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On the stability efficiency of anchorage self-tapping screws: Ex vivo experiments on miniscrew implants used in orthodontics

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ABSTRACT

Background: The clinical success of orthodontic miniscrews is strictly related to primary stability, which depends on bone viscoelastic properties too. In this study, we evaluated the short time mechanical response of native bone to miniscrews, by a laboratory test based on dynamic loading.
Methods: Thirty-six segments of porcine ribs were first scanned by cone-beam computerized tomography to obtain insertion-site cortical thickness, cortical and marrow bone density. Twelve different types of miniscrews were implanted in the bone samples to evaluate the elastic compliance of the implants in response to a point force applied at the screw head normally to the screw axis. The compliance was measured dynamically in a Dynamic Mechanical Analysis apparatus as the Fourier Response Function between the signals of displacement and force. The measurements were repeated in five days successive to the insertion of the miniscrew.
Findings: The elastic compliance was positively related to observation timepoints, but it was not related neither to the screw type nor to the value of the insertion torque.
Interpretation: Stability behavior is significantly related to the short time response of native bone rather than to the screw design or the insertion torque values.

1. Introduction

In orthodontics the achievement of absolute anchorage to obtain efficient teeth movement or orthopedic force control is critical. Temporary anchorage devices have been introduced in the last years to develop a new anchor unit as alternative both to traditional orthodontic appliances and intraosseous dental implants (Costa et al., 1998; Kanomi, 1997; Cornelis et al., 2007; Favero et al., 2002; Wehrbein and Diedrich, 1999; Ohmae et al., 2001).

Temporary anchorage devices or miniscrews have relatively high failure rates when compared to dental implants, with failure rates from 9% to 16.4% (Lim et al., 2009; Dalessandri et al., 2014). The clinical success of a miniscrew is strictly related to the strength of the connection between bone and the device, also called primary stability (Migliorati et al., 2012). Many factors have been proposed to be associated to success rate: bone remodeling after screw placement, maximum insertion torque, and root proximity, though the majority of them still need additional evidence to support any possible associations (Serra et al., 2010; Motoyoshi et al., 2006; Kim et al., 2008; Meursinge Reynders et al., 2012; Park and Cho, 2009; Asscherickx et al., 2008; Watanabe et al., 2013; Papageorgiou et al., 2012).

Recently, a randomized clinical trial found that there was a statistically significant torque relative loss of 37.5% between miniscrew placement time and one week postplacement. These data were interpreted under the consideration that once the miniscrew is inserted into the bone, a so-called relaxation phenomenon occurs (Migliorati et al., 2016a). This relaxation would be due to bone viscoelastic properties; in fact a similar torque loss was observed both in vivo and in vitro (Lakes and Katz, 1979; Migliorati et al., 2016b). Moreover bone is a viscoelastic material with both organic and mineral phases, as Yamashita et al. indicated (Yamashita et al., 2001, 2002). Since viscoelastic materials dissipate energy, this concept is important when time dependent loads are present.

Most theoretical studies analyzing bone stress after implant placement, such as finite element models, are made under the assumption that cortical bone is described by its Young modulus, which is

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experimentally derived by a stress-strain curve under a monotonic loading (Wirth et al., 2011; Perillo et al., 2015; Guo and Kim, 2002). The majority of the experiments and researches based on Young modulus rely on the concept of linear elasticity and static tests; however, in order to provide a more accurate simulation of the reality, it would be necessary to describe not only the elastic response, but also the dissipated energy.

Dynamic Mechanical Analysis is a laboratory discipline where material properties are investigated through stress-strain curves under an oscillating loading, a condition allowing to comprehend the dissipated energy and particularly suitable to describe a viscoelastic behavior (Menard, 1999; Abdel-Wahab et al., 2011). Here we report the results of the short time mechanical response of native bone to orthodontic miniscrews, which was performed to investigate whether the normalized torque is associated with the compliance to lateral load.

2. Methods

2.1. Miniscrews

Twelve different types of miniscrews of 10 different producers with a screw length of 10 mm were analyzed. Nominal (outer) diameters ranged between 1.4 and 2 mm, while the pitch varied from 0.57 to 0.93 mm. Two screws (Biomat red and Biomat pink) had two threads in the cylindrical shank with pitches, respectively of 0.674–0.344 mm and 0.640–0.348 mm. The thread having a smaller pitch was a little more prominent than the other, and it interlaced the other for a length of 2.8 mm in both screws. A summary of the screw geometrical characteristics are reported in the results section. The geometrical characteristics were evaluated at SEM (model S-2500; Hitachi, Tokyo, Japan) at different enlargements ($\times 20$, $\times 80$, $\times 100$) by means of an image processing software (Imagej version 1.47b, National Institute of Health, Maryland, USA).

