“Peroperative Estimation of Bone Quality and Primary Dental Implant Stability”

Benjamin Voumard¹, Ghislain Maquer¹, Peter Heuberger², Philippe K. Zysset¹*, Uwe Wolfram¹,³

¹ Institute for Surgical Technology and Biomechanics, University of Bern, Stauffacherstrasse 78, 3014 Bern, Switzerland
² Biomechanics Research, Nobel Biocare Services AG, Balsberg Balz Zimmermann-Strasse 7, 8302 Kloten, Switzerland
³ Institute for Mechanical, Process and Energy Engineering, Heriot-Watt University, UK EH14 4AS, Edinburgh, United Kingdom

*Corresponding author: Philippe Zysset, Institute for Surgical Technology and Biomechanics, University of Bern, Stauffacherstrasse 78, 3014 Bern, Switzerland, Tel.: +41 31 631 59 25; fax: +41 31 631 59 60. philippe.zysset@istb.unibe.ch

ABSTRACT

Objectives:

Dental implants are widely used to restore function and appearance. It may be essential to choose the appropriate drilling protocol and implant design in order to optimise primary stability. This could be achieved based on an assessment of the implantation site with respect to bone quality and objective biomechanical descriptors such as stiffness and strength of the bone-implant system. The aim of this ex vivo study is to relate these descriptors with bone quality, with a pre-implantation indicator of implant stability: pilot-hole drilling force (Fdrilling), and with two post-implantation indicators: maximal implantation torque (Timplantation) and resonance frequency analysis (RFA).

Methods:

Eighty trabecular bone specimens were cored from human vertebrae and bovine tibiae. Bone volume fraction (BV/TV), a representative for bone quality, was obtained through micro-computed tomography scans. Implants were kept in controlled laboratory conditions following standard surgical procedures. Forces and torques were recorded and RFA was assessed after implantation. Off-axis compression tests were conducted on the implants until failure. Implant stability was identified by
stiffness and ultimate force ($F_{\text{ultimate}}$). The relationships between BV/TV, Stiffness, $F_{\text{ultimate}}$ and $F_{\text{drilling}}$, $T_{\text{implantation}}$, RFA were established.

Results:

$F_{\text{drilling}}$ correlated well with BV/TV of the implantation site ($r^2=0.81$), stiffness ($r^2=0.75$) and $F_{\text{ultimate}}$ ($r^2=0.80$). $T_{\text{implantation}}$ correlated better with stiffness ($r^2=0.86$) and $F_{\text{ultimate}}$ ($r^2=0.94$) than RFA ($r^2=0.77$ and $r^2=0.74$, respectively).

Conclusion:

Our results indicate that BV/TV and bone-implant stability can be directly estimated by the force needed for the pilot drilling that occurs during the site preparation before implantation. Moreover, implantation torque outperforms RFA for evaluating the mechanical competence of the bone-implant system.

Graphical Abstract:

Trabecular bone samples were embedded and microCT scanned to evaluate the bone volume fraction, a bone quality substitute. Starting with the implantation procedure, a pilot hole was drilled and the axial force measured. Dental implants were inserted and the torque recorded. A resonance frequency analysis was performed directly after implantation. A mechanical test until failure was conducted to determine the stiffness and strength of the bone-implant system. All the metrics of primary stability were compared to each other and with stiffness and ultimate force (red arrows).

fx1

Keywords:

dental implant, primary stability, bone-implant system, bone quality, immediate loading, drilling force
In tooth replacements, dental implants are widely used to restore the natural functionality and appearance. The traditional implantation method, delayed loading, requires an unloaded period of 3-4 months in the lower jaw and 5-6 months in the upper jaw (Adell et al., 1981). To save time and lower the burden for the patient, immediate loading of the implant is increasingly used (Tarnow et al., 1997). Such procedure requires sufficient primary stability (Gapski et al., 2003), i.e. sufficient load bearing capabilities of the bone-implant system directly after implantation and before any bone remodelling takes place (Steiner et al., 2015). It is generally accepted that micro-motions of the implant between 50 and 150 µm are optimal for osseointegration, high secondary stability (Lioubavina-Hack et al., 2006), and to avoid fibrous encapsulation (Szmukler-Moncler et al., 1998).

