlapping; for other cephalometric points (Porion) the localization is equally accurate in the two methods.[19,20] At the same time, the 3D cephalometry allows to pinpoint the points on the tooth (eg, the apex[21]) with great precision, evaluating their localization simultaneously in the three sections of the space (axial, sagittal and coronal), even if this takes more time and more skills by the clinician.[3,22] However, there are no studies in the literature with a sufficiently large sample to establish with certainty which of the two techniques work better. Although 3D cephalometry is accurate, its use is limited to cases requiring combined orthodontic-surgical treatment and for which exposure to a high dose of ionizing radiation is justifiable. For cases resolvable with orthodontics alone, 2D cephalometry performed on latero-lateral tele radiography remains today the "gold standard."

The anatomical features to be considered in the orthodontic surgery treatment not involve just the hard tissue of the jaws. The periodontal ligament which acts as a "shock absorber" due to the presence of fluid in the periodontal space and which allows the tooth a certain degree of protective mobility and bending of the alveolar bone generating piezoelectric currents without damage protects the bone. If the pressure stimulus is prolonged over time, the fluid contained in the periodontal space is expelled and the tooth is pushed against the periodontal ligament, which in turn is compressed on the alveolar bone.[23] Physiologically the teeth are kept in their position thanks to a balance of forces exerted by the lips/cheeks and the tongue, in opposition to each other. If one force prevails over the other, the tooth moves in the direction of the weaker, lingual or vestibular force. This principle is used in the orthodontic field through the application of a force able to determine a controlled movement of the tooth. There are two main conventionally accepted theories today to explain the orthodontic movemen:[1]

- the bioelectrical theory is based on the fact that the bone metabolism is controlled by the biological electricity created when a tooth is subjected to a pressure force;
- the pressure-voltage theory according to which the variation of the blood flow within the periodontal ligament generates chemical mediators which, producing second messengers, induce dental movement.[24]

At the time of this writing, it is believed that biological electricity plays a fundamental role in physiological bone metabolism but it does not affect the beginning of orthodontic movement. The pressure-tension theory is currently the most accredited: the prolonged pressures force the tooth to move in the periodontal ligament space compressing the alveolar bone, with consequent reduction of the blood flow (pressure side) and generating space that allows the maintenance of blood circulation (tension side).[25–34] This phenomenon causes immediately after the application of force to increase the levels of prostaglandins and interleukin-1, important mediators of the cellular response, while within a few hours increase the levels of adenosine monophosphate (cAMP), responsible of cell differentiation. The prostaglandin E2 (PgE2) is released by the focal adhesion kinase (FAK), which appears to be the mechanoreceptor of the periodontal ligament. In orthodontic-surgical combined treatment orthodontics plays a fundamental role: in the pre-surgical phase, it allows to perform the movements necessary for surgery, during the surgical phase and the healing period it stabilizes the teeth and the bone, in the post-surgical phase allows you to perform the finishing movements and to obtain the stabilization of the ideal occlusion.[35–37] During the pre-surgical phase, the orthodontist ideally positions the teeth in relation to their specific apical bases and the planning of what will be the post-surgical position of the skeletal bases.. The 3D alignment of the dental elements (incisor and molar group) is the objective of this first phase because it allows the surgeon to position and stabilize the dento-skeletal structure.[38–40] A key element in the preparation for surgery is the sagittal and vertical positioning of the incisors. However, despite the study by Choi et al[41,42] suggests evaluating periodontal tissues at the end of the whole treatment, Sun et al[43] demonstrated the importance of paying close attention in the patients with class III malocclusion to the proclination of lower incisors that risk losing too much periodontal support. Therefore, an accurate pre-surgical planning is fundamental, today based on Cone Beam Computer Tomography (CBCT). During this pre-surgical planning orthodontists need to analyze the possibility to move sagittally or buccally the teeth and, if possible, to better understand if there is enough cortical bone to apply correct orthodontic force to avoid bone or roots damage.[43–49]

## MATERIAL AND METHODS

### Study Design

The subjects involved in this study were selected from the Oral and Maxillofacial Surgery Unit of the Sant'Orsola University Hospital of Bologna. All the patients underwent orthodontic surgery from 2008 to 2014. According to the operative protocol of the School of Maxillofacial Surgery of Bologna (Bologna Workflow) the CBCT radiological examination was performed at the beginning of the pre-surgical orthodontic treatment (T0) and just before the surgery (T1). This Workflow is in accordance with the guidelines of SEDENTEXCT and EADMFR of 2008 (Figs. 2 and 3).

### Sample

The sample consists of 32 subjects: 14 males and 18 females patients (Graph 1) aged between 17 and 47 years (mean age 26 years) at the time of the first CBCT. (Graph 2).

