Layer Distribution Assessment of Bone Density Using Peak and Accumulated Drilling Torque Value

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ABSTRACT

Objectives: This *in vitro* study investigated whether combining peak and accumulated drilling torque value improves assessment of bone density distribution at implant sites using simulated bone models with predefined density patterns.
Material and Methods: Three-layer polyurethane bone models composed of D1- and D4-equivalent materials were fabricated with identical overall compositions but different density distributions (D1-4-4, D4-1-4, and D4-4-1). After initial osteotomy with a 2.0-mm twist drill, drilling was performed using a 2.7-mm torque-measurement drill. Torque was recorded continuously at 0.05-second intervals. Peak and accumulated drilling torque values were calculated and compared among the three density distribution models (n = 5).
Results: Representative torque profiles showed that the timing of peak drilling torque value varied with the position of the D1 layer, occurring earlier when the high-density layer was located in the upper layer. Peak drilling torque did not differ significantly among models. In contrast, accumulated drilling torque decreased significantly as the D1 layer was positioned deeper (D1-4-4: 187.6 (SD 22.7), D4-1-4: 125.7 (SD 28.1), and D4-4-1: 78.4 (SD 13.8) Ncm; $P < 0.05$).
Conclusions: Peak drilling torque reflected maximum local mechanical resistance but could not distinguish internal bone density distributions. Accumulated drilling torque provided additional information on density distribution throughout the osteotomy. Combined evaluation of both torque values may therefore provide a more comprehensive assessment of bone conditions at implant sites than peak drilling torque alone.

Keywords: bone density; dental implantation; dental implants; torque.

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INTRODUCTION

Achieving adequate primary stability and subsequent successful osseointegration requires accurate evaluation of the bone condition at the implant placement site. Bone mineral density (BMD) at implant sites can be evaluated using preoperative computed tomography (CT) scans and intraoperative drilling assessments [1]. Intraoperative evaluations based on both drilling sensation and torque measurements have been reported [2].

Evaluating bone density by measuring torque during drilling is useful because it enables numerical assessment without relying solely on the surgeon's experience [3-7]. Unlike radiographic assessments based on CT values, this approach reflects the actual mechanical resistance encountered during bone drilling.

We previously established a method for directly and objectively assessing cancellous bone density at implant sites by measuring drilling torque during implant socket preparation and investigated its clinical usefulness [8-10].

Previous torque-based evaluations have used relatively large-diameter drills (≥ 3 mm), which are incompatible with the smaller-diameter drilling protocols recommended for low-density bone. In our previous study [8], we developed a 2.7-mm-diameter torque-measurement drill capable of measuring torque in low-density bone. This drill distinguished among simulated BMDs corresponding to Misch classifications D2 to D5 [11] and demonstrated a strong correlation between drilling torque and CT values in bovine rib specimens. These torque measurements were based on peak drilling torque.

Drilling torque measurement is particularly advantageous because it enables evaluation of the bone condition at the implant site before implant placement, with a primary focus on cancellous bone and without the influence of cortical bone. Cortical bone thickness and morphology can be assessed using CT imaging. However, when the cortical bone is thin and cannot be expected to provide sufficient implant support, evaluation of the cancellous bone becomes particularly important.

We previously reported [9] that peak drilling torque values enable the classification of bone quality according to the Misch classification [11]: D2 corresponding to 850 - 1250 Hounsfield units (HU), D3 to 350 - 850 HU, D4 to 150 - 350 HU, and D5 to <150 HU. However, relying solely on the peak value may result in the assessment being strongly influenced by a localized region of high bone density; therefore, the peak value may not accurately represent the overall bone condition at the implant site.

Because biological bone has a heterogeneous and complex internal structure, drilling torque values recorded throughout the drilling process may reflect variations in local bone density along the osteotomy.

In our previous study [12], we compared peak and accumulated torque during implant insertion using homogeneous simulated bone models. Under these uniform conditions, accumulated torque showed a strong correlation with peak torque, suggesting that both parameters similarly reflected overall bone density. Similarly, Di Stefano et al. [13] reported the usefulness of the insertion torque–depth curve integral for evaluating primary implant stability in homogeneous polyurethane foam blocks.

