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Research Paper

Biomechanical and histologic basis of osseodensification drilling for endosteal implant placement in low density bone. An experimental study in sheep

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ABSTRACT

A bone drilling concept, namely osseodensification, has been introduced for the placement of endosteal implants to increase primary stability through densification of the osteotomy walls. This study investigated the effect of osseodensification on the initial stability and early osseointegration of conical and parallel walled endosteal implants in low density bone. Five male sheep were used. Three implants were inserted in the ilium, bilaterally, totaling 30 implants ($n=15$ conical, and $n=15$ parallel). Each animal received 3 implants of each type, inserted into bone sites prepared as follows: (i) regular-drilling (R: 2 mm pilot, 3.2 mm, and 3.8 mm twist drills), (ii) clockwise osseodensification (CW), and (iii) counter-clockwise (CCW) osseodensification drilling with Densah Bur (Versah, Jackson, MI, USA): 2.0 mm pilot, 2.8 mm, and 3.8 mm multi-fluted burs. Insertion torque as a function of implant type and drilling technique, revealed higher values for osseodensification relative to R-drilling, regardless of implant macrogeometry. A significantly higher bone-to-implant contact (BIC) for both osseodensification techniques ($p<0.05$) was observed compared to R-drilling. There was no statistical difference in BIC as a function of implant type ($p=0.58$), nor in bone-area-fraction occupancy (BAFO) as a function of drilling technique ($p=0.22$), but there were higher levels of BAFO for parallel than conic implants ($p=0.001$). Six weeks after surgery, new bone formation along with remodeling sites was observed for all groups. Bone chips in proximity with the implants were seldom observed in the R-drilling group,

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but commonly observed in the CW, and more frequently under the CCW osseodensification technique. In low-density bone, endosteal implants present higher insertion torque levels when placed in osseodensification drilling sites, with no osseointegration impairment compared to standard subtractive drilling methods.

1. Introduction

Endosteal implants are used in a variety of medical procedures, varying from dental implants to orthopedic treatments. These devices play a key role in allowing for the rehabilitation of damaged tissue due to trauma and pathology (Coelho and Jimbo, 2014). The endosteal implant functions as anchorage into the bone, which ensures long-term stability. Osseointegration is achieved when there is a lack of negative responses in the periimplant tissue, generated for instance by surgical trauma, infection, or insufficient initial stability (Albrektsson et al., 1981).

The stability of the implant can be defined either as the mechanical stability between the implant and the bone, or the biological stability that is achieved by osseointegration (Raghavendra et al., 2005). Primary stability is achieved upon insertion of implant. It is based on the physical interactions between the bone and the implant (Halldin et al., 2011). It is directly related to bone quality and quantity (Yoon et al., 2011) as well as the macrogeometric aspect of the implant which keeps the implant in place through mechanical interlocking between the two solids (Coelho et al., 2015). It is essential to have substantial primary stability in order to avoid implant micromovement during initial bone remodeling. Primary stability reaches its highest level at the time of implant insertion and has been demonstrated to decrease over time (Gomes et al., 2013). The transition in the type of stability occurs as bone apposition to the implant progresses, which securely stabilizes the device in place (Gomes et al., 2013).

The speed of secondary stability establishment fluctuates due to the fact that it is based on the extent and rate of bone remodeling around the implant. The bone remodeling rate that is key for the transition between primary and secondary stability has been known to vary depending on patient and implant system design related factors (Albrektsson et al., 1981). Thus, the overall stability of the implant follows a positive parabolic function, where it decreases at first due to the reduction in the primary stability as a function of time, then begins to increase again due to the initiation of secondary stability to secure device biomechanical competence.

Surface engineering and implant macrogeometric engineering have been the most investigated variables with respect to how endosteal implant temporal stability is affected, whereas the literature concerning drilling effects on implant primary stability and osseointegration is smaller by at least one order of magnitude (Coelho et al., 2015). While a substantially smaller body of literature concerns surgical instrumentation methods effects on osseointegration, recent work has pointed that osseointegration may be accelerated through adjustments in drilling protocol sequence, drill velocity, and design (Galli et al., 2015; Giro et al., 2011, 2013; Sarendranath et al., 2015; Yeniyol et al., 2013). A previous investigation has demonstrated that site preparation with multi stepped drills have increased implant primary stability relative to conical shaped drills further supporting the key role that surgical instrumentation plays on the overall bone/implant system biomechanical behavior (Abboud et al., 2015). The vast majority of studies investigating drilling methods for endosteal implant placement comprises the subtractive bone activity of the drills performed under the assumption that bone particles would be drilled out so the device may be properly inserted in place.