The population is divided as follows (Fig. 1A–C):

- 73% of subjects present a class III malocclusion;
- 24% a class II malocclusion;
- 3% a class I malocclusion

The mean treatment time of the pre-surgical orthodontic phase was 17 months, according to the literature (Fig. 1D).

### Method

All the CBCTs were carried out at the same center (RadMedica, Bologna, Italy) and performed by the same machine (NewTom VGi, Verona, Italy) set up with a wide FOV (16 × 16) (maxilla and mandible). The CBCT at T0 (before the start of treatment) and T1 (at the end of the pre-surgical orthodontics) for each subject, were elaborated with the SimPlant O & O software (Materialize,

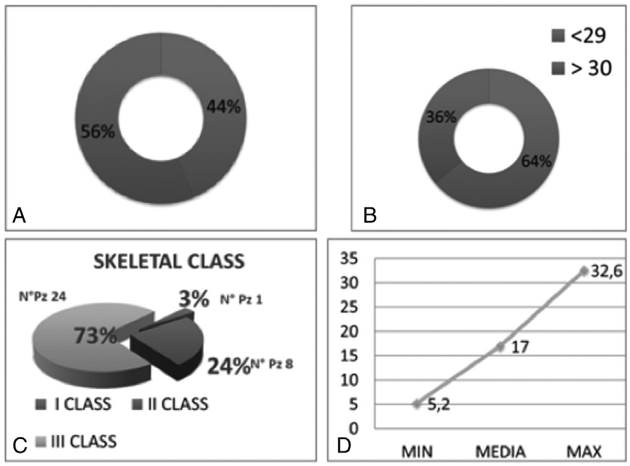


**FIGURE 1.** Division in base of gender. (Blu = M; Red = F) (A); Show the median age of population sample (B). Skeletal Class on sample (C). Pre-surgeon orthodontic treatment duration (D).

Belgium) in order to obtain a virtual reconstruction of the massive facial of the subject. A specific 3D cephalometry was performed in the virtual image obtained by the CBCT in order to obtain the necessary measurements for the analysis of the vestibular bone cortex.[6,50–55] For each subject, at the time T0 and T1, 6 dental elements out of 32 were analyzed.

The elements evaluated in the upper jaw are:

- Right central incisor (11)
- First molar on the right (16)
- First molar on the left (26)

The elements evaluated in the lower maxilla are:

- Right central incisor (41)
- First molar on the right (46)
- First molar on the left (36)

All the elements listed above allowed evaluating the total features of the both jaws and the variation in these sectors (front and back) can be considered to represent the entire mouth. On the vestibular side of each tooth the following points have been identified:

- CEJ-D: coronal point, corresponding to the enamel-cement junction;
- Apical-D: apical point, corresponding to the root apex;
- Medium-D: intermediate point between CEJ-D and Ap-D

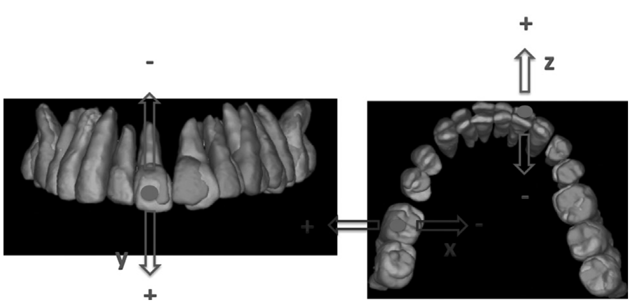


**FIGURE 2.** Movement evaluated in the 3 planes of the space.


**FIGURE 3.** starting poi of clinical case a, front (A), lateral (B), intraoral view (C). Beginning of orthodontic treatment of clinical case a, front (D), lateral (E), intraoral view (F). End of treatment of clinical case a, front (G), lateral (H), intraoral view (I).

These points were projected onto the vestibular cortex obtaining the following points:

- Alveolar: more coronal point of the cortical bone;
- Apical-C: point on the cortex corresponding to the Apical-D point;
- Medium-C: intermediate point on the cortical corresponding to Middle-D

The points thus positioned were used to obtain the linear measurement of the distance between the buccal surface of the dental element and the corresponding points on the buccal cortical bone. In addition, for analyzing the cortical bone, the dental movements in relation to the 3 planes established by the 3D cephalometry have been investigated:

- Frankfurt Plan;
- Sagittal Plan;
- Coronal Plan

Measurements of the cortical bone and dental movements have enabled:

1. To observe the average changes for the buccal bone. For each sample tooth (11, 16, 26, 41, 36, 46) by measuring the distances (in mm) between the points Ap, Middle and CEJ identified on the tooth and the respective points located on the buccal cortex;
2. To observe the extent of extrusion/intrusion movements for each tooth and the resulting change in thickness of the cortical bone. To determine the extrusion/intrusion movement we calculated the variation of the distance between T0 and T1 of the midpoint from the Frankfurt plane. The sample was then divided into the "Extrusion" group and the "Intrusion" group and for each tooth belonging to each group the variation of the cortical bone was observed in the 3 points (MAlv, M2, and MAp)
3. To observe the amount of advancing/retracting movements of the elements 11 and 41 and the consequent variation of the bone thickness. To determine the forward/retract movement, we calculated the variation of the distance between T0 and T1 of the midpoint from the coronal plane. The sample was then divided into an "Advance" group and a "Backward" group and then it proceeded as described above
4. To observe the sagittal movement of the elements 16-26-36-46 and the resulting bone variation. To determine the displacement, the variation of the distance between T0 and T1 of the midpoint from the sagittal plane was calculated. The sample was then divided into the "Positive expansion" group and the "negative expansion" group and then the bone variation was calculated using the same method.

 

5. To determine for the elements 11 and 41 the type of tipping (vestibular-lingual or linguo-vestibular), its degree in degrees and the variation in bone correlated to it. To determine the tipping movement of the element 11 we calculated the difference between T0 and T1 of the measurement of the angle formed between the long axis of the tooth (line passing through the points Apical, Medium, CEJ) and the Frankfurt plane. For the element 41 the Mandibular Plane has been taken as reference plane (plane passing through the Menton, Gonion left and right points). The sample was then divided into a "Vestibular Tipping" group and into a "Tipping Palatal/ Lingual" group. For each group the variation between T0 and T1 was observed in degrees of the tipping movement and the behavior for each tooth of the cortical bone in the 3 points (Alveolar, Medium, Apical).
6. To observe the variation in height of the buccal cortical bone and its correlation with extrusion/intrusion movements, advancement/retraction, sagittal expansion and tipping. The distance of the CEJ from the Alveolar point to T0 and T1 has been calculated. It was then observed in the groups "Extrusion," "Intrusion," "Advancement," "Retraction," "Positive sagittal expansion," "Negative sagittal expansion," "Vestibular Tipping" and "Tipping Lingual" the variation in height of cortical bone
7. To determine the correlation between dental movement entities and bone variation for each tooth.
8. To determine the most frequent dental movements during pre-surgical orthodontics.[6–9,56–60]

## RESULTS

The analyzed dental movements were divided into movements of:

- Forward/backward (items 11 and 41)
- Extrusion/intrusion
- Tip (items 11 and 41)

Analysis of buccal cortical bone variation considers:

- Affixing
- Resorption

Supplementary Digital Content, Table 1, http://links.lww.com/SCS/B417 shows the average variation of cortical bone considering the 3 measures (M-Alveolar, M2, M-Apical) performed at the level of central incisors 11 and 41.

To measure the advancing/retraction movements, the difference in the distance between the M2 point of each sample tooth and the Coronal plane between T0 and T1 was measured. To measure intrusion/extrusion movements, the difference in the distance between the M2 point of each sample tooth and the Frankfurt plane between T0 and T1 was measured. The elements were then divided into two groups depending on the movement made.

The tipping movement was evaluated only for the elements 11 and 41 due to a technical limitation in the Simplant program, which did not allow the evaluation of the angles for the posterior teeth. By evaluating the variation of the angle between the long axis of the tooth and the Frankfurt plane for element 11, it was possible to determine the type of tipping and divide the sample into two groups: "Vestibular Tipping" and "Palatal Tipping."

To determine the tipping movement of the element 41 the variation between T0 and T1 of the angle formed between the tooth axis and the Mandibular Plane was measured. Table shows the average variation of cortical bone considering the 3 measures (M-Alveolar, M2, M-Apical) performed at the level of the first upper molars (16 and 26).

The transverse movement of the elements 16 and 26 was then evaluated through the difference in the distance of the midpoint of each tooth from the Sagittal plane between T0 and T1. The sample was divided into 2 groups: "Positive Expansion," if the distance between the tooth and the Sagittal plane was increased and "Negative Expansion" if the distance was instead decreased. For the Intrusion and Extrusion movements, all the sample elements of both the arches were analyzed. The elements were then divided into two groups depending on the movement made. After the evaluation of the variation in thickness of the cortical bone for each movement, the variation in height was analyzed, measuring the distance to T0 and T1 between the CEJ point (enamel-cement junction) and the Alveolar point. This variation was then related to the different movements for each sample tooth. The transverse movement of the elements 36 and 46 was then evaluated through the difference in the distance of the midpoint of each tooth from the Sagittal plane between T0 and T1. The sample was divided into 2 groups: "Positive Expansion," if the distance between the tooth and the Sagittal plane was increased and "Negative Expansion" if the distance was instead decreased.

For the intrusion and extrusion movements, all the sample elements of both the arches were analyzed. The elements were then divided into two groups depending on the movement made.[61–65] After the evaluation of the changing in thickness of the cortical bone for each movement, the variation in height was analyzed, measuring the distance to T0 and T1 between the CEJ point (enamel-cement junction) and the Alveolar point. This variation was then related to the different movements for each sample tooth.