Primary stability is mainly influenced by the bone quality at the implantation site, the implant geometry, and the drilling sequence (dos Santos et al., 2011). Primary stability can be comprehended on two levels. First, under small displacements and rotations, i.e. when the bone-implant system is deformed elastically, stability is affected by the cracks generated during drilling and implantation in the surrounding bone. The appropriate mechanical variable is the stiffness of the bone-implant interface. Second, under large displacements and rotations, the bone-implant system is overloaded causing damage that propagates further, and the implant’s motion becomes irreversible. Stability is, thus, also affected by the damage state of the bone of peripheral regions that were initially intact after implantation. Eventually, damage accumulates until failure of the bone-implant system.

The surgical implantation procedure usually starts with an X-ray image of the implantation site (Handelsman, 2006). Then, a small pilot hole is drilled as guidance for several subsequent drilling steps to create the implant hole depending on bone density (Handelsman, 2006; Nobel Biocare, 2013). This first procedure is referred to as “pilot drilling” or “site preparation”. Once the implantation site has been prepared, the implant is placed and the implantation torque can be measured through the implantation device. The whole procedure is critically dependent on the early stage assessment of bone quality, which is usually realised by the subjective classification of Lekholm and Zarb (Juodzbalys and Kubilius, 2013) and based on the experience of the surgeon (Chugh et al., 2013; Lindh et al., 2014). If the bone of the implantation site is defined as soft, the implant will be inserted into a small diameter hole (press-fit). Otherwise, a larger diameter hole will be drilled for a dense bone. Implantation torque may finally be used to evaluate primary stability, but resonance frequency analysis (RFA) conducted with an ad hoc device such as the Osstell ISQ (Integration Diagnostics AB, Göteborg, Sweden) can be used for measuring post-implantation stability (Ahn et al., 2012; Bayarchimeg et al., 2013; Farré-Pagès et al., 2011; Pommer et al., 2014; Turkyilmaz et al., 2009). Two limitations can be identified; the clinician does not have an objective assessment of bone quality and...
RFA only assesses the stiffness of the bone-implant interface (Sennerby and Meredith, 2008) without accounting for what occurs under larger deformations.

Bone apparent density is the primary variable determining bone quality (Seeman and Delmas, 2006) and the main determinant of bone strength (Carter and Hayes, 1977) and primary stability (Pommer et al., 2014). Due to the nearly constant degree of mineralisation of bone tissue (Roschger et al., 2003), bone apparent density can be converted into bone volume fraction (BV/TV) (Parfitt et al., 1987) and vice versa if the imaging modality is calibrated or provides sufficient resolution (Dall’Ara et al., 2011). Therefore, BV/TV correlates with bone strength (Schwiedrzik et al., 2013; Wolfram et al., 2011; Zysset and Curnier, 1996). Cone-beam computed tomography devices can be clinically used to estimate bone apparent density (Huang et al., 2014; Klintström et al., 2016). However, they are costly, not always available, expose the patient to X-rays, and are not comparable to ex vivo micro-computed tomography (µCT) devices in terms of accuracy. Since the initial X-ray is also not suitable to assess bone density, other means are necessary to evaluate the implantation site.

It would be desirable to assess bone apparent density at an early stage of the surgical procedure to be able to choose an appropriate implant setting without additional efforts. It would be even more desirable if means were available to validate this choice with a post-operative assessment that also allows a decision on immediate loading. We therefore propose that it is possible to estimate bone apparent density and the related bone-implant system strength during the site preparation without changing the surgical procedure. To address this question, the objectives of this study were to (i) identify a pre-implantation representative of BV/TV; (ii) identify the best pre- and post-implantation indicators of bone-implant system stiffness and ultimate force. Additionally, the damage accumulation in the bone surrounding the implant was to be evaluated.

2 MATERIAL AND METHODS
To realise reproducible implantations according to the clinical procedure, we developed a standardised experimental workflow (Figure 1).
Figure 1: Experimental work flow: 1) bone embedding, 2) bone morphology obtained through µCT scans, 3) drilling force measurement, 4) implantation torque measurement, 5) resonance frequency analysis, 6) Stiffness and ultimate force of the bone-implant system measurement. Sources of illustrations 4: www.nobelbiocare.com with permission

