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Research article

Primary stability evaluation of different morse cone implants in low-density artificial bone blocks: A comparison between high-and low-speed drilling

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ABSTRACT

This study aimed to evaluate various biomechanical parameters associated with the primary stability of Maestro and Due Cone implants placed in low-density artificial bones, prepared using high-speed drilling with irrigation and low-speed drilling without irrigation. The insertion torque (IT), removal torque (RT), and implant stability quotient (ISQ) values were recorded for Maestro and Due Cone implants placed in low-density polyurethane blocks (10 and 20 pounds per cubic foot (PCF) with and without a cortical layer) prepared using high-speed and low-speed with or without irrigation using a saline solution, respectively. A three-way ANOVA model and Tukey's post-hoc test were conducted, presenting data as means and standard deviations. *P*-values equal to or less than 0.05 were considered statistically significant. No statistically significant differences in IT, RT, and ISQ between drilling speeds were observed. However, Maestro implants exhibited lower IT and RT values after high- and low-speed drilling across almost all polyurethane blocks, significantly evident in the 20 PCF density block for IT and in the 20 PCF density block with the cortical layer for the RT with low-speed drilling (IT: 47.33 ± 10.02 Ncm and 16.00 ± 12.49 Ncm for Due Cone and Maestro implants, respectively, with $p < 0.01$; RT: 44.67 ± 22.81 Ncm and 20.01 ± 4.36 Ncm for Due Cone and Maestro implants, respectively, with $p < 0.05$) and among the same implant types inserted in different bone densities. Additionally, the study found that for all bone densities and drilling speeds, both implants registered ISQ values exceeding 60, except for the lowest-density polyurethane block. Overall, it can be inferred that low-speed drilling without irrigation achieved biomechanical parameters similar to conventional drilling with both implant types, even with lower IT values in the case of Maestro implants. These findings suggest a

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promising potential use of low-speed drilling without irrigation in specific clinical scenarios, particularly when focusing on preparation depth or when ensuring proper irrigation is challenging.

1. Introduction

The lasting success of dental implants relies on the interface quality between the implant and the bone. Branemark et al. [1] suggested that the healing of bone, coupled with osseointegration, is intricately linked to the initial stability of dental implants or their ability to resist micromotion. This stability, in turn, is influenced by different factors such as implant design, surgical technique, bone quality, applied load, and drilling speed [2]. Numerous in vitro and in vivo studies have concentrated on factors influencing and potentially jeopardizing osseointegration, resulting in implant failure. Preparing the bone site for the implant is pivotal in the development of osseointegration, as it facilitates the creation of an implant bone bed that corresponds to the dimensions of the fixture, thereby ensuring primary implant stability. While the focus has frequently been on the instruments used for bone preparation, the surgical protocol is also a commonly studied aspect. Generally, the implant bed can be prepared through single or gradual drilling [3–6]. The rise in temperature resulting from the preparation of implant sites and conventional drilling processes has the potential to impact the adjacent bone. Complications such as bone necrosis, delayed osseointegration, and implant failure may arise from thermal overload during implant site preparation, leading to irreversible damage to the bone after prolonged temperatures around 47 °C for 1 min [7–10]. Consequently, maintaining low temperatures during osteotomy is crucial, and it is highly recommended to employ a minimally traumatic approach when drilling into the bone in order to preserve bone tissue without compromising its potential for healing [11,12]. The irrigation method stands out as one of the most extensively studied parameters for managing the heat generated during the preparation of the implant site. Cooling methods include internal, external, or a combination of both. Typically, it is assumed that the largest increase in mean temperature occurs without any coolant irrigation, followed by external, internal, and combined irrigation, respectively [13–15].

Additionally, it is crucial to acknowledge that frictional forces during drilling procedures and implant insertion are also critically linked to the generation of titanium particles, which can induce immunological reactions and osteolysis, impacting the long-term success of implants. High-speed drilling may cause greater frictional wear on both the bone and the metallic surface. This can lead to the higher release of titanium particles. However, high-speed drilling might reduce mechanical friction by facilitating smoother cuts through the bone, potentially mitigating particle release. Instead, low-speed drilling may result in higher mechanical friction due to slower cutting, potentially increasing the generation of titanium particles. However, it might be less likely to cause thermal damage, provided heat dissipation is effectively managed. Moreover, irrigation helps cool the drill site, reduce thermal damage frictional forces, decrease the wear on the implant surface, and release titanium particles. The influence of drilling speeds and irrigation becomes even more significant in preclinical scenarios mimicking denser cortical bone regions compared to maxillary bones. The higher density and mechanical properties of cortical bone increase frictional forces during drilling and implant insertion, and high-speed drilling with irrigation is likely necessary to manage heat and reduce particle generation. Without irrigation, both high- and low-speed drilling can lead to significant particle release and thermal damage [11,16,17]. Nevertheless, no universally recognized optimal surgical drilling protocol exists, and various study models with differing approaches have been employed. In this context, the introduction of healing chambers on the implant body aims to alleviate peri-implant bone compression and the risk of bone necrosis [18,19]. This is associated with the empty spaces formed between the macro-structure of the implant and the bone hole site, swiftly filled by a blood clot upon implant insertion. Consequently, new bone forms through a process known as intra-membranous [20–23].