### Additional Analysis

Clinical case:

This 45-year-old female patient was treated with a combined surgical-orthodontic approach. The overall duration of treatment was approximately 30 months. The surgical technique used is the BSSO (bilateral sagittal split osteotomy) and maxillary advancement acc. To a Le Fort I osteotomy, while the orthodontic technique has provided for a fixed vestibular orthodontics (Fig. 3 A–I)).

The containment phase was managed with a removable device at the top, and with a fixed retainer from 3.3 to 4.3. There was a 5-year follow-up period.

## DISCUSSION

Different works in the literature investigated the virtual planning before doing facial orthognathic surgery trying to state predictable and safe protocols for having long term excellent clinical results. Especially following the advent of digital techniques such as Digital Smile Design, this has been extensively evaluated.[66–71] Evaluations on the results of very invasive surgeries on the maxillo-facial district involving soft tissues were also performed. Moreover, thanks to the contributions brought in literature by some computerized and bioengineering calculation tools, such as finite element analysis; it is now possible to perform evaluations on implant rehabilitations,[72] implant prosthetics, prosthetics,[47,73,74] orthodontics[75] and surgical procedures before starting the therapy. The results obtained with the present study seem to give credit to the theory of Melsen,[30] according to which one cannot simply speak of an "apposition front" and of a "reabsorption front," but the periodontal ligament and the bone alveolar should be considered as 3D structures that, as such, undergo the movement of the dental element undergo a remodeling on all three planes of space.[46] The impossibility in the pre-orthodontic phase of decomposing in a precise and reproducible way what will be the movement of the tooth in the three planes of space, makes it difficult to predict the consequent bone remodelling.[76–78] As already seen in the previous paragraphs, the use of digital instruments has allowed a more predictable evaluation of orthodontic cases, thanks to the possibility of making measurements also on soft tissue loading. It is also very important to make a reliable diagnosis and a careful evaluation of the treatment necessary for our patients. The orthodontic treatment as already mentioned, can improve both the clinical and psychological conditions of our patients,[35–37] even in pediatric patients.[79] Surely the first step for a proper planning is to perform instrumental examinations, both radiographic but also through the realization of plaster models of our patients, in this way it will be possible to make all the necessary measurements, the material to be elected in this case, it is alginate.[80]