Recently, a drilling concept has been introduced for the placement of endosteal implants through an osseodensification drilling (Huwais, 2014, 2013). The theory behind this technique is that drill designing allows the creation of an environment that increases the initial primary stability through densification of the osteotomy site walls by means of non-subtractive drilling. The rationale for the utilization of this process is that densification of the bone that will immediately be in contact to the endosteal device will not only result in higher degrees of primary stability due to physical interlocking (higher degrees of contact) between the bone and the device, but also in faster new bone growth formation due to osteoblasts nucleating on instrumented bone that is in close proximity with the implant (Jimbo et al., 2014b). In summary, osseodensification is performed in an attempt to develop a condensed autograft surrounding the implant (Huwais and Meyer, 2016).

In contrast to the conventional drilling process, which uses a positive rake angle to extract a small thickness of material with the passing of each flute creating an osteotomy with no bone residue remaining in the hole, the osseodensification drilling process begins with the creation of an osteotomy using a tapered, multi-fluted bur drill. This procedure utilizes four tapered flutes at a negative rake angle to create a layer of compact, dense bone surrounding the wall of the osteotomy. The densifying bur presents a cutting chisel and tapered shank allowing it to progressively increase the diameter as it is moved deeper into the bone site, which controls the expansion process. The expansion occurs at high speed and can operate in both counterclockwise (CCW) or clockwise (CW) cutting directions, where the former more efficiently exerts the densification process than the later and thus are respectively indicated for low and high density bones. While the osseodensification drilling process has been demonstrated in bench top in vitro studies (Huwais and Meyer, 2016) and in an animal study (Trisi et al., 2016), quantification of its biomechanical and biological basis in a highly translational preclinical large animal model is warranted.

The objective of this study was to evaluate the effect of osseodensification on the initial stability and early osseointegration of endosteal implants presenting a conical and a parallel wall macrogeometries. Two hypotheses were tested, and included (i) both macrogeometries would present higher insertion torque levels when placed in osseodensification drilling sites, (ii) no osseointegration impairment or decrease would be observed for implants placed in osseodensification drilled sites relative to control subtractive methods.

2. Materials and methods

Two types of implants, the conical (Axis, TAG, Israel) (C) and the parallel (Massif, TAG, Israel) (P), were included in this study. Both implant types presented a textured surface. Implant dimensions were 4.2 mm in diameter and 10 mm in length. Details about the implants design (according to the manufacturer) are as follows. The Massif implant presents a parallel configuration along its length with a microthreads at the cerivical region along with a progressive reverse buttress double threads of 1.6 mm pitch. The Axis implant presents a conical configuration along its length with microthreads at the cervical region along with reverse buttress double threads of 2.0 mm pitch. The surface roughness and microgeometry of the implants were achieved by blasting the surface with aluminum oxide followed by double acid etching. The roughness index, Ra is 1.8–2.2 um. The implants were sterilized by gamma-radiation.

3. Preclinical *in vivo* model

A highly translational large preclinical animal model was used in the present study. The sheep hip model was selected due to its low density bone configuration and its size that would allow the placement of all experimental groups nested within each subject so statistical power was maximized and the number of animals minimized. The study was conducted according to the ethical approval from the Institutional Animal Care and Use Committee of the Ecole Veterinaire d'Alfort under ARRIVE guidelines. Five male sheep (each weighing approximately 120 pounds) were used in this study. Three implants were inserted in the ilium bilaterally resulting in a total of 30 implants ($n=15$ conical and $n=15$ parallel walled). Each animal received 3 implants of each type, inserted into bone sites prepared through different methods: (i) regular drilling (R-recommended by manufacturer) in a 3 step series of a 2 mm pilot, 3.2 mm and 3.8 mm twist drills, (ii) clockwise (CW) drilling with Densah Bur (Versah, Jackson, MI, USA) 2.0 mm pilot, 2.8 mm, and 3.8 mm multi fluted tapered burs, and (iii) osseodensification counterclockwise (CCW) drilling with Densah Bur (Versah, Jackson, MI, USA) 2.0 mm pilot, 2.8 mm, and 3.8 mm multi fluted tapered burs. Drilling was performed at 1100 rpm and saline irrigation. Experimental group distribution was interpolated as a function of animal subject to minimize location bias.