2.1 Sample preparation

Human (low BV/TV) and bovine (medium BV/TV) trabecular bones were chosen to represent bone densities of the mandible as well as the ones of the maxilla. Fifty-five cylindrical samples (14 mm in diameter) were extracted from human lumbar vertebral bodies of 14 spinal segments (six donors, 63-89 years old) along the structural main axis of the vertebra with a hollow diamond drill bit. The segments have been used in an earlier study for non-destructive flexibility tests of the intervertebral disc (Maquer et al., 2014). The structural integrity of the samples was verified by µCT imaging. To extend the bone apparent density range, six bovine tibias were obtained from a local abattoir and 25 trabecular bone samples with the same diameter were cored in the sub-tibial plateau along the main tibial axis. The resulting 82 cylindrical samples were cut to 19 mm length and embedded in poly(methyl methacrylate) (PMMA) (Technovit 3040, Heraeus Kulzer, Germany) similar to a material testing setup (and not infiltrated as in classic histology). This way, a low viscosity PMMA establishes a form closure between PMMA and the specimen, but cannot infiltrate the tissue.

2.2 Micro-computed tomography imaging Imaging

To determine BV/TV, the embedded trabecular bone samples were submerged in saline solution (0.9% NaCl) and imaged with a spatial resolution of 36 µm (µCT 40, SCANCO Medical AG, Switzerland). The images were masked and three volumes of interest (VOIs) were defined (Figure 2). The first VOI consisted of a 14 mm diameter cylinder containing the whole bone sample (Figure 2, VOI green). The second one comprised a 2 mm cylinder that circumscribed the pilot drill bit (Figure 2, VOI red). The last VOI was a hollow cylinder with an inner diameter of 2 mm and outer diameter of 4...
mm containing the bone directly surrounding the implant (Figure 2, VOI blue). BV/TV was computed in each VOI (BV/TV 14, BV/TV 2, BV/TV hollow) using the Python library Numpy (Oliphant, 2007).

VOI: BV/TV 14  VOI: BV/TV 2  VOI: BV/TV hollow

Figure 2: Three volumes of interest (VOIs) were defined in the segmented images of the samples for each step of the implantation procedure: a 14 mm cylinder (green) for bone classification, a 2 mm cylinder (red) for drilling, and a hollow cylinder with an inner diameter of 2 mm and outer diameter of 4 mm for implantation and mechanical testing (blue).

2.3 Drilling
The samples were separated into two groups with matching means and ranges of BV/TV 14 to evaluate the influence of the drilling protocol. One group (soft) was implanted with a drilling protocol for low-density bone using a single hole of 2 mm diameter × 13 mm depth (Figure 3, a). A second group (dense) was implanted with a drilling protocol for dense bone, where a drill diameter of 2 mm was followed by a stepped drill bit with 2.8/3.2 mm diameter × 13 mm depth. Drill bits were changed after 10 uses. We followed the procedure recommended by the implant manufacturer (Nobel Biocare, 2013) (Figure 3, a). The bone samples were drilled with a CNC portal driller (i-TM 100-2, ISEL, Germany) able to control feed rate (1 mm/s) and depth of drilling (Figure 3, b). During drilling to 13 mm depth, the axial force ($F_{\text{drilling}}$) was recorded by a load cell (M-2025 with 0.2 % accuracy class, Lorenz Messtechnik GmbH, Germany) situated underneath the sample holder (Figure 3, b). $F_{\text{drilling}}$ was defined as the mean axial force along the 13 mm drilling path.
Figure 3: a) Drilling procedure for soft bone (2 mm diameter, pilot drilling) and dense bone (2 mm followed by 2.4/2.8 mm and 2.8/3.2 mm diameter drill bits). b) Drilling of a sample with a CNC drilling machine and a load cell placed underneath. c) Placement of a NobelActive implant of diameter 3.5 × 13 mm length. d) Implantation by hand with a guide, maximal implantation torque was recorded by the insertion device and a load cell situated underneath. Illustrations a) and c) adapted from NobelActive manual (Nobel Biocare, 2013) with permission.

2.4 Implantation
Eighty-two titanium NobelActive implants (diameter 3.5 × 13 mm length (Figure 3, c)) were manually inserted using the manufacturer’s implantation device (Osseocare Pro; Nobel Biocare, Sweden) and a custom-made guiding rig to ensure reproducible implantation (Figure 3, d). The implantation device measured the implantation torque that was compared with the torque measured by a load cell underneath the sample holder of the custom-made guiding system (M-2025 with a 0.2 % accuracy class, Lorenz Messtechnik GmbH, Germany). \( T_{\text{implantation}} \) was defined as the maximum implantation torque during implant insertion.