The dental displacement, associated with orthognathic surgery, involves a displacement of all periodontal tissues.[81–84] Observing the average variation of the cortical bone, it is noted that in the upper incisors there is an average apposition of 0.29 mm while in the lower incisors the reabsorption prevails, on average 0.58 mm. As shown, the major advance is at the level of the lower arch elements with an average of 3.35 mm. Going to observe the variation in thickness of cortical bone per mm of progress, it can be seen how for both arches there is bone apposition and as this is minimal, with a maximum apposition for tooth 11 at Apical level of 0.48 mm for each mm of progress. For both elements (11 and 41) the advancement movement was predominant with respect to the backward movement. For the backward motion, the amount of movement is much greater than the forward movement with an average of 4.59 mm for the upper jaw and 5.51 mm for the lower jaw. However, also in this case the cortical bone responds with affixing but always minimal: in fact, there is a maximum apical apposition of the element 11 of 0.14 mm of bone for each mm of tooth retraction and a small Apical reabsorption area of the element 41 of 0.03 mm for each mm of displacement of the element. Results show the extrusion movement, predominant with respect to the intrusion both for the upper incisors (18/32) and for the lower incisors (19/32). The element 41 was extruded more than the element 11 with an average of 3.33 mm, followed by a slight bone apposition: in fact, the bone formed for each mm of extrusion is 0.02 mm to Alveolar level, 0.01 mm at the midpoint and 0.05 mm at the Apical point. The element 11, which carried out an average extrusion of 1.46 mm, responded with greater bone apposition, reaching the maximum peak at the apical level with 0.66 mm of bone affixed for each mm of extrusion of the element. The Intrusion movement, of similar magnitude in the 2 elements, found bone apposition for the element 11 (0.09 mm M-Alveolar, 0.27 mm M2 and 0.45 mm M-Apical) and prevalent resorption for element 41 (0.11 mm M-Alveolar, −0.40 mm M2 and −0.11 mm M-Apical). Analyzing the tip movement, for the element 11 the sample divided exactly in half: for the teeth with vestibular tipping the angular variation was an average of 7.1° and the bone response always positive with a maximum bone apposition of 0.13 mm per degree of vestibular tipping at the Apical level; for the elements with palatal tipping, the variation of mean angle was 5.5° with bone positivity always positive and maximum at the Apical level with 0.07 mm of new bone for degree of tipping. Observing the tip movement for the element 41, most of the sample underwent a vestibular tipping movement with an average variation of 5.17° and a positive bone response in the Alveolar and Middle points (respectively 0.04 mm and 0.02 mm of apposition by degree of tipping) and negative in the Apical point with a resorption of 0.03 mm per degree of vestibular tipping. Observing the lingual tipping movement (angular variation of 2.95°) it is possible to notice how the bone resorption prevails in the Alveolar and Middle points (respectively 0.03 mm and 0.15 mm per degree of tip), whereas it is affixed in the Apical point (0.19 mm per degree of lingual tipping). Of the 17 elements that made a forward movement, 10 had a negative bone response with an average resorption of 0.21 mm of bone for each mm of advancement. Considering the backward movement, 9 out of 14 elements had a positive bone response with a bone gain in an average height of 0.18 mm per mm of retraction. For the extrusion movement, the sample split in half between the positive and negative response respectively of 0.38 mm and 0.45 mm. For the intrusion movement, on the other hand, the resorption is 0.56 mm per mm of displacement in 7 elements versus 0.23 mm of apposition per mm of displacement in 9 elements. Following the vestibular tipping movement, 10/16 sample elements underwent an increase in bone height of 0.06 mm per tip grade, and 6/16 a resorption of 0.08 mm. Observing the bone variation in height during the palatal tipping movement, in 10 cases out of 16 there was an average reabsorption of 0.18 mm per tip degree and in only six cases out of 16 the apposition was on average 0.39 mm by grade of tip. It can therefore be stated that the most frequent movements in pre-surgical orthodontics for element 11 are the advancement (17/32), on average of 1.6 mm and the extrusion (18/32), on average of 1.46 mm. The thickness of the bone response is positive for both movements: for the advancement movement there is affixation of 0.01 mm Alveolar, 0.18 mm at the Middle point and 0.48 mm at the apical level. For the extrusion movement the apposition is 0.1 mm Alveolar, 0.34 mm in the Middle point and 0.66 mm in the apical point. Both movements are correlated, however, with a negative response of the bone in height respectively of 0.21 mm and 0.45 mm per mm of displacement, certainly influenced by the movement of the tip. Of the 18 elements that made a forward movement, nine had a negative bone response with an average resorption of 0.18 mm of bone for each mm of progress, while the other nine had an average bone height increase of 0.27 mm. Considering the backward movement, 10 out of 13 elements had a positive bone response with a bone apposition in an average height of 0.08 mm per mm of retraction, while the remaining three elements had a mean resorption of 0.04 mm. Following the extrusion movement, 11 out of 19 elements presented an average vertical bone increase of 0.34 mm for each mm of extrusion, while the remaining eight suffered an average reduction of 0.14 mm. Following the intrusion, on the other hand, the reabsorption, which involved only four elements out of 13, was 0.18 mm per mm of displacement, while 9 elements out of 13 had a bone increase in verticality of 0.48 mm per mm of intrusion. Following the vestibular tipping movement 7/18 sample elements underwent a decrease in bone height of 0.05 mm per tip grade, and 11/18 increase of 0.11 mm per tip grade. Observing the bone variation in height during the lingual tipping movement, in only 5 cases out of 14 there was an average reabsorption of 0.32 mm per tip degree and in the remaining 9 cases the apposition was on average 0.25 mm for grade of tip. It can, therefore, be underlined that the most frequent movements in pre-surgical orthodontics for element 41 are the progression (18/32), on average of 3.34 mm, the extrusion (19/32), on average of 3, 33 mm and the vestibular tipping. The thickness of the bone response is positive for all movements: for the advancement movement there is affixation of 0.01 mm Alveolar, 0.1 mm at the Middle point and 0.06 mm at the Apical level for every mm of advance. For the extrusion movement the apposition is 0.02 mm Alveolar, 0.01 mm in the Middle point and 0.05 mm in the Apical point for each mm of extrusion. For the vestibular tipping movement the apposition is 0.04 mm Alveolar, 0.02 mm in the point Medium and a slight resorption at the Apical point of 0.03 mm per degree of tip (Supplementary Digital Content, Tables 1–4, http://links.lww.com/SCS/B417).

Observing the average variation of cortical bone, it is noted that in the first upper right molar (16) there is an average apposition of 0.28 mm while in the first left upper molar (26) the apposition is markedly greater, on average 0.91 mm (Supplementary Digital Content, Table 5, http://links.lww.com/SCS/B417)