Prior to surgery, anesthesia was induced with sodium pentothal (15–20 mg/kg) in Normasol solution into the jugular vein and maintained with isofluorane (1.5–3%) in O_2/N_2O (50/50). Animal monitoring included ECG, end tidal CO_2, and SpO_2 and body temperature which was regulated by a circulating hot water blanket. Prior to surgery, the surgical site was shaved and iodine solution was applied to prepare surgical site. A 10 cm incision was placed in the antero-posterior direction over the ilium, dissections of fat tissue were performed and muscular tissue was reached. Dissection of muscular plane was performed with blunt dissection and the ilium was exposed using a periosteal elevator. Three implants per animal were inserted in the right and left ilium bones resulting in a total of 30 implants ($n=15$ conical and $n=15$ parallel walled). Each animal received $n=3$ implants of each type, inserted into bone sites prepared through different methods: (i) regular drilling (R-recommended by manufacturer), (ii) clockwise (CW) drilling with Densah Bur (Versah, Jackson, MI, USA), and (iii) osseodensification counterclockwise (CCW) drilling with Densah Bur (Versah, Jackson, MI, USA). Drilling was performed at 1100 rpm and saline irrigation. The outer final diameter of all drills utilized was 3.8 mm. Experimental group distribution was interpolated as a function of animal subject to minimize location bias. The insertion torque of all implants was performed to the cortical level and was recorded by a digital torque meter (Tonichi STC2-G, Tonishi, Japan). Layered closure with Vicryl 2-0 for muscle and 2-0 nylon for skin was performed. Cefazolin (500 mg) was administered intravenously pre-operatively and post-operatively. Post-operatively, food and water ad libitum was offered to the animals. Six weeks after surgery, the animals were sacrificed by anesthesia overdose.

4. Histological preparation and histomorphometry

Each experimental group was processed for histological and histomorphometric evaluation via progressive dehydration in ethanol and methyl salicylate prior to final embedding in methylmethacrylate (MMA). Standard non-decalcified histological sections were prepared for each implant specimen according to standardized methodology. The samples were then sectioned along the implant's long axis with a slow-speed precision diamond saw (Isomet 2000, Buehler Ltd., Lake Bluff, IL, USA) as thin slices of $\sim$300 μm thickness. Each tissue section was glued to an acrylic plate with a photolabile acrylate-based adhesive (Technovit 7210 VLC adhesive, Heraeus Kulzer GMBH, Wehrheim, Germany) before grinding and polishing under abundant water irrigation with progressively rougher silicon carbide (SiC) abrasive papers (400, 600, 800, and 1200) (Metaserv 3000, Buehler Ltd., Lake Bluff, IL, USA) to a final thickness of 50 μm. The final sections were subsequently stained with Stevenel's Blue and Van Gieson's Picro Fuschin (SVG) stains. Histological observations and images were collected with an automated slide scanning system and specialized computer software (Aperio Technologies, Vista, CA, USA). Histomorphometric evaluation was completed with specific image analysis software (ImageJ, NIH, Bethesda, MD). Bone-implant contact (BIC) and bone area fraction occupancy

(BAFO) were quantified to evaluate the osteogenic parameters around the peri-implant surface. BIC determines the degree of osseointegration by tabulating the bone percentage of bone contact over the entire relevant implant surface perimeter. BAFO measures the quantity of bone (newly formed and non-vital autografted/native bone due to instrumentation) within the implant threads as a percentage.

5. Statistical analysis

All histomorphometric and biomechanical testing data are presented as mean values with the corresponding 95% confidence interval values (mean±95% CI). Insertion torque, %BIC, and %BAFO data were used to generate a linear mixed model with fixed factors of implant macrogeometry (C and P) and surgical drilling method (R, CW, CCW) and a random intercept. Given a significant omnibus test, post-hoc comparison of the 3 drilling technique means was accomplished using a pooled estimate of the standard error. Preliminary analyses showed homogeneous variances in the analysis of all 3 dependent variables (Levene test, all $p > .25$). All analysis was completed with IBM SPSS (v22, IBM Corp., Armonk, NY).

6. Results

Uneventful immediate post-operative clinical parameters were observed for all subjects. Five days post-operatively, one subject presented signs of infection on the surgical site and was immediately treated with antibiotics. Due to infection presence, only the insertion torque data collected from this subject was included (BIC and BAFO excluded) in the statistical analysis.

Insertion torque was approximately 25 N cm in the R condition, which increased to near 100 N cm in the CW and CCW conditions (Fig. 1a). Statistical analysis of insertion torque as a function of drilling technique (collapsed over implant type) showed that both osseodensification drilling techniques (CCW and CW) presented significantly higher insertion torque values relative to R drilling ($p < 0.001$) (Fig. 1a). There was no statistical difference in insertion torque as a function of implant type (collapsed over drilling technique) ($p = 0.60$) (Fig. 2a). When insertion torque was evaluated as a function of both implant type and drilling technique, osseodensification instrumentations (CCW and CW) presented higher values relative to R drilling irrespective of implant type considered (Fig. 3a).