2.5 Resonance frequency analysis
After implantation, RFA was performed with the Osstell ISQ device (Integration Diagnostics, Sweden) and its implant stability quotient (ISQ) scale was used to evaluate primary stability. If the RFA measure is below 65 ISQ, immediate loading is not recommended (Bornstein et al., 2009; Gallucci et al., 2014). ISQ values were determined as the average of successive measurements along two orthogonal directions both perpendicular measurements to the implant axis.

2.6 Mechanical testing
The mechanical testing configuration (Figure 4, a) corresponds to the ISO 14801 standard test for dental implants, but the fatigue protocol was replaced by a cyclic loading scheme with increasing amplitudes (Mirzaali et al., 2015; Wolfram et al., 2011) and the implant was inserted until its top surface was aligned with the bone surface. This progressive overloading scheme has the key ad-
vantage to provide information about stiffness reduction, irreversible displacement and energy dissipation at each cycle. The mechanical tests were realised at quasi-static loading rates on a servo-hydraulic system (858 Mini Bionix, MTS, USA) to determine stiffness, ultimate force, irreversible displacement, and damage of the bone-implant interface (Figure 4).

Forces were measured by a load cell (662-04D, MTS, USA) placed underneath the fixation system. The samples were placed into a custom-made clamping system in the same position as in the previous protocol stages (Figure 4, a, b) and tilted 30° to mimic maximum biting forces. Infrared markers were placed on the fixation system to determine deflection during loading with a motion capture camera (Optotrak Certus, NDI, Canada) with an in-plane resolution of approximately 0.1 mm. The deflection of the set-up was subtracted from the displacement measured by the loading machine to account for device compliance. The loading punch was free to move along X and Y axes. Samples were loaded with a displacement rate of 0.0024 mm/s (Figure 4, c). After three pre-conditioning cycles between 0.04 mm deformation and zero load, the samples were loaded to 2.56 mm with increasing displacement amplitudes and three repetitions per step. Force-displacement curves (Figure 4, d) were analysed with a Python script (Python 2.7, www.python.org and the Numpy package (Oliphant, 2007). Python is an open-source programming language that does not require compilation and support numerous libraries to fulfil diverse scientific computation needs in array manipulation, statistics, plots, and imaging).

A polynomial function was fitted through the inflection points of the loading steps (Figure 4, d green) to obtain the envelope approximating the load-displacement curve of a monotonic loading experiment (Wolfram et al., 2011). Initial stiffness was measured as the initial slope of the load-deflection curve and was used to describe primary implant stability under small displacements (Figure 4, d cyan). An increasing load causes progressive breakdown of the bone structure around the implant and reduces the initial stiffness. This stiffness reduction is measured at each displacement step using the secant of the third cycle of the respective load step (Figure 4, d blue). A scalar damage variable (D) ranging between 0 (intact) and 1 (destroyed) was defined as one minus the reduced stiffness normalised to the initial stiffness. Eventually, accumulated damage leads to specimen failure. Maximum bearable load (F_{\text{ultimate}}) was thus defined as the first local maximum of the approximated force-displacement curve and was chosen to reflect the primary stability under large deformations (Figure 4, d red).
Figure 4: Setup of the cycling overloading tests: a) shows the compressive test setup with the implant tilted by 30°. b) Loading punch on the hemispherical cup. Active infrared markers (red arrows) are used to check the implant displacement and measure the compliance of the clamping system. c) illustrates the loading protocol consisted of seven increasing displacement steps of three consolidation cycles with a displacement increasing from 0.04 mm to 2.56 mm and back to zero force. d) shows a resulting force-displacement curve of the implant cyclically loaded with the envelope of the cyclic test in green, the ultimate force in red, the stiffnesses in blue at different displacements and the initial stiffness in cyan.

To verify the adjustment of the hemispherical cup on the abutment and to account for machine compliance, a mock-up made of an abutment screwed to a steel cylinder was embedded and tested following the same loading protocol. A toe region was observed in the force-displacement curve and identified as a settling of the hemispherical cup on the abutment. This toe region was thus not taken into account when processing the load-displacement data presented in this study. The dissipated energy was stable after 2 pre-conditioning cycles.

2.7 Comparison with polyurethane material

To test reproducibility, polyurethane (PU) foam blocks with a density of 28% (block 20 PCF, Sawbones Pacific Research Laboratories, USA) were milled to the same dimensions as the embedded
bone samples. Implantation and testing followed the previously described procedure to establish a comparative group.