Low-density bone, often encountered in patients with conditions such as osteoporosis, presents a significant challenge in dental implantology. This demographic is frequently the target patient group for dental implants, necessitating a thorough understanding of implant performance in compromised bone conditions. Furthermore, numerous studies have indicated that lower initial stability is observed in low-density bone, and the thickness of the cortical layer significantly affects the initial stability of implants [24–26]. Poor primary stability in the low-density bone can lead to implant micro-movements, which impede osseointegration, reduce healing time before loading, and increase the early implant failures. Additionally, the choice of bone model has been diverse. In vitro studies commonly utilize rabbit or porcine bone models [27–29], although synthetic foam blocks, composed of polyurethane and exhibiting oral bone-like characteristics, have also been employed [30–33]. These blocks enable excellent reproducibility for testing dental implants and examining biomechanical parameters [34]. Indeed, synthetic bone blocks categorized according to the Misch classification [35,36] are accessible and divided into four distinct groups: (i) 40 pounds per cubic foot (PCF): simulating D1 bone, which is characterized by dense cortical bone and limited or absent trabecular bone (commonly found in the mandible symphysis); (ii) 30 PCF: representing D2 bone, with thick cortical bone and dense trabecular tissue (common in the anterior mandible and anterior maxilla); (iii) 20 PCF: corresponding to D3 bone, displaying thinner cortical bone and less dense trabecular bone (typical of the posterior mandible and maxilla); (iv) 10 PCF: emulating D4 bone, with sparse or absent cortical and thin trabecular tissues (typically found in the posterior maxilla).

Several in vivo and in vitro investigations assessed the implant primary stability by quantifying the maximum insertion torque (IT) during the implant placement process [37–40]. IT values can denote the force needed for the maximum clockwise movement that removes the bone. Employing an elevated IT proves beneficial in attaining primary stability by minimizing implant micromotion. Typically, for implant placement in healed ridges or fresh extraction sockets, forces of 30 Ncm or greater are frequently utilized, especially when immediate loading is part of the treatment plan. Higher IT values (≥50 Ncm) can help to reduce micromotion without harming the surrounding bone [41]. Conversely, the removal torque (RT) is the force needed to extract the implant from the material, offering a dependable method for evaluating primary stability. Importantly, it indirectly indicates the level of bone-to-implant contact (BIC) [42]. Resonance frequency analysis (RFA) is a crucial parameter for evaluating the implant stability quotient (ISQ) after the implant is placed. This technique proves invaluable in assessing the risk of implant failure and adds valuable insights on the predictability of dental implant procedures [43].

The collective impact of these factors on primary dental implant stability, especially in low-density and low-quality bone, remains uncertain [20,44]. This paper explores the influence of bone quality, and, notably, drill speed with or without irrigation on implant IT, RT, and ISQ in low-density artificial bone blocks. It also considered the impact of implant macro-geometry, specifically the introduction of healing chambers on a conical Morse cone implant (Maestro) compared to its control (Due Cone). The aim is to identify factors that mitigate damage when drilling dental implant sites and to address a critical gap in dental implantology. This study may be particularly relevant for improving the clinical management of patients with osteoporosis, who represent a significant portion of the implant-requiring population.

2. Materials and methods

2.1. Bone models

Osteotomies were conducted on four artificial bone blocks (Nacional Ossos, São Paulo, Brazil), each representing distinct bone densities based on the Misch classification [35,36].

- A polyurethane block with a density of 10 PCF (cod. 10PCF-CP), equivalent to a density of 0.16 g/cm^3, simulating extremely low-density bone with poor mechanical properties, often representative of severely osteoporotic bone (D4 bone type);
- A polyurethane block with a density of 10 PCF and an additional layer at 40 PCF (cod. 10PCF-CP1), representing densities of 0.16 g/cm^3 and 0.96 g/cm^3, respectively, and mimicking a condition found in osteoporotic patients where the inner trabecular bone is compromised, but a thin, denser cortical bone layer remains (D4 bone type with a D1 cortical bone layer);
- A polyurethane bone block with a density of 20 PCF (cod. 20PCF - CP), corresponding to 0.32 g/cm^3, representing moderate osteoporosis: low-density bone that is somewhat better than severely osteoporotic bone but still represents compromised bone quality (D3 bone type);
- A polyurethane bone block with a density of 20 PCF and a 40 PCF density layer (cod. 20PCF-CP1), representing densities of 0.32 g/cm^3 and 0.96 g/cm^3, respectively. This configuration simulates moderate osteoporosis or localized areas of low bone density with preserved cortical integrity: low-density cancellous bone with a denser cortical bone layer with a slightly better overall bone quality than 10 PCF + 40 PCF (D3 bone type with a D1 cortical bone layer).

In this regard, the Misch classification systematically categorizes natural bone based on its cortical and trabecular microstructure