BIC (Fig. 1b) values were approximately 50% in the R condition, which increased to above 60 and near 70% in the

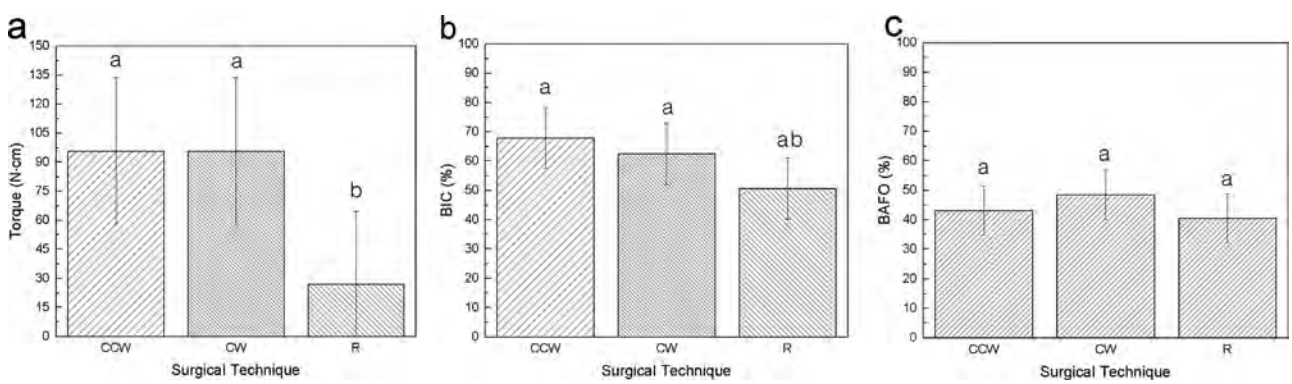

Fig. 1 – (a) Insertion torque, (b) BIC, and (c) BAFO as a function of drilling technique (collapsed over implant type). The letters indicate statistically homogeneous groups.

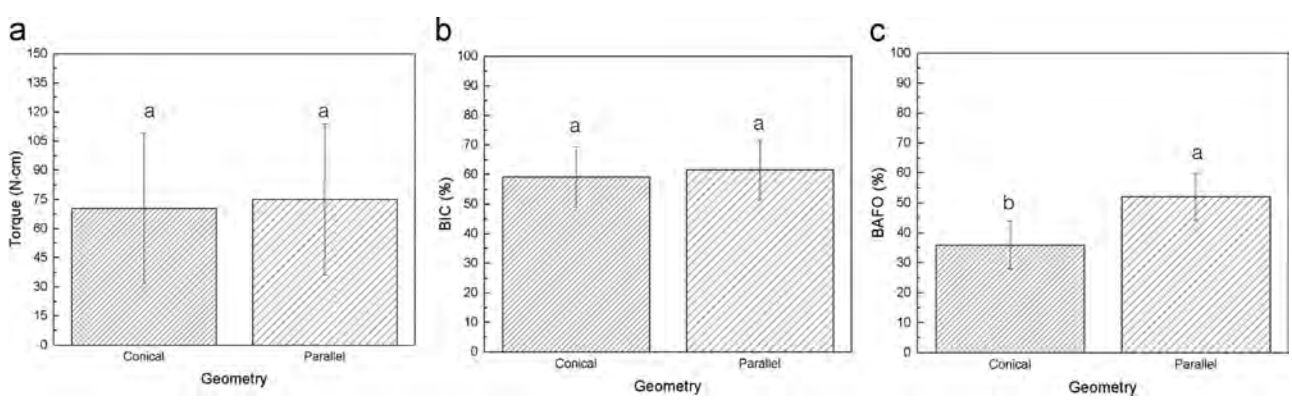

Fig. 2 – (a) Insertion torque, (b) BIC, and (c) BAFO as a function of implant type (collapsed over drilling technique). The letters indicate statistically homogeneous groups.

CW and CCW osseodensification conditions, respectively. Statistical analysis showed an effect of drilling technique ($p=0.01$) and post-hoc tests indicated significantly higher levels of BIC% for both osseodensification (CCW and CW) drilling techniques ($p<0.05$) relative to R technique. There was no statistical difference in BIC as a function of implant type (collapsed over drilling technique) ($p=0.58$) (Fig. 2b). While the CW drilling technique for the P implant type was higher than the R drilling technique, the CW drilling technique presented intermediate values between CCW and R for the C implant type (Fig. 3b).

There was no statistical difference in BAFO as a function of drilling technique (collapsed over implant) ($p=0.22$) (Fig. 1c). Fig. 2c shows BAFO% of about 35% in the conic type implant and above 50% in the parallel wall implant. Statistical analysis showed higher levels of BAFO% for parallel than conic implants ($p=0.001$). There was no statistical difference in BAFO as a function of both implant type and drilling technique ($p=0.52$) (Fig. 3c).