2.8 Statistics

Statistical analyses were performed in Python 2.7 using Scipy stats and Numpy 1.131.1 libraries (Oliphant, 2007) with a critical value (alpha) = 0.05. Log-log representations were used to compute linear regressions between BV/TV, $F_{\text{drilling}}$, $T_{\text{implantation}}$, RFA, initial stiffness, and $F_{\text{ultimate}}$. After log transformation, a normality test (Shapiro-Wilk) revealed a non-normal distribution of the independent variables. To compare the difference between soft and dense groups, an analysis of covariance (ANCOVA) was conducted using the following formula:

$$\ln(\text{dependent}) = \alpha + \beta \cdot \ln(\text{independent}) + \gamma \cdot \text{protocol}_{\text{soft}} + \delta \cdot \ln(\text{independent}) \cdot \text{protocol}_{\text{soft}}$$

Where $\alpha$ and $\beta$ are the intercept and the slope respectively of the dense group. The indicators $\gamma$ and $\delta$ are the difference between soft and dense groups of the intercept and the slope respectively. The independent variables are: BV/TV 2, BV/TV hollow, $F_{\text{drilling}}$, $T_{\text{implantation}}$, RFA, and irreversible displacement. The dependent variables are: $F_{\text{drilling}}$, Stiffness, $F_{\text{ultimate}}$, and $1 - D$.

ANCOVAs were performed with R (R Core Team, 2015). PU samples were not included in the regressions.

3 RESULTS

3.1 Pre-implantation indicators of primary stability: BV/TV and $F_{\text{drilling}}$

BV/TV2, BV/TV14, and BV/TV hollow were not significantly different (Table 1). The distributions of human and bovine BV/TV, however, were significantly different ($p<0.001$), but overlapped (Figure 5). $F_{\text{drilling}}$ explained 81% of the variation in BV/TV2, BV/TV14, and BV/TV hollow. The correlations between BV/TV hollow, initial stiffness ($r^2=0.76$), and $F_{\text{ultimate}}$ ($r^2=0.75$) of the bone-implant system were significant (Figure 6, a, b). $F_{\text{drilling}}$ also correlated significantly with initial stiffness ($r^2=0.75$) and $F_{\text{ultimate}}$ ($r^2=0.80$) (Figure 6, c, d). The soft and dense drilling protocols did not significantly affect the relationships between BV/TV, $F_{\text{drilling}}$, Stiffness, and $F_{\text{ultimate}}$.

Table 1: Bone volume percentage (BV/TV) is given for the different volumes of interest: 14 mm diameter cylinder, 2 mm diameter cylinder and hollow cylinder. Soft and dense refer to the chosen drilling protocols.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Human</th>
<th>Bovine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median [min, max]</td>
<td>Median [min, max]</td>
</tr>
<tr>
<td>BV/TV 14 dense</td>
<td>10.93 [6.77, 16.40]</td>
<td>30.95 [15.33, 47.72]</td>
</tr>
<tr>
<td>BV/TV 14 soft</td>
<td>10.94 [8.14, 17.18]</td>
<td>29.38 [15.04, 42.69]</td>
</tr>
<tr>
<td>BV/TV 14 total</td>
<td>10.94 [6.77, 17.18]</td>
<td>30.50 [15.04, 47.72]</td>
</tr>
</tbody>
</table>
Table 2: Regression statistics and ANCOVA