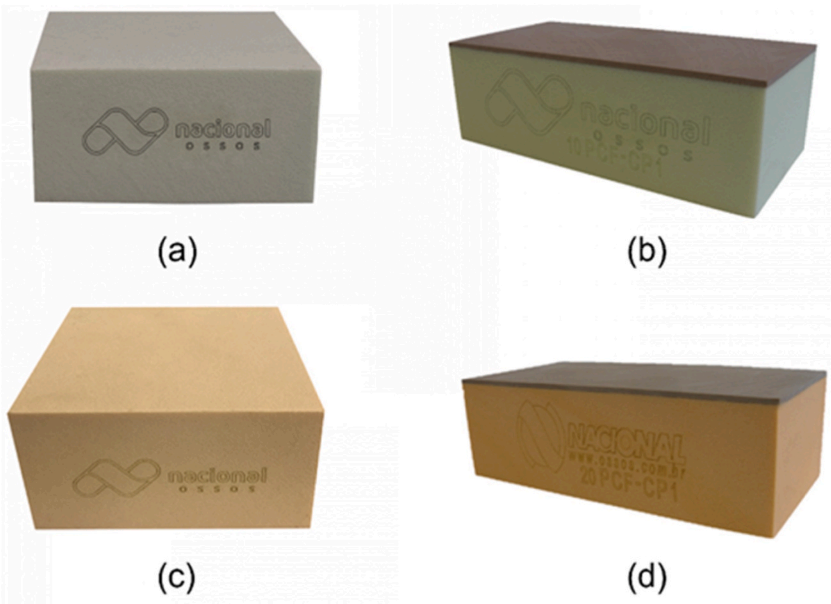

Fig. 1. Polyurethane foam blocks employed in the current study. (a) A block with a density of 10 pounds per cubic foot (PCF); (b) a block with a density of 10 PCF featuring a cortical layer with a density of 40 PCF; (c) a block with a density of 20 PCF; (d) a block with a density of 20 PCF incorporating a cortical layer with a density of 40 PCF.

density. Clinically, D1, D3, and D4 bone types correspond to the anterior mandible, posterior mandible and maxilla, and posterior maxilla, respectively. The synthetic bone blocks used in this study comprised solid, rigid polyurethane foam measuring 95 × 45 × 30 mm. These blocks either included or lacked a 1-mm thickness cortical layer. They served as a substitute for testing human cancellous bone. Although this material does not precisely mimic the structure of human bone, it exhibits mechanical properties within the range of human cancellous bone, as outlined by the ASTM F-1839-08 standard [34], and demonstrates high dimensional stability. Consequently, its current features position it as an excellent material for comparing the performance of screws, medical devices, and other instruments [45–47]. The artificial bone blocks used in this study are shown in Fig. 1 (a-d).

2.2. Implant drill

Two distinct implant models from Implacil De Bortoli (Cambuci, São Paulo, Brazil) were utilized: Maestro and Due Cone implants. Both implants share identical conical designs, surface treatments involving blasting with microparticles of titanium oxide, followed by the application of maleic acid, as well as progressive trapezoidal threads and internal Morse cone fittings. The macro-geometry features a straight head without micro-threads. The Maestro implants are characterized by grooves and healing chambers on the body, designed to enhance the stability of blood clots and facilitate early bone formation without inducing bone compression during the installation of the implant into bone tissue [48]. In contrast, the Due Cone implants have a more traditional design and thread configuration. All implants included in the study are 9 mm long and 4 mm in diameter. Fig. 2 (a,b) illustrates the implant designs.

The polyurethane samples were affixed to a metal base. Graphite marks were designed to indicate the center of the drilling zones. The perforations were performed 1 cm apart from each other. The drilling procedure adhered to the manufacturer's specifications and was calibrated by a single operator (NDB Jr). Notably, the manufacturer's drilling sequence was followed, starting with an initial Ø 2 mm drill and Ø 3.5 mm conical drill for bone bed under-sizing, particularly due to low bone densities. Drilling took place either at calibrated low speed (200 rpm) without irrigation or at high speed (800 rpm) with external irrigation using a saline solution, operating at 40 Ncm and 20 Ncm for low-speed and high-speed drilling, respectively.

2.3. Study design

Four implant groups were established according to the implant design and drilling method.

- Maestro implants inserted in all blocks using high-speed and external irrigation;
- Maestro implants inserted in all blocks with low speed and no irrigation;
- Due Cone implants inserted in all blocks using high-speed and external irrigation;
- Due Cone implants inserted in all blocks with low speed and no irrigation.

All groups underwent testing in four polyurethane bone models with various densities, as described earlier.

This study involved a total of 160 implants (80 Maestro and 80 Due Cone implants), following the scheme outlined in Fig. 3.

2.4. Biomechanical measurements

Implant insertion into the bone site was carried out using a surgical contra-angle handpiece (W&H Dentalwerk Bürmoos GmbH,

Fig. 2. Illustrative images of the utilized implants. (a) Maestro implants with healing chambers; (b) traditional conical Due Cone implants.

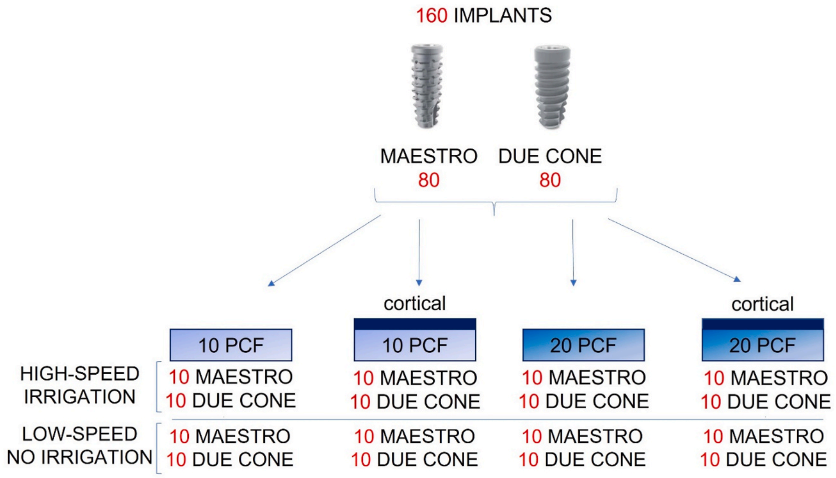

Fig. 3. Experimental study design.