When the new bone to autografted/native bone presence was accounted relative to the total bone amount observed between threads, a significantly higher value was observed for the CCW group relative to the R group ($p=0.041$) (CW presenting intermediate values) (Fig. 4a). No differences in the amount of autografted bone/native bone was observed between implant type ($p=0.18$) (Fig. 4b). Comparisons between all drilling techniques and implant type showed that the CCW surgical instrumentation presented overall higher values relative to CW, followed by the R groups (Fig. 4c). The only significant difference ($p=0.04$) within implant group was detected between CCW and R for the parallel implant group (Fig. 4c).

Survey histologic evaluation showed osseointegration of all implants considered for statistical analysis (Figs. 5 and 6). The osseointegration pattern for both conical (Fig. 5) and parallel walled (Fig. 6) implants presented similar features. Regardless of implant type and drilling technique employed, the cortical shell surrounding the implant presented extensive remodeling with sites of bone resorption along with sites of new bone formation in close proximity with the implant surface (Figs. 5 and 6). Survey imaging showed new bone formation for both implant types placed under the R drilling technique at both cortical and trabecular regions with seldom presence of bone chips (Figs. 5a and 6a), whereas the presence of drilling bone chips were present in proximity with both implant types placed under the CW (Figs. 5b and 6b) and CCW (Figs. 5c and 6c) osseodensification drilling techniques to lower and higher extent, respectively. The presence of bone chips was more pronounced for implants placed in the CCW drilling technique, where these bone chips were observed along the length and within thread regions of both implant types (Figs. 5c and 6c). Regardless of implant

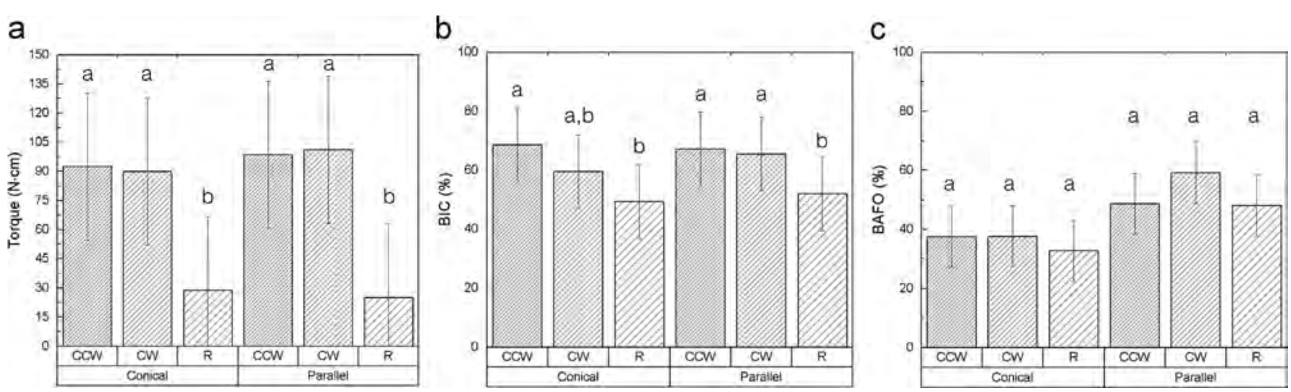

Fig. 3 – (a) Insertion torque, (b) BIC, and (c) BAFO as a function of implant type and drilling technique. The letters indicate statistically homogeneous groups.

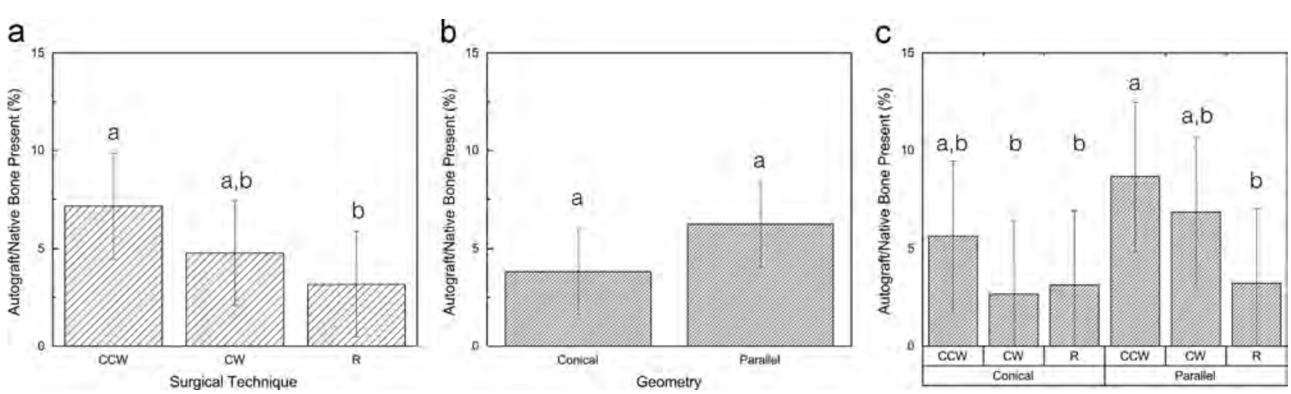

Fig. 4 – Autograft/native bone % presence between threads as a function of (a) drilling technique, (b) Implant type, and (c) drilling technique and implant type. The letters indicate statistically homogeneous groups.