<table>
<thead>
<tr>
<th>dependent var.</th>
<th>independent var.</th>
<th>p-value</th>
<th>p-value</th>
<th>DoF</th>
<th>DoF</th>
<th>r²</th>
<th>r²</th>
<th>r²</th>
<th>p-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness</td>
<td>BV/TV hollow</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>27</td>
<td>28</td>
<td>0.81</td>
<td>0.72</td>
<td>0.76</td>
<td>0.503</td>
<td>0.687</td>
</tr>
<tr>
<td>F_upper</td>
<td>BV/TV hollow</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>28</td>
<td>28</td>
<td>0.83</td>
<td>0.68</td>
<td>0.75</td>
<td>0.817</td>
<td>0.579</td>
</tr>
<tr>
<td>Stiffness</td>
<td>F_drilling</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>30</td>
<td>31</td>
<td>0.79</td>
<td>0.72</td>
<td>0.75</td>
<td>0.265</td>
<td>0.570</td>
</tr>
<tr>
<td>F_upper</td>
<td>F_drilling</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>27</td>
<td>28</td>
<td>0.83</td>
<td>0.77</td>
<td>0.8</td>
<td>0.397</td>
<td>0.818</td>
</tr>
<tr>
<td>Stiffness</td>
<td>T_implantation</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>28</td>
<td>28</td>
<td>0.91</td>
<td>0.93</td>
<td>0.86</td>
<td>0.094</td>
<td>0.535</td>
</tr>
<tr>
<td>F_upper</td>
<td>T_implantation</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>28</td>
<td>28</td>
<td>0.92</td>
<td>0.97</td>
<td>0.94</td>
<td>0.184</td>
<td>0.849</td>
</tr>
<tr>
<td>Stiffness</td>
<td>RFA</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>28</td>
<td>27</td>
<td>0.73</td>
<td>0.84</td>
<td>0.77</td>
<td>0.469</td>
<td>0.503</td>
</tr>
<tr>
<td>F_upper</td>
<td>RFA</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>28</td>
<td>26</td>
<td>0.69</td>
<td>0.82</td>
<td>0.74</td>
<td>0.263</td>
<td>0.247</td>
</tr>
</tbody>
</table>

Figure 5: Axial force during pilot hole drilling ($F_{\text{drilling}}$) correlated with the trabecular bone volume fraction of the drilling VOI (BV/TV2).
3.2 Post-implantation indicators of primary stability: RFA and $T_{\text{implantation}}$

$T_{\text{implantation}}$ correlated significantly with initial stiffness ($r^2=0.86$) and $F_{\text{ultimate}}$ ($r^2=0.94$) (Figure 7, a, b). The significant correlations obtained between RFA and stiffness ($r^2=0.77$), and RFA and $F_{\text{ultimate}}$ ($r^2=0.74$) were lower in comparison (Figure 7, c, d). The soft and dense drilling protocols did not significantly influence the relationships established between $T_{\text{implantation}}$, RFA, stiffness, and $F_{\text{ultimate}}$. However, $T_{\text{implantation}}$ measured on bovine samples with high BV/TV was significantly affected by the drilling protocol ($p=0.014$).
3.3 Damage mechanism at the bone-implant interface

Damage (D), defined as the relative reduction in (elastic) stiffness, accumulated monotonically during mechanical testing and correlated significantly with the irreversible displacement (Figure 8). At $F_{\text{ultimate}}$, the irreversible displacement was between 0.5 and 1.0 mm, which is equivalent to a damage level of 30 to 40%. Maximum irreversible displacement reached on average $2.18 \pm 0.21$ mm at the last loading step.
DISCUSSION

This study was undertaken to investigate potential pre-implantation representative measures for bone quality and whether stiffness and strength of the bone-implant system could be assessed from the pilot drilling that occurs during the site preparation without changing the surgical procedure. Using a novel experimental framework, we showed that the force used while drilling the pilot hole was a suitable pre-implantation estimator of primary stability and that the implantation torque outperformed RFA as a post-implantation estimator of primary stability. This knowledge, generated during the surgery, may help the clinician to choose the right implantation protocol and decide on immediate loading.

4.1 The choice of samples

Our samples featured BV/TV ranging from 6.8 to 47.7%, which corresponds to the lower-middle density range of the trabecular core found in the maxilla 13.2-73.0% (Fanuscu and Chang, 2004; González-García and Monje, 2013) and the mandible: 29.9-70.0% (Akça et al., 2006; Fanuscu and Chang, 2004). Human vertebrae and bovine tibial plateaus were chosen because these anatomical sites allow reproducible extraction of a suitable amount of trabecular bone material to test implants. BV/TV of the human samples was clearly lower than BV/TV of the bovine samples. However, two bovine samples were found within the BV/TV range of the human samples (15.0 and 15.3 %) so that the two BV/TV distributions could be expected to merge (Hodgskinson and Currey, 1992) if more samples were prepared. BV/TV was thus treated as a continuous variable.

Bone volume fraction was in the same range for the three VOIs with a difference of the medians lower than 1% for human bone and lower than 2.7 % for bovine samples. This indicates a good comparability of the generated sample groups with regards to the investigated tissue.
A cortical shell or neighbouring teeth would have limited the magnitude of irreversible displacements we encountered towards the end of the loading protocol. However, such impingement would have shadowed the trabecular damage effect that could dominate the onset of micro-motion in the bone-implant system. Without the support of a rigid neighbourhood, our implants were, therefore tested in a worst-case scenario.