Bürmoos, Austria) with a calibrated speed of 20 rpm, registering the IT and RT values in the last mm of the implant housing, which was considered at the level of the polyurethane surface profile. The maximum IT value was registered for each sample, and subsequently, the implants were extracted, and the maximum RT was recorded. The measurements for both IT and RT, expressed in Ncm, were acquired using a calibrated torque meter ranging from 5 to 80 Ncm (UNIKA, Oralplant Suisse, Mendriso, Switzerland) and documented using an advanced force and torque indicator (AFTI, Mecmesin, Slinfold, West Sussex, UK). After each installation, the ISQ was gauged using Smart-Pegs (Osstell Mentor Device, Integration Diagnostic AB, Savadelen, Sweden) screwed into the implant. The obtained values were processed using an electronic database within the ImpDat Plus software package v. 3.95 (East Lansing, MI, USA).

The ISQ values were measured on a scale ranging from 1 to 100, with a frequency range between 3,500 and 85,000 Hz. They were then classified into three categories: low stability (<60 ISQ), medium stability (60–70 ISQ), and high stability (>70 ISQ). The measurements were taken in two directions, with each sample being measured at a 90° angle apart in the bucco-lingual (BL) and mesio-distal (MD) directions.

2.5. Sample size calculation and statistical analysis

The study's sample size calculation and power analysis were conducted using the G*Power 3.1.9.7 program (Heinrich Heine Universität Düsseldorf, Düsseldorf, Germany) within the F tests family and an analysis of variance (ANOVA): fixed effects, special,

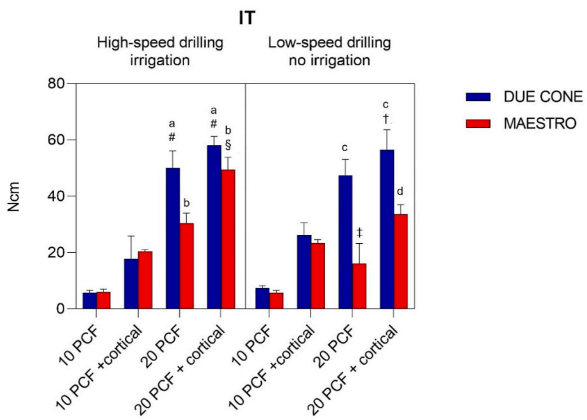

Fig. 4. Mean insertion torque (IT) values recorded for the implant types tested across various artificial bone densities and drilling speeds. a: statistical significance compared to Due Cone implants in the 10 PCF density block and high-speed drilling; b: statistical significance compared to Maestro implants in the 10 PCF density block and high-speed drilling; c: statistical significance compared to Due Cone implants in the 10 PCF density block and low-speed drilling; d: statistical significance compared to Maestro implants in the 10 PCF density block and low-speed drilling; #: statistical significance compared to Due Cone implants in the 10 PCF density block with cortical and high-speed drilling; §: statistical significance compared to Maestro implants in the 10 PCF density block with cortical and high-speed drilling; †: statistical significance compared to Due Cone implants in the 10 PCF density block with cortical and low-speed drilling; ‡: statistical significance compared to Due Cone implants in the 20 PCF density block and low-speed drilling.

main effects, and interactions statistical test (effect size: 0.4; α err: 0.05; power (1-β): 0.8; numerator df: 7; number of groups: 16). The dependent variables considered for the sample size calculation were the IT, RT, and the BL and MD ISQ measurements, while the independent variables were the implant designs (Maestro and Due Cone), the drilling conditions (high-speed with irrigation and low speed without irrigation), the bone densities (10 PCF and 20 PCF), and the presence or absence of a cortical layer. Consequently, the minimum sample size required for statistical significance was determined to be 112 implants, considering 7 samples per group. However, this study utilized a total of 160 implants, with 10 implants per group.

The 2 × 2 × 4 factorial design, incorporating the factors "drilling technique" (high-speed with irrigation and low-speed without irrigation), "implant type" (Maestro implants and Due Cone implants), and "artificial bone density" (10 PCF, 10 PCF + cortical, 20 PCF, and 20 PCF + cortical), was analyzed with a three-way ANOVA model, followed by Tukey's post-hoc test. Descriptive statistics were presented as means and corresponding standard deviations (SD). *P*-values equal to or less than 0.05 were considered statistically significant. The statistical analyses were conducted using GraphPad 9.0 software package (Prism, San Diego, CA, USA).

3. Results

3.1. Insertion torque (IT) outcomes

Fig. 4 compares average IT values across different implant types, artificial bone densities, and drilling techniques. The statistical significance for each intergroup comparison is detailed in Table 1 (Supplementary material S1).

The IT values measured for the Due Cone implants were significantly higher than those of the Maestro implants only in the 20 PCF density block with low-speed drilling and no irrigation (47.33 ± 10.02 Ncm and 16.00 ± 12.49 Ncm, respectively, with $p < 0.01$). Contrarily, no statistically significant differences between the implant types and drilling speeds were observed in all the other tested bone densities. The lowest IT values were registered in the 10 PCF density block for both implants and drilling speeds (5.67 ± 1.53 and 6.01 ± 1.73 Ncm for Due Cone and Maestro implants with high-speed and irrigation, respectively, and 7.33 ± 1.53 and 5.68 ± 1.54 Ncm for Due Cone and Maestro implants with low-speed and no irrigation, respectively). Moreover, both Due Cone and Maestro implants exhibited the highest IT values in the 20 PCF density block with the cortical layer with both high-speed drilling and irrigation (58.01 ± 5.57 Ncm and 49.33 ± 7.77 Ncm, respectively) and low-speed drilling (56.33 ± 12.66 Ncm and 33.67 ± 5.86 Ncm, respectively), without showing any significant differences between the two drilling speeds.