Fig. 5 – Survey optical micrographs for conical implants placed on (a) R, (b) CW, and (c) CCW drilling techniques. The white arrows depict bone chip residues from surgical instrumentation.

Fig. 6 – Survey optical micrographs for parallel-walled implants placed on (a) R, (b) CW, and (c) CCW drilling techniques. The white arrows depict bone chip residues from surgical instrumentation.

type and drilling technique employed and the amount of bone chips from surgical instrumentation present at the interface, the bone chips yielded new bone formation on their surface (Figs. 7 and 8).

Higher magnification evaluation of the bone-implant interface of all groups further supported survey observations, where remodeling was occurring along with bone formation at interfacial cortical regions for all groups (Figs. 7 and 8). At trabecular

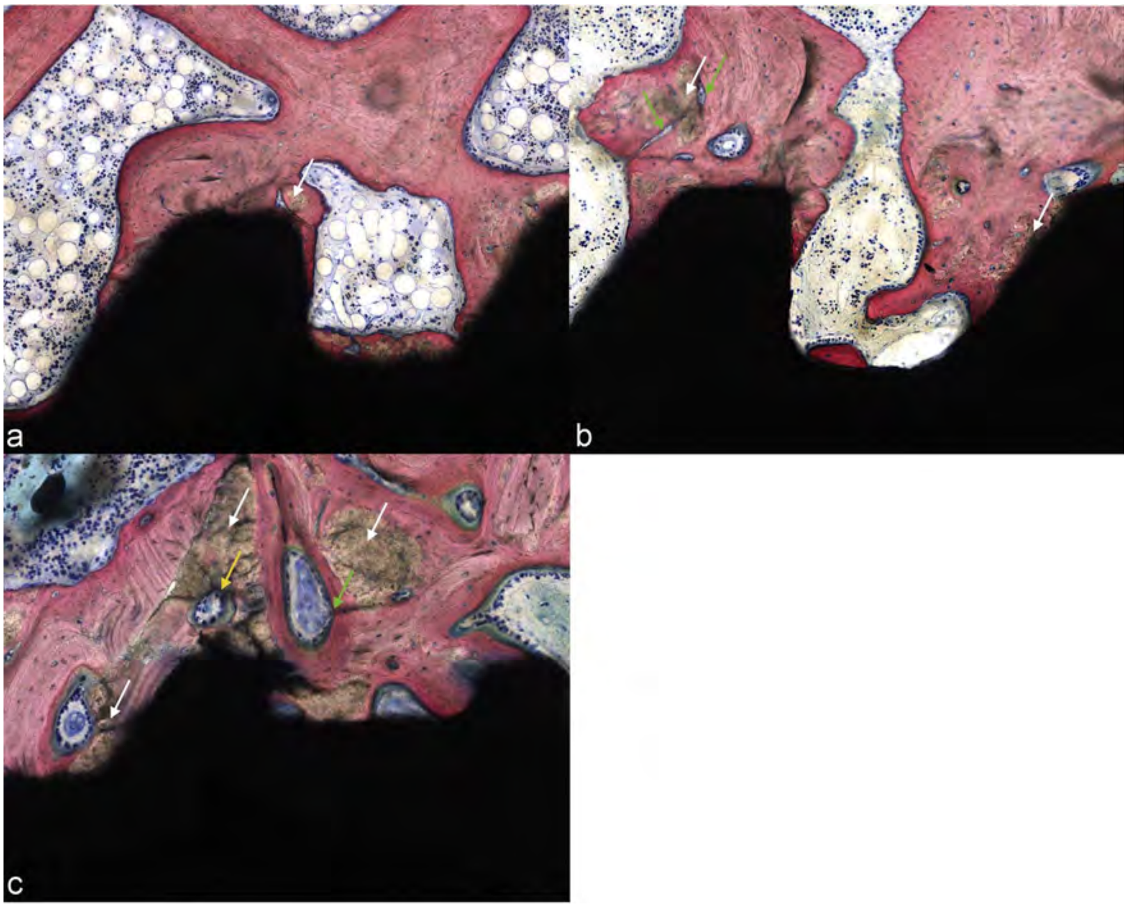

Fig. 7 – Higher magnification optical micrographs depicting the bone-conic implant interface for the (a) R, (b) CW, and (c) CCW drilling techniques. The white arrows depict bone chip residues from surgical instrumentation, yellow arrows through bone chip remodeling sites, and green arrows bone chip surface remodeling sites. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

regions, new bone formation occurred in proximity with the implants of all groups. New bone growth around the CW and CCW osseodensification drilling techniques also took place at the bone chips surface present around both implant types (Figs. 7b–c and 8b–c). Surface and bulk bone chip remodeling sites were also evident at high magnification (Figs. 7b–c and 8b–c).