Bovine and human trabecular samples seemed also to be better approximations of the mandibular and maxillary bone than homogeneous PU foam used in other studies (Freitas et al., 2012; Möhlhenrich et al., 2016; VanSchoiack et al., 2006). Despite a closed pore structure, a much lower pore size compared to trabecular bone (between 0.07 and 0.3 mm) (Fanuscu and Chang, 2004), and a higher ductility, our PU group yielded drilling force, maximal implantation torque, stiffness, and ultimate force within the obtained upper and lower bounds with the real bone samples. However, one specific PU foam density cannot substitute the variability of bone volume fraction of bovine or human bone.

4.2 The choice of experimental set-up

Loading the implants cyclically allowed it to measure the exponential decrease of stiffness of the bone-implant interface due to crack accumulation in the surrounding bone. A similar behaviour was observed for trabecular (Wolfram et al., 2011) and cortical bone (Mirzaali et al., 2015). The form closure between the implant’s threads and the peripheral bone is actually built on a bone region that had been already damaged during the implantation. This zone could be then prone to a rapid damage accumulation under low cycle large amplitude testing. At the ultimate point, this resulted in a stiffness reduction of 40%. The ultimate forces measured with our set-up (30° compression) ranged between 5.5 and 456 N. This might seem low compared to the maximal biting forces of 200-700 N recorded by other authors (Miyaura et al., 1999; Ortug, 2002). Our experiment was not designed to exactly mimic a human jaw, but rather constitutes a worst-case scenario for the implant due to the off-axis loading (30°), the absence of support from the cortical shell and the neighbouring teeth, and the lack of osseointegration.

4.3 Influence of the drilling protocol

The aim of a soft drilling protocol is to account for low bone mass in an implantation site. The idea is to compact the trabeculae around the implant by decreasing the implantation hole diameter with respect to the implant. This should increase the ultimate pull-out force as well as the maximal implantation torque (Green et al., 1999; Huwais and Meyer, 2017; Kold et al., 2005). Pull-out force was not measured in this study. The drilling protocol had no significant impact on the slopes and intercepts of the regressions. Only a tendency at the intercepts has been observed between Stiffness and
At the same stiffness, the insertion torque was higher with the soft drilling protocol (compaction) than the dense drilling protocol. This can be explained by the press fit generated by the soft drilling protocol, which induces additional friction. $T_{\text{implantation}}$ and $F_{\text{ultimate}}$ were also found to be higher when the soft drilling protocol was used on the PU samples ($p<0.001$). The absence of differences in stiffness and ISQ could be explained by the damaged layer around the implant that may have been sufficient in both protocols to shadow any effect.

### 4.4 Pilot hole drilling force: A pre-implantation estimator of stability

Bone volume fraction correlated highly with stiffness and ultimate force of the bone-implant system, which is in agreement with the known relationships existing between BV/TV, elastic modulus and ultimate strength ($S_{\text{ultimate}}$) of trabecular bone samples (Carter and Hayes, 1977; Helgason et al., 2008; Hernandez et al., 2001; Rincón-Kohli and Zysset, 2009). To further compare our results to the available literature, we used a power function $F_{\text{ultimate}} = a \frac{BV}{TV}$ fitted to the experimental data after log transformation (Figure 6, b)). The exponent $b = 1.82$ was very close to the one determined by Hernandez et al. (Hernandez et al., 2001) when fitting strength $\sigma = \frac{F}{A} = \tilde{a} \frac{BV}{TV}$ with $\tilde{a} = A\sigma$ and where $b = 1.9$. The high correlation between BV/TV and $F_{\text{drilling}}$ indicates that the axial force measured during the drilling of the pilot hole is a potential way to assess BV/TV and, thus, bone quantity prior to implant placement. The pilot hole drilling force also showed high correlations with stiffness and ultimate force of the bone-implant system. This is not surprising since the drilling process is akin to an indentation experiment where the chisel edge at the tip of the drill bit acts as a conical indenter tip in the fashion of what was used to quantify the material properties of bone in compression (Deckelmann et al., 2010; Lee et al., 2012; Sneppen et al., 1981). Pilot hole drilling force could, thus, be used to determine a threshold between soft and dense bone.