With high-speed drilling and irrigation, IT values of Due Cone implants in the 10 PCF density block were significantly lower than those registered for the 20 PCF density block with ($p < 0.0001$) and without the cortical layer ($p < 0.0001$). Due Cone implants inserted in the 10 PCF density block with the cortical layer also showed significantly lower values than those inserted in both the 20 PCF density block with ($p < 0.0001$) and without the cortical layer ($p < 0.01$). The same pattern was observed with Maestro implants, with $p < 0.0001$ and $p < 0.05$ when comparing the 10 PCF density block to 20 PCF density blocks with and without the cortical layer and the 10 PCF density block with cortical with the highest density block ($p < 0.01$).

On the other hand, with low-speed drilling and no irrigation, Due Cone implants inserted in the lowest density block exhibited significantly lower values compared to the 20 PCF density block with and without the cortical layer ($p < 0.0001$) Maestro implants also reported this behavior only towards the highest density block, with a $p < 0.01$. Additionally, Due Cone implants in the highest density block reported significantly higher results than those inserted in the 10 PCF density block with the cortical layer ($p < 0.01$).

3.2. Removal torque (RT) outcomes

The comparisons and statistical significance of the RT values recorded in all experimental groups are detailed in Fig. 5 and Table 2

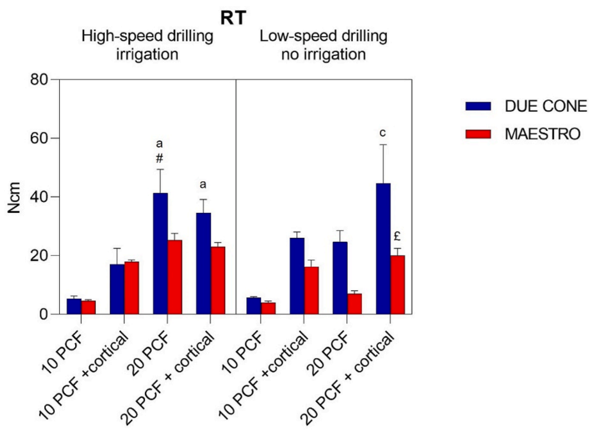

Fig. 5. Mean removal torque (RT) values recorded for implant types tested across various artificial bone densities and drilling speeds. £: statistical significance compared to Due Cone implants in the 20 PCF density block with cortical and low-speed drilling.

(Supplementary material S2).

No differences were noticed between the two implants in the 10 PCF, 20 PCF, and the corresponding density blocks with the cortical layer using high-speed drilling and irrigation. Similarly, no statistically significant differences were reported for the 10 and 20 PCF density blocks and the 10 PCF density block with the cortical layer using low-speed drilling. With low-speed drilling, both implants exhibited the highest RT values in the 20 PCF density block with cortical (44.67 ± 22.81 Ncm and 20.01 ± 4.36 Ncm for Due Cone and Maestro implants, respectively), reporting the only statistically significant difference between implant types, with $p < 0.05$.

Interestingly, the highest RT values expressed by both implants using high-speed drilling and irrigation were detected in the 20 PCF density block (41.33 ± 14.01 Ncm and 25.33 ± 4.04 Ncm for Due Cone and Maestro implants, respectively), even though no significant differences were reported compared to the highest density block. Overall, for Due Cone implants, the highest RT values were shown in the highest density block using low-speed drilling, whereas, for Maestro implants, they were found in the 20 PCF density block using high-speed drilling with irrigation.

Additionally, significantly higher RT values were found for Due Cone implants when comparing the lowest density block to the highest density blocks using high-speed drilling and irrigation ($p < 0.001$ vs. the 20 PCF density block, and $p < 0.01$ vs. the 20 PCF density block with the cortical layer) and the same density block to the 20 PCF density block with the cortical layer using low-speed drilling ($p < 0.0001$). Moreover, Due Cone implants inserted with high-speed drilling and irrigation reported significantly higher results when comparing the RT between the 10 PCF density block with cortical and the 20 PCF density block ($p < 0.05$). Contrarily, regarding the lowest RT values, Due Cone and Maestro implants inserted in the 10 PCF density block with high-speed and irrigation showed 5.33 ± 1.53 Ncm and 4.67 ± 0.58 Ncm, respectively.

3.3. Resonance frequency analysis (RFA) outcomes

Concerning the RFA, no statistical differences were shown in ISQ values when Due Cone and Maestro implants were compared in each polyurethane bone density and drilling technique. However, both implants displayed significantly lower ISQ values ($p < 0.001$ and $p < 0.0001$) when inserted into the 10 PCF density block with both drilling modes compared to all the other density blocks in MD and BL orientations.

Notably, in the MD direction, the lowest ISQ values were 49.33 ± 0.58 ISQ for Due Cone implants and 49.33 ± 6.03 ISQ for Maestro implants when inserted with high-speed drilling and irrigation, while 50.33 ± 2.31 ISQ for Due Cone implants and 45.33 ± 3.22 ISQ for Maestro implants using low-speed drilling. In the BL orientation, instead, the ISQ values were 46.33 ± 2.52 ISQ for Due Cone implants and 52.33 ± 0.58 ISQ for Maestro implants when inserted using high-speed drilling and irrigation, while 50.01 ± 1.73 ISQ for Due Cone implants and 52.02 ± 1.01 ISQ for Maestro implants using low-speed drilling.