In all cases of positive expansion, there was bone resorption in at least one of the three reference points, with a maximum of 0.19 mm in the midpoint of the element 16. A small bone apposition was found in the Alveolar points (0, 12 mm) and Apical (0.45 mm) of the element 26. (Supplementary Digital Content, Table 6, http://links.lww.com/SCS/B417). For the elements subject to negative expansion, the bone response was very variable: element 16 had affixation in all three points with a maximum of 1.88 mm at the Apical level; the element 26 instead has had reabsorption in all three points with a maximum of 0.35 mm average always at the Apical level. Analyzing the extrusion movement, it can be seen that at the Middle level of the element 26 there has been the greatest resorption (0.64 mm per mm of displacement), and that the only apposition areas are at the alveolar level of the element 16 (0.03 mm of bone for each mm of extrusion) and at the apical level of the element 26 (0.29 mm of bone for each mm of extrusion). Evaluating the extrusion movement, it should be kept in mind that the element, extruding, passes from an apical area where the bone thickness is greater than a more coronal area where the bone thickness is physiologically lower and therefore the reabsorption and apposition values may not be completely truthful. Analyzing the intrusion movement, predominant for the elements 16 and 26 with respect to the extrusion movement, it can be seen how the bone apposition predominates on the reabsorption reaching a peak of 1.82 mm (per mm of intrusion) at the apical level of the element 16 In some areas, middle and apical of the element 26, there is a slight resorption (0.06 mm and 0.19 mm for each mm of intrusion), explainable with other movements that the tooth has made, such as the variation of torque. Supplementary Digital Content, Table 5, http://links.lww.com/SCS/B417 shows the correlation between the movements made by the element 16 and the bone variation in height. For the extrusion movement, which involved a total of 7 elements, 4 out of 7 were associated with a bone height increase of about 0.23 mm per mm of extrusion, while the remaining 3 elements underwent a vertical resorption of 0.44 mm of bone for each mm of extrusion. Considering the intrusion movement, on the other hand, the reabsorption is 0.61 mm per mm of displacement in 14 elements versus 0.31 mm of apposition per mm of displacement in 11 elements. Analyzing the positive sagittal expansion movement, only 3 out of 7 elements had an average bone apposition of 0.15 mm for each mm of expansion, while the remaining 4 elements underwent a resorption of 0.31 mm for each mm of positive expansion. The majority of the sample underwent a negative sagittal expansion movement, in which 14 elements are associated with bone augmentation (0.6 mm per mm displacement) and 11 bone resorption elements (0.31 mm per displacement mm). It can, therefore, be said that the most frequent movements in pre-surgical orthodontics for element 16 are the intrusion (25/32), on average of 0.98 mm and the negative sagittal expansion (24/32), on average of 0.94 mm. The thickness of the bone response is positive for both movements: for the movement of intrusion, there is an average displacement for each mm of displacement of 0.14 mm Alveolar, 0.23 mm at the Middle point and 1.82 mm at the Apical level. For the negative sagittal expansion movement, the average bone apposition for each mm of displacement is 0.2 mm Alveolar, 0.28 mm in the Middle point and 2 mm in the Apical point. Both movements are correlated more frequently to an increase in bone height respectively of 0.61 mm (14 cases out of 25) and 0.6 mm (14 cases out of 25) for each mm of tooth displacement. Results show the correlation between the movements performed by the element 26 and the bone variation in height. For the extrusion movement, which involved 11 elements, five were associated with a bone height increase of about 0.33 mm per mm of extrusion, while the remaining 6 elements underwent a vertical resorption of 1.37 mm of bone for each mm of extrusion. Considering the intrusion movement, on the other hand, the reabsorption is 0.49 mm per mm of displacement in 9 elements versus 0.83 mm of apposition per mm of displacement in 12 elements. Analyzing the positive sagittal expansion movement, 6 out of 12 elements had an average bone apposition of 0.24 mm for each mm of expansion, while the remaining 6 elements underwent a resorption of 0.2 mm for each mm of positive expansion. Most of the sample underwent a negative sagittal expansion movement, in which nine elements are associated with bone augmentation (0.26 mm per mm displacement) and 10 bone resorption elements (0.34 mm per displacement mm). It can, therefore, be stated that the most frequent movements in pre-surgical orthodontics for element 26 are the intrusion (21/32), on average of 1.09 mm and the negative sagittal expansion (20/32), on average of 3.43 mm. Bone response in thickness is negative for both movements: for the intrusion movement there is an average displacement for each mm of 0.05 mm Alveolar displacement, but reabsorption of 0.06 mm in the Middle point and 0.19 mm at the Apical level. For the negative sagittal expansion movement, the average resorption for each mm of displacement is 0.01 mm Alveolar, 0.08 mm in the middle point and 0.1 mm in the Apical point. Despite diffuse resorption in thickness, the intrusion movement is related to an increase in bone verticality of 0.83 mm (for each mm of intrusion). For the negative sagittal expansion movement, instead, the vertical bone behavior is in line with the horizontal one, that is, in most cases (10/19) there is an average reabsorption of 0.34 mm (per mm of negative expansion).