### 4.5 Maximal implantation torque: A post-implantation estimator of stability

The variation of RFA was slightly better explained with stiffness than ultimate force of the bone-implant system. This may be because RFA evaluates the stability as a function of the stiffness (Sennerby and Meredith, 2008) due to the micro-motion induced on the freshly inserted implant. RFA, thus, indirectly measures the micro-motion of the damaged trabeculae surrounding the implant. The maximal implantation torque correlated moderately with BV/TV ($r^2=0.66$) but remarkably well with stiffness and $F_{\text{ultimate}}$ ($r^2=0.86$ and 0.94 resp.). The former is supported by prior work reporting a significant relationship between the maximal implantation torque and bone apparent density ($r^2=0.74$ for Beer et al. (Beer et al., 2003) and $r^2=0.59$ for Turkyilmaz et al. (Turkyilmaz et al., 2009)). The fact that $T_{\text{implantation}}$ seems to be a much better post-implantation estimator of primary stability than $F_{\text{drilling}}$ is interesting. Our samples had been cored along the trabecular main axis. The axial force measured during the pilot hole drilling ($F_{\text{drilling}}$) is thus mainly affected by the trabeculae aligned
along the drilling axis. Implantation torque, on the other hand, primarily triggers shear in the transverse plane of the implant axis, which may lead to trabecular bending. Since we mimicked biting forces through a 30° tilted setup of a fully-inserted implant, which is akin to short beam bending, the load situation leads to a superposition of normal stress and shear. Most likely, the failure mechanism in our experimental setup was dominated by shear (Bevill et al., 2006). Furthermore, bending of axial trabeculae strongly depends on the density of thinner transverse trabeculae, which is not directly captured by BV/TV (Musy et al., 2017), but by $T_{\text{implantation}}$. Together, this could explain the superior predictive performance of $T_{\text{implantation}}$ over $F_{\text{drilling}}$.

4.6 Limitations

During mechanical testing, the contact point between the hemispherical cup and the load cell shifted slightly as the implant tilted. We controlled the influence of this off-axis loading with a sphere between two parallel planes. A shift of 2.5 mm induced a force error lower than 2%. The trabecular bone samples used in this study were more homogeneous than the mandibular and maxillary bone that is highly heterogeneous and composed of both trabecular and cortical bone. In such a situation, $F_{\text{drilling}}$ could only be representative of the bone directly around the drill bit. A rigid neighbourhood around the implant (cortical shell, other teeth) would limit its transverse displacements, which could lower the predictive performance of $T_{\text{implantation}}$. The laboratory drilling conditions are not fully reproducible in clinics and the measure of $F_{\text{drilling}}$ could be perturbed by varying feed rates or changes in drilling direction. Finally, even though $T_{\text{implantation}}$ outperformed RFA as an indicator of stability it can be measured only once during the implantation but RFA can be used for follow-ups, which is a clear benefit.

5 Conclusion

This study, conducted under laboratory conditions indicates that an implantation site can be evaluated during the site preparation at the beginning of the surgical procedure without changing its sequence. Drilling force measured when drilling the pilot hole may provide pre-implantation means to assess bone density, choose a personalised drilling protocol, and to estimate bone-implant system strength. Maximal implantation torque could then provide an independent post-implantation measure to validate the pre-implantation assessment and choice.

Although clinical applicability and verification are yet to be evaluated, drilling force and maximal implantation torque will help clinicians in establishing optimal or even personalised implantations and subsequent decisions on immediate loading.

Acknowledgements

We would like to thank Mark Siegrist (Department for BioMedical Research of the University of Bern) for support with the $\mu$CT scans, Urs Rohrer and the team of the ISTB workshop for manufacturing the
experimental hardware, Florian Fuchs (Nobel Biocare Services AG) for his support during the study design and providing the equipment for realising the implantation procedure, and Jasmin Wandel for her support with the statistics.

Conflict of Interest

This study was supported by Noble Biocare Services AG and Peter Heuberger is an employee of Nobel Biocare Services AG. Apart from this, no conflict of interest exists.

References


Highlights:

- Evaluation of the axial force during pilot hole drilling as a measurement of dental implant primary stability.
- Comparison of the pre-implantation drilling force and standard intra- and post-implantation measurements of primary stability with mechanical testing.
- Bone volume fraction and bone-implant stability can be directly estimated by force measured during pilot drilling before implantation.