Furthermore, significant distinctions were identified when comparing both implants inserted in the 10 PCF density block with the cortical layer to those inserted into the highest density block. Specifically, in the MD orientation, Due Cone implants expressed 63.00 ± 2.02 ISQ and 74.67 ± 1.16 ISQ ($p < 0.01$) with high-speed drilling and irrigation, and 63.01 ± 1.73 ISQ and 77.33 ± 2.52 ISQ ($p < 0.0001$) with low-speed drilling, respectively. Maestro implants showed 63.67 ± 3.79 ISQ and 74.33 ± 3.79 ISQ ($p < 0.01$) with high-speed drilling and irrigation, and 62.00 ± 2.03 ISQ and 76.04 ± 2.65 ISQ ($p < 0.0001$) with low-speed drilling, respectively. Additionally, with low-speed drilling and MD direction, Due Cone implants exhibited a significant difference in ISQ values between the 20 PCF and the 20 PCF density blocks with cortical ($p < 0.05$).

In the BL direction, Due Cone implants displayed 61.67 ± 0.58 ISQ and 73.68 ± 1.53 ISQ ($p < 0.0001$) between the 10 PCF density

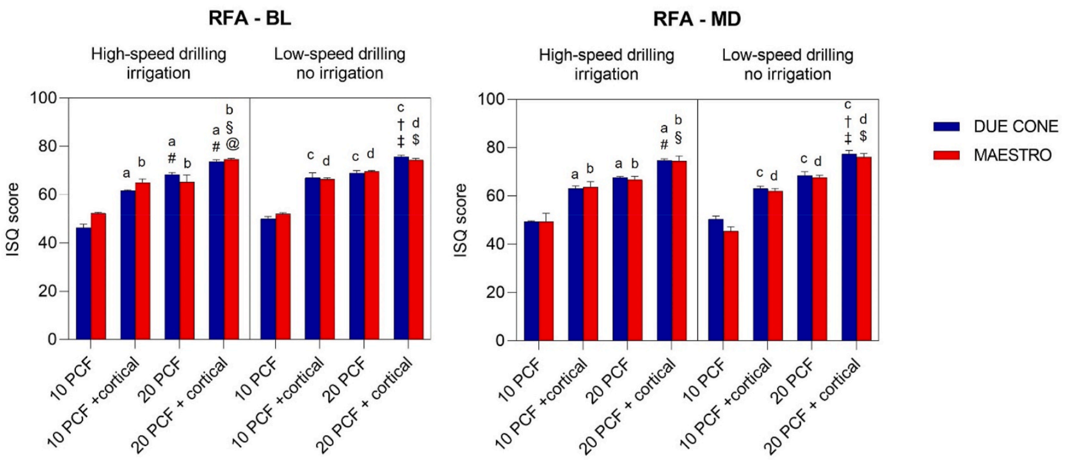

Fig. 6. Mean resonance frequency analysis (RFA) values recorded in bucco-lingual (RFA-BL) and mesio-distal (RFA-MD) orientations for implant types tested across varying artificial bone densities and drilling speeds. $: statistical significance compared to Maestro implants in the 10 PCF density block with cortical and low-speed drilling; @: statistical significance compared to Maestro implants in the 20 PCF density block and high-speed drilling.

block with cortical and highest density blocks with high-speed drilling and irrigation, and 67.03 ± 3.46 ISQ and 75.68 ± 0.58 ISQ ($p < 0.01$) with low-speed drilling, respectively. Maestro implants showed 65.01 ± 2.65 ISQ and 74.67 ± 0.58 ISQ ($p < 0.001$) with high-speed drilling and irrigation, and 66.33 ± 1.16 ISQ and 74.33 ± 1.16 ISQ ($p < 0.01$) with low-speed drilling, respectively. Moreover, the ISQ values registered for Due Cone implants placed in the 10 PCF density block with cortical using high-speed drilling and irrigation were significantly lower even when compared to the 20 PCF density block ($p < 0.05$). The same implants also registered significant differences when comparing the 20 PCF density block with the corresponding block with the cortical layer after low-speed drilling ($p < 0.05$). The same conditions reported a significant difference also per Maestro implants after high-speed drilling and irrigation ($p < 0.001$) (Fig. 6). Tables 3 and 4 in the Supplementary materials (S3 and S4) include Confidence Intervals (CI) and *p*-values for each intergroup comparison.

4. Discussion

Achieving optimal primary stability for dental implants is essential to ensure successful osseointegration and long-term success. The literature identifies various potential influencing factors, including implant macro- and micro-morphology, implant insertion force, bone quality, and drilling speed [1,2]. Hence, the focus of the present in vitro research was to assess various biomechanical parameters associated with implant primary stability in different implants placed in low-density artificial bones, prepared using either high rotational speed with irrigation or low rotational speed without irrigation. Based on the findings obtained, although no significant differences in IT, RT, and ISQ were identified between the drilling speeds, significantly higher IT and RT values were recorded for Due Cone implants compared to Maestro implants in the 20 PCF density block without and with the cortical layer, respectively, after low-speed drilling without irrigation. Similarly, significant variations were observed among the same implant inserted in different bone densities, underscoring the importance of bone quality and implant design as critical factors influencing implant primary stability [32,47,49].