7. Discussion

This study investigated the effect of osseodensification drilling procedure in a sheep hip model. Since the hip model represents a poor density situation (Galli et al., 2015; Jimbo et al., 2014c; Yoo et al., 2014), it was selected a suitable model to test the effect of the technique. The results unequivocally showed that the osseodensification drilling regimen significantly enhanced insertion torque values, considered in this study as a method to gauge device primary stability. After 6 weeks *in vivo*, histometric results suggest that the experimental groups drill design positively influenced osseointegration when utilized in both clockwise or counterclockwise (osseodensification) rotation directions.

No differences could be observed when bone area fraction occupancy percentage (BAFO%) was evaluated. These results can be explained by the fact that the osseodensification is influential at the intimate interface between the implant and the bone as represented by the increased insertion torque values in the test groups (Jimbo et al., 2014a, 2014b). Further, the histological micrographs showed that the condensed bone that allowed increased degrees of insertion torque for the osseodensification groups acted as nucleating surfaces that facilitated bridging gaps between the implant and the bone enabling larger degrees of bone apposition towards the implant surface. Our results showed that BAFO was significantly affected by implant macrogeometry and such result likely is related to interplay between the different implant inner thread diameter relative to the instrumentation diameter observed between implant types that led to smaller areas to be filled for the parallel walled implant design.

The concept of improving the quality/quantity of bone around the implant to increase its stability has been previously explored and mainly focused on achieving improved initial stability in sites where sinus elevation is necessary (Summers, 1994, 1998; Zitzmann and Scharer, 1998). The so-called osteotome technique compresses the surrounding bone by gradual expansion using the hand driven devices leading to enhanced insertion torque values that is often perceived by clinicians as an indication of improved primary