Observing the average variation of cortical bone, it is noted that in the first lower right molar (46) there is an average placement of 0.92 mm whereas in the first left lower molar (36) the reabsorption prevails, averaging 0.94 mm. For both elements during the Positive expansion there was bone resorption in at least one of the three reference points, with a maximum of 0.54 mm in the Apical point of the element 46. Instead, a small bone apposition was found in the Middle points (0.07 mm), Apical (0.33 mm) of the element 36 and Alveolar (0.2 mm) of the element 46. (Supplementary Digital Content, Table 7, http://links.lww.com/SCS/B417). For the elements subject to negative expansion, the bone response was generally positive with a maximum apposition of 0.13 mm (for 1 mm of negative expansion) at the Apical level of the element 46. The maximum reabsorption was observed at the Alveolar level of the same element (0.02 mm per mm of negative expansion) Analyzing the extrusion movement, it can be seen how the bone behavior is similar in the two elements 36 and 46: minimum apposition in the Alveolar point (respectively 0 mm and 0.03 mm) and reabsorption in the Middle points (0.09 mm and 0.12 mm respectively) and Apical (respectively 0.14 mm and 0.16 mm). By evaluating the extrusion movement, it should be kept in mind that the extruding element passes from an apical area where the bone thickness is greater than a more coronal area where the bone thickness is physiologically lower and therefore the values of reabsorption and apposition may not be completely truthful. By analyzing the Intrusion movement, which is predominant for the elements 36 and 46 with respect to the extrusion movement, bone apposition can be found in all the zones reaching a peak of 0.74 mm (per mm of intrusion) at the Apical level of the element 36. There is a correlation between the movements performed by the element 36 and the bone variation in height. For the extrusion movement, which involved 17 elements, 10 were associated with a bone augmentation in height of about 0.2 mm per mm of extrusion, while the remaining seven elements underwent a vertical bone resorption of 0.31 mm for every mm of extrusion. Considering the intrusion movement, on the other hand, the reabsorption is 0.62 mm per mm of displacement in seven elements versus 0.17 mm of apposition per mm of displacement in 6 elements. Analyzing the positive sagittal expansion movement, 5 out of 10 elements had an average bone apposition of 0.15 mm for each mm of expansion, while the remaining 5 elements underwent a resorption of 0.18 mm (for each mm of positive expansion). The majority of the sample performed a negative sagittal expansion movement, in which 9 elements are associated with bone augmentation (0.34 mm per displacement mm) and 10 bone resorption elements (0.05 mm per displacement mm). It can therefore be stated that the most frequent movements in pre-surgical orthodontics for element 36 are extrusion (19/32), on average of 2.51 mm and negative sagittal expansion (22/32), on average of 4.75 mm. The thickness bone response is negative for the extrusion movement as it has average resorption for each mm of displacement of 0.00 mm Alveolar, 0.09 mm at the midpoint and 0.14 mm at the apical level and partially positive for the expansion movement negative with mean displacement per mm of displacement of 0.04 mm Alveolar, 0.03 mm Apical and a small resorption of 0.01 mm at the midpoint. Both movements are more frequently related to bone resorption in height respectively of 0.2 mm (10 cases out of 19) and 0.05 mm (11 cases out of 22) for each mm of tooth displacement. For both the extrusion and negative sagittal expansion movements, in 2 cases the height of the bone remained unchanged.

For the extrusion movement, which involved a total of 18 elements, 8 were associated with a bone height increase of about 0.15 mm per mm of extrusion, while the remaining 10 elements underwent a vertical resorption of 0.1 mm of bone for each mm of extrusion. Considering the intrusion movement, the resorption is 0.45 mm (per mm displacement) in 5 elements versus 0.79 mm of apposition (per mm displacement) in 3 elements. Analyzing the positive sagittal expansion movement, 10 out of 15 elements had an average bone apposition of 0.23 mm for each mm of expansion, while the remaining 5 elements underwent a resorption of 0.07 mm for each mm of positive expansion. Analyzing the negative sagittal expansion movement, 7 elements are associated with bone apposition (0.04 mm per mm displacement) and 5 bone resorption elements (0.09 mm per mm displacement). It can, therefore, be said that the most frequent movements in pre-surgical orthodontics for element 46 are extrusion (22/32), on average of 2.41 mm and positive sagittal expansion (20/32), on average of 5.99 mm. The thickness bone response is negative for both movements in the Middle points (respectively of 0.12 mm and 0.06 mm) and Apical (respectively 0.16 mm and 0.09 mm) while it is positive for both movements in the Alveolar point (respectively 0, 03 mm and 0.03 mm). The extrusion movement is correlated more frequently (10 cases out of 18) to a decrease in bone verticality, on average of 0.1 mm for each mm of extrusion. On the contrary, in 10 cases out of 20, the vertical bone apposition of 0.23 mm was corrected for each mm of tooth displacement. Following the extrusion movement in 4 cases out of 22 the bone height remained unchanged, as well as in 5 of the 20 cases of positive sagittal expansion. As previously mentioned, therefore, orthodontic treatment can have a whole series of contraindications, even against the dental elements.[82] Some studies demonstrate that integration of computer planning and intraoperative navigation for facial transplantation are possible with submillimeter accuracy. This approach can potentially improve preoperative planning, allowing ideal donor-recipient matching despite significant size mismatch, and accurate surgical execution. Furthermore, real-time cephalometry may be a valuable adjunct for adjusting and measuring "hybrid occlusion" in face-jaw-teeth transplantation and other orthognathic surgical procedures[83–88] However, it is always necessary to evaluate the final result and above all the cost/benefit ratio for the patient. These types of treatments in addition to solving orthodontic, orthopedic and functional problems, often solve aesthetic problems, influencing the patient's satisfaction with the treatment, despite precisely what involves the surgery, such as postoperative pain (Supplementary Digital Content, Table 6, 7, http://links.lww.com/SCS/B417).[89]