Indeed, concerning the two drilling speeds employed in this study, no statistically significant differences were observed in IT, RT, and ISQ between the high-speed rotational drilling with irrigation and the low-speed rotational drilling without irrigation for both implants. However, it is worth noting that Maestro implants exhibited lower IT and RT values when subjected to low-speed drilling without irrigation across all polyurethane blocks. Specifically, for IT, low-speed drilling yielded values of 5.68 ± 1.54 Ncm, 23.33 ± 2.08 Ncm, 16.00 ± 12.49 Ncm, and 33.67 ± 5.86 Ncm in blocks with increasing density, in contrast to 6.01 ± 1.73 Ncm, 20.33 ± 1.16 Ncm, 30.33 ± 6.43 Ncm, and 49.33 ± 7.77 Ncm when the same implants were inserted with high-speed drilling and irrigation in the corresponding blocks. Similarly, for RT, low-speed drilling produced values of 4.02 ± 1.04 Ncm, 16.33 ± 3.79 Ncm, 7.03 ± 1.73 Ncm, and 20.01 ± 4.36 Ncm in blocks with increasing density, while high-speed drilling and irrigation resulted in values of 4.67 ± 0.58 Ncm, 18.02 ± 1.01 Ncm, 25.33 ± 4.04 Ncm, and 23.04 ± 2.65 Ncm in the same blocks with varying density.

In a clinical context, other investigations have indicated that low-speed drilling without irrigation appears analogous to traditional drilling when creating implant osteotomies. This approach achieves comparable levels of osseointegration, viability of bone cells, new bone formation, and bone resorption [50–52]. In specific scenarios, drilling at low speeds without irrigation may have benefits compared to traditional drilling, such as producing a greater quantity of harvested bone with more favorable cellular and histomorphologic properties, as well as longer drilling times and improved precision in creating osteotomies, leading to increased patient comfort [53,54]. Nevertheless, it is essential to note that differences in overheating and healing have been observed, especially when using very high rotational speeds [55]. The drilling process before implant insertion can generate high temperatures, potentially causing impaired turnover activity and necrotic zones in the surrounding bone [8,9,56]. Although low-speed drilling without irrigation may initially seem risky in high bone densities due to potential thermal damage, the temperatures during this process do not exceed the critical threshold for osteonecrosis, even in high bone densities, as indicated by in vitro thermal studies [57,58]. Nonetheless, the higher density and mechanical properties of cortical bone may increase frictional forces during drilling and implant insertion. Lower-density bone in the maxilla may generate fewer titanium particles due to reduced frictional forces. However, optimizing drilling protocols with appropriate speeds and irrigation is still crucial to minimizing particle release and ensuring primary stability [11,16,17].

Additionally, using artificial bone models allows for a controlled environment to systematically evaluate the influence of different drilling speeds, irrigation methods, and implant designs on primary stability. These models provide a reliable representation of the various bone qualities encountered in clinical practice, particularly in osteoporotic patients. Understanding the performance of implants in these artificial models directly informs clinical practices. The findings can lead to adjusting speeds and irrigation techniques based on bone density to enhance primary stability while minimizing thermal damage, choosing appropriate implant designs that offer better stability in low-density bone scenarios, and developing tailored treatment plans for patients with osteoporosis, ensuring higher success rates and improved outcomes. In this study, the more advanced design of the Maestro implants, including bone decompression niches, causes the accumulation of a significant amount of polyurethane debris, which clinically simulates a condition where bone chips would accumulate, acting as osteopromotive areas for osseointegration [20,22,31].

Furthermore, in accordance with existing literature [47,59], the IT values registered in this study were higher than the RT values across all polyurethane densities and implant designs. This discrepancy between IT and RT can be attributed to the limited viscoelastic properties of the synthetic bone surrounding the implant site, reducing resistance during removal [31]. As previously mentioned, the only statistically significant differences observed in this study for both IT and RT measurements were identified when comparing the two implant designs in the 20 PCF density block with low-speed drilling and no irrigation (IT values: 47.33 ± 10.02 Ncm and 16.00 ± 12.49 Ncm, for Due Cone and Maestro implants, respectively, with a $p < 0.01$) and in the 20 PCF density block with cortical layer under the same drilling conditions (RT values: 44.67 ± 22.81 Ncm and 20.01 ± 4.36 Ncm for Due Cone and Maestro implants, respectively, with a $p < 0.05$). Moreover, analogous to the RFA measurements, the current findings consistently demonstrated significantly higher values for both implants inserted in blocks with greater density (20 PCF and 20 PCF with cortical) than in the lowest density blocks of 10 PCF with and without the cortical layer. Besides this, significant RFA-MD and RFA-BL differences were also observed between the 10 PCF density blocks with and without a cortical layer recorded for the same implant type.

These results have been corroborated by other literature findings, emphasizing the impact of bone density and the presence of a cortical layer on biomechanical parameters associated with primary implant stability [24,26,60,61]. Mainly, whether using artificial bone blocks, animal bones, or human bones, a consistent positive correlation between bone density and the presence of a cortical layer and values related to IT, RT, and RFA has always been observed, regardless of the use of irrigation [62–65].