2.2. Bone samples

Thirty-six samples of porcine bone (three for each screw type) were prepared and encased in plaster blocks to be used in the compliance tests. 30 mm long bone sectors were sliced from fresh pig ribs obtained by the same animal the day of the experiment. To reduce the effects of the axial curvature of the ribs, only mediotoracic ribs were considered and the terminal portions (ventral and dorsal) of each rib were excluded. The screw insertion direction was chosen as the rib radial direction which was normal to the flattest cortical plate. Bone samples were first scanned in the pre-determined insertion site by cone-beam computerized tomography (Promax 3D Max; PlanmecaOy, Helsinki, Finland) with a mean exposure time of 12.38 s, 66 kV, and a voxel size of 100 µm (isotropic) at XXXXX Radiological Centre (XXXX, XXXX), to obtain insertion-site cortical thickness (CT) in millimeters as well as both cortical and marrow bone density, expressed in Hounsfield units (HU). These measurements were made by using a dedicated imaging software (Romexis, PlanmecaOy, Helsinki, Finland). A conversion from HU units to relative density was made on the basis of correlation tables generated for three patient populations (pelvis patients, thorax patients and head patients) in a previous study based on cone beam computerized tomography images and their reference computerized tomography for a pixel value calibration (Richter et al., 2008). Pig ribs have weaker bone characteristics than the human mandible, but their cortical characteristics provide a reliable simulation.

A description of the CT and density data are to be found in Table 1.

2.3. Experimental set-up preparation

Each bone sample was partially incorporated in a plaster (type IV, Noritake, Japan) block, with an emerging crest of about 5 mm in height. The plaster was cast into a slate mold whose inner walls were covered with a thin layer of silicone gel to facilitate the removal. A cylindrical hole was left in the cast to bolt the block to the testing machine (Fig. 1).

The specimens were stored while not undergoing tests, at room temperature, in physiological saline Sodium- Chloride 0.9%, pH 5.5, with the addition of antibiotic powder (Augmentin, GlaxoSmithKline, Brentford, UK).

2.4. Screwing Torque measurements

The screws were inserted manually by the same operator (one in each bone sample) and the insertion torque was measured continuously by means of a digital torsiometer (Cedar DID4, Imada Northbrook, Illinois). The maximum insertion torque (IT), which occurred at the engagement of the cylindrical shank, was taken as the measurement output. Successively, after completion of the compliance tests, the residual torque was measured on unscrewing.

2.5. Dynamic Mechanical Analysis (DMA)

The compliance to a lateral load was measured in five consecutive days, with a device which is currently used in the Dynamic Mechanical Analysis (DMA) of materials (Seminara et al., 2011). The plaster block containing the bone sample with the inserted screw was bolted to the fixed head of the testing machine. As the mini-screw heads emerged from the cortical plate for different lengths, a stainless steel empty cylinder (9 mm length) was glued with dental cement (CEKA SITE, CEKA PRECI-LINE, Waregem, Belgium) to the mini-screw abutment. An adjustable grip connected this cylinder to the moving head of the machine (Mini-shaker, type 4810, Brüel & Kjær, Nærum, Denmark) where a piezoelectric force sensor (Load cell, model 208 M116, PCB Piezotronics, Depew, US) was mounted. The grip was designed as a hinge, preventing any displacement relative to the screw abutment, but allowing for rotation. The load line was vertical and perpendicular to the screw axis with a fixed lever arm of 7.5 mm with respect to the bone surface. The displacement of the screw in the load direction was measured by a laser vibrometer (OFV 3000, Polytec, Waldbronn, Germany) with a resolution of 0.01 µm, which focused on the grip head. A view of the test setup is shown in Figs. 1 and 2.

The test consisted of loading cyclically the sample at frequencies which are included in a very narrow interval around 2 and 2.5 Hz. The frequencies scanned in each test were 10, a single oscillation being applied for 20 cycles. The amplitude of the applied oscillating force was about 0.35 N. The DMA device processed the time records of force and displacement via a Frequency Response Function (FRF), which provided a complex compliance spectrum of the sample. The real part of the spectrum corresponds to the elastic compliance, while the ratio of imaginary to real part (loss factor) provides an estimate of the energy dissipated in a cycle. In the present case, a very narrow frequency interval was scanned, so that the spectrum may be represented by a single value of compliance and a single value of loss factor for each test, which are reported as results. These tests were repeated on 5 consecutive days after the implantation.

2.6. Error analysis

The repeatability of the measures of depth, pitch, diameter and bone quantity and density was evaluated with the intraclass correlation coefficient. The intraclass correlation coefficient value for the geometric measurements of the screws was 0.987; for bone characteristics it was 0.971 in the case of cortical thickness and greater than 0.868 for bone density. For every bone sample, the reported Complex Compliance value is the average value resulting from four different tests, with an error varying from 8.5% to 10% across all the bone samples.