## CONCLUSION

The 3D study of the dental movements and the evaluation of the variation of the associated cortical buccal bone, suggests that a certain orthodontic movement of the dental element does not achieve an easily predictable bone variation. The same dental element, during the orthodontic treatment, is subjected to forces that push it in different directions and the final movement is determined by the predominance of one of these forces on the others. There are therefore no "purely unidirectional" movements. This impossibility enters in apparent opposition to the Pressure-Voltage Theory, according to which it can be expected that, following a movement of advancement of the incisors, a bone reabsorption on the pressure front is determined, perhaps also directly correlated to the extent of the move. With the present study it has been noticed how, both for the element 11 and for the element 41, a bone apposition on the pressure front, albeit small (from 0.01 to 0.48 mm for each mm of progress). The same slight bone apposition was however also found for the backward movement, for which, based on the Pressure-Tension Theory, one would have expected an opposition, but a decidedly greater entity; instead, the measured apposition is in the order of hundredths of a millimeter. Furthermore, the current study suggests that there is no direct proportionality relationship between the extent of bone apposition/resorption and the extent of dental movement: in fact, the results show relatively low values of bone formation and resorption. This relationship between the tooth and the bone has two main repercussions: on the one hand it protects the orthodontist in the movements of arch or advancement expansion, as the amount of the bone reabsorbed will be relatively lower than the dental movement that will be performed, on the other hand, if a patient presents a gingival recession, the orthodontist should consider that it will be necessary to move back a few millimeters a lower incisor to obtain a minimum of bone apposition on the buccal side. Since such large dental movements are often not possible, this need is an important limitation in the orthodontic field. The movements of advancement, retraction, intrusion and extrusion analyzed in the present study are consistent with the discrepancy diagram proposed by Profit (Fig. 3), which however does not take into account the alveolar bone surrounding the tooth but which, as shown now widely used in literature, it covers a fundamental role in the final result of orthodontic treatment together with soft tissues. It is therefore necessary to construct a diagram of ad hoc discrepancies for each patient in which the limits to dental movements are determined by the evaluation of the thickness of the cortical bone on CBCT. Finally, the present study suggests that the initial assessment of the patient through a CBCT examination may prove to be an important aid for the clinician, as it is able to provide "precious" information on the bone biotype for the choice of the most suitable treatment for each case. Today, in fact, we tend to avoid extraction treatments (which involve the extraction of 4 premolars) due to the psychological discomfort that is created to the patient and the aesthetic canons imposed by the society according to which a bi protrusion profile is optimal. This implies the need for an expansion of the dental arches through the orthodontic movement. If, however, the 3D evaluation of CBCT shows that the patient has a very thin thickness of vestibular cortical, non-extraction treatment would not be possible, or rather, could cause long-term periodontal damage difficult to solve and then opt for extraction of premolars and the resolution of malocclusion. If, on the other hand, the CBCT was found to be extensive, the patient could opt, also in accordance with the patient's aesthetic requirements, or for an extractive or non-extractive treatment. In more complex cases, where the decision is between an orthodontic camouflage and orthognathic surgery, the CBCT evaluation would provide indispensable information as the measurement of cortical bone thickness would allow the orthodontist to determine the limits of orthodontic treatment and then to assign the patient to a combined orthodontic-surgical treatment. For the more complex orthodontic cases, an assessment of bone thickness through CBCT would facilitate the therapeutic decisions of orthodontist and maxillofacial surgeon and avoid long-term periodontal damage to the patient. However, this protocol is not easy to be applied because the high exposure to ionizing radiation limits the use of the CBCT, according to the guidelines dictated by the SEDENTEXCT and EADMFR, to the cases that certainly need a combined ortho-surgical treatment. The presented study is the first work in the literature that addressed this topic by recruiting a relatively large number of patients. Moreover, it would be interesting to observe the bone behavior of the lingual cortical, which in the present study was not considered, and to divide the sample by orthodontic biomechanics technique used, in order to determine the possible existence of a more conservative technique than others.

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