Concerning the scores recorded for the parameters employed in this research to evaluate implant stability, it is recognized that an IT falling within the range of 32–35 Ncm and an ISQ spanning from 60 to 65 would facilitate the possibility of immediate implant loading [66]. Based on the obtained results, it is evident that both Due Cone and Maestro implants demonstrated their highest IT values in the 20 PCF density block with cortical, regardless of whether high-speed drilling with irrigation (58.01 ± 5.57 Ncm and 49.33 ± 7.77 Ncm, respectively) or low-speed drilling was employed (56.33 ± 12.66 Ncm and 33.67 ± 5.86 Ncm, respectively). Notably, only the IT levels in the 10 PCF density blocks, with or without the cortical layer, were inadequate, except for Maestro implants, which achieved IT values exceeding 32 Ncm solely in the highest density block. As outlined in the literature [67], it is noteworthy that a high IT may not always correlate with a high ISQ, with high RFA values being potentially more favorable for immediate loading protocols to ensure enhanced BIC. Indeed, irrespective of bone density, both implants registered RFA values exceeding 60 ISQ, except for the lowest density polyurethane bone block, without reporting significant differences between implant designs but significant variations based on bone density and the presence of the cortical sheet. Consequently, it can be inferred that Maestro implants exhibited comparable implant stability to Due Cone implants despite having a lower IT. This phenomenon may be attributed to healing chambers on the Maestro surface, strategically designed to prevent peri-implant bone compression during installation, that mitigate the risk of bone necrosis and expedite the osseointegration process for enhanced secondary implant stability [68]. Although the function of healing niches could be enhanced by irrigation, helping to maintain bone health, preserve delicate bone structures, and prevent overheating, in this study, no statistically significant discrepancies in stability were noticed between the two drilling techniques.

From a clinical standpoint, the multi-step drilling involved in implant site preparation poses challenges for practitioners and patients. Therefore, streamlining the drilling process in implant surgery would be immensely beneficial, and a proposed solution involves the adoption of low-speed osteotomy without irrigation. This approach, widely utilized in guided implant surgery, enhances convenience for patients and surgeons. The objective of this study was to streamline the implant drilling process through low-speed drilling to improve the overall surgical procedure. Essentially, the aim was to assess whether biomechanical parameters related to implant stability could be deemed acceptable and valuable in conditions involving low speed and the absence of irrigation. Consequently, as a result of the obtained outcomes, it can be inferred that low-speed drilling without irrigation may achieve optimal primary stability comparable to high-speed drilling, except for the D4 bone type, regardless of the implant macro-design used, even with lower IT values in the case of Maestro implants. These findings may also hold clinical significance, suggesting that low-speed drilling without irrigation could be beneficial in specific clinical scenarios where a meticulous approach with a clearer view of the operating area is recommended. For example, this approach could be applicable during site preparation near important anatomical structures, when focusing on the depth of preparation, or when ensuring proper irrigation is challenging due to the use of surgical stents [69]. While low-speed drilling offers potential benefits in terms of reduced thermal damage and decreased procedure time, it also presents certain limitations that need to be addressed in clinical practice. They encompass the potential for incomplete osteotomy due to reduced cutting efficiency, especially in dense bone, the demand for a heightened level of operator skill and experience to accurately oversee the drilling process, and the possibility of bone fragmentation and debris accumulation. To mitigate these risks, it is imperative to implement precise drilling techniques, employ sharp and high-quality drills, utilize sequential drilling steps for ongoing process monitoring, offer comprehensive training and practice, and adopt fluted drill designs to facilitate the evacuation of bone chips. These measures are pivotal in ensuring a proper osteotomy.

In terms of the limitations of this study, it is essential to note that although rigid polyurethane foam blocks are commonly used in implant research due to their consistent and replicable testing properties and as an alternative to human cadaver and animal bones [34], they do not completely mimic the intricate characteristics of authentic bone. This includes the variations in human physiology, the natural response of bones, and the intricate microenvironment present in both healthy and diseased bone tissues. Consequently, due to the fact that this bone model is artificial, it is important to note that any results obtained from it cannot be directly compared to real-life clinical conditions. Furthermore, the absence of adequate lubrication during the in vitro procedure, such as the blood supply, may lead to potential overexpression of outcomes within this study. Nonetheless, validating this data by conducting both animal and clinical studies is imperative to ensure its future applicability and successful implementation. Moreover, further investigations encompassing other bone densities may be warranted to assess the stability of low-speed drilling comprehensively. Then, to enhance the practicality of using polyurethane blocks as a model for human bone to study implant behavior, particularly the stress and local deformations at implant-material contact points within healing chambers, the benefits of conducting biomechanical assessments through Finite Element Analysis (FEA) studies could be explored [70]. Additionally, in vitro and clinical investigations are warranted to enhance the scientific understanding of this matter, such as exploring the interplay between heat generation and biomechanical variables for measuring osseointegration, with the aim of establishing an ideal surgical drilling protocol. To ensure the long-term success of dental implants, it is also essential to refine drilling protocols in order to minimize titanium particle generation, particularly in low-density and dense cortical scenarios. The current study did not include measurements of titanium particle release or imaging of the implant surface post-drilling, but recognizing the importance of this factor, these evaluations will be incorporated into future investigations to refine our understanding of the best practices for minimizing adverse tissue responses.

5. Conclusions

In this in vitro study involving non-human bone tissue, the utilization of low-speed drilling without irrigation with both types of implants (Due Cone and Maestro) appears to exhibit biomechanical parameters similar to traditional drilling when preparing dental implant osteotomies. Furthermore, it was suggested that low-speed drilling without irrigation might enhance the clinical management of osteoporotic patients and contribute to more predictable and successful implant therapies in this demographic.

Data availability statements

All data are referenced and included in the article or supplementary material.

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CRediT authorship contribution statement

Tea Romasco: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Nilton De Bortoli Jr:** Supervision, Resources, Project administration, Conceptualization. **Joao Paulo De Bortoli:** Resources, Methodology. **Sergio Jorge Jayme:** Validation, Methodology. **Adriano Piattelli:** Supervision, Project administration, Conceptualization. **Natalia Di Pietro:** Writing – review & editing, Visualization, Validation, Supervision, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e35225.

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