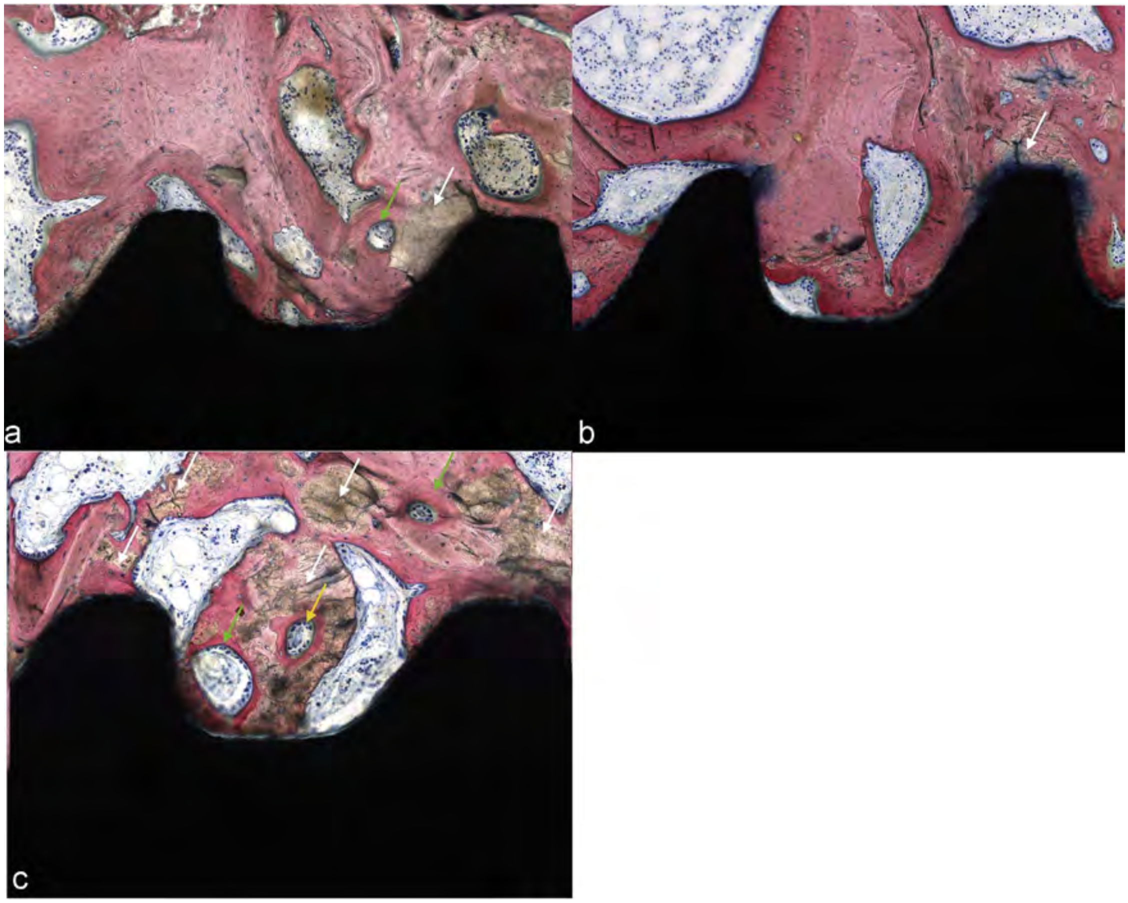

Fig. 8 – Higher magnification optical micrographs depicting the bone-parallel-walled implant interface for the (a) R, (b) CW, and (c) CCW drilling techniques. The white arrows depict bone chip residues from surgical instrumentation, yellow arrows through bone chip remodeling sites, and green arrows bone chip surface remodeling sites. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

stability. To date, there is insufficient evidence that this technique results in superior clinical outcomes than the other available site preparation techniques.

It has been reported by (Buchter et al., 2005) that the osteotome technique hampers the bone remodeling unit and causes ultrastructural microdamage, and that the biomechanical stability may be significantly decreased shortly after implant placement (Zitzmann and Scharer, 1998). In their study, the osteotomed group presented microfractures, which was evident histologically and the removal torque values measured were significantly lower for the same group compared to the non-condensed group. It was concluded in their study, that the traumatic damage caused in the bone delays the achievement of secondary stability, since of time needs to be dedicated to repair the microdamage, which stimulates osteoclast activation (Frost, 1998; Mori et al., 1993).

Another technique previously used to improve the quality/quantity of bone around the implant in challenging scenarios comprises ridge expansion or spreading utilizing screw type expanders is reported to expand bone and create an osteotomy without removing any bone stock but rather displacing it (Cortes and Cortes, 2010). Mazzocco et al. (2011) reported that the motorized rotary expander technique appears to be as effective as the lateral ridge augmentation technique in increasing the thickness of atrophic ridges. On the other hand, buccal plate fracture during this procedure, may affect implant insertion stability (Lee and Anitua, 2006). The Rotary expanders threading pattern creates a direct relationship between the feed rate and the expansion rate, which may negatively affect the surgeon's control (Huwais, 2013).

The osseodensification drilling technique utilized in the current study, however, presented different outcomes. While interfacial remodeling was observed where primary engagement existed between the bone cortical shell and both implant types regardless of surgical instrumentation, no negative bone response features such as extensive microcracks and extensive remodeling leaving large void spaces between implant and native bone that could potentially compromise the system biomechanical competence was observed, regardless of implant type and surgical instrumentation employed. At trabecular regions, osseointegration proceeded for all groups despite the presence of non-vital bone debris that were in close proximity with the implant bulk for the clockwise experimental group and more so for the counterclockwise osseodensification group. These non-vital bone debris acted as autografts as previously reported by Jimbo et al. (2014b) in a sheep model. Our histologic observations also demonstrated that these autografted particles were under active superficial and bulk remodeling, and presented direct new bone formation on their surfaces and through their bulk often times bridging particles and implants.

The lack of negative osseointegration events may be explained by our histomorphologic and histometric results, where it was observed that osseodensification does not only improve primary stability and bone contact through the reversed compression exerted due to elastic bone springback effect (Huwais and Meyer, 2016), but also due to site densification due to instrumentation related autografting. The seldom observation of non-vital bone particles acting as new bone formation nucleating sites around implants placed under the R drilling technique strongly suggests that the bone debris were either removed or rinsed away by the R subtractive method. Our histologic sections demonstrated that the experimental drill design when employed in CW mode also resulted in the presence of autograft particles around the implant albeit to lower extent relative to the CCW osseodensification instrumentation.

The postulated null hypotheses which stated that: (i) both macrogeometries would present higher insertion torque levels when placed in osseodensification drilling sites, and (ii) that no osseointegration impairment or decrease would be observed for implants placed in osseodensification drilled sites relative to control subtractive methods were accepted. The results of the current study suggest that regardless of implant macrogeometry, the experimental osseodensification drilling techniques have presented improvements in primary stability and bone-to-implant contact due to the densification of autologous bone debris acting as compacted autograft. Future studies comprising shorter and longer term *in vivo* time points are warranted so the osseointegration pathway through osseodensification is further characterized.

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