Several studies have evaluated torque measurements using simulated bone models [14,15]. Comuzzi et al. [16] measured torque during implant placement in a multilayer simulated bone model and found that insertion torque was higher when a dense cortical layer was positioned on top. However, these previous studies [12-16] have primarily examined models with uniform density distributions or dense upper layers, and torque measurements have not been validated in models with various internal density distributions.

Therefore, we hypothesized that calculating accumulated torque throughout the drilling process could provide a more comprehensive assessment of bone density distribution than a single peak torque value.

Accordingly, this *in vitro* study aimed to investigate the usefulness of combining peak and accumulated drilling torque measurements to evaluate bone density distribution using simulated bone models with various predefined density distributions.

MATERIAL AND METHODS

Solid, rigid polyurethane bone blocks with densities corresponding to the Misch classification [11] were used as artificial bone substitutes: 30 PCF (1522-04), corresponding to D1 (0.48 g/cc), and 5 PCF (1522-23), corresponding to D4 (0.08 g/cc) (Sawbones® - Pacific Research Laboratories, Inc.; Washington, USA). Three-layer models were constructed using D1- and D4-equivalent polyurethane blocks. Each model consisted of an upper layer (1 mm), a middle layer (1 mm), and a lower layer (2 mm). One layer in each model was assigned as D1, and the other two layers were assigned as D4, creating three bone density distribution patterns from the top to the bottom layer: D1-4-4, D4-1-4, and D4-4-1 (Figure 1).

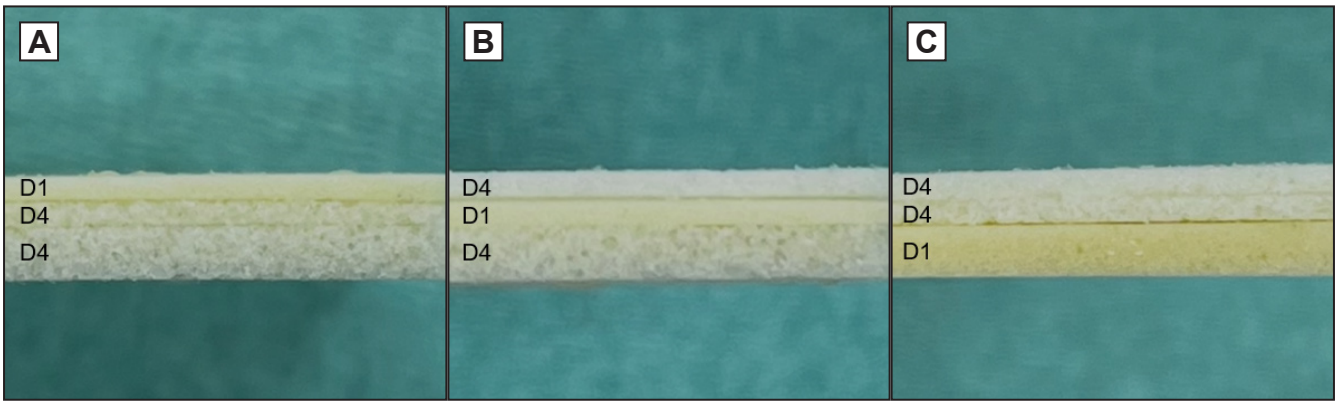

Figure 1. Three-layer bone density-distribution models: A = D1-4-4; B = D4-1-4; C = D4-4-1.

For torque measurement, an initial osteotomy was prepared to a depth of 4 mm using a 2.0-mm-diameter twist drill (Nobel Biocare AB; Göteborg, Sweden) at a rotational speed of 1,200 rotations per minute (RPM) under irrigation (Figure 2A). The measurement sites were spaced at least 1 cm apart. Subsequently, drilling torque was measured using the 2.7-mm-diameter torque-measurement drill developed in our previous study [8-10]. The rotational speed of 35 RPM was selected based on our previous experimental experience with torque measurement [8,9]. A higher rotational speed may make accurate torque measurement difficult, whereas a lower rotational speed may result in unstable torque measurements. Therefore, drilling was performed at 35 RPM to a depth of 3 mm, allowing evaluation of the entire three-layer density distribution while preventing perforation of the base of the bone block, under irrigation (n = 5 per model was considered the minimum number) (Figures 2B and 2C).

Torque values were continuously recorded at 0.05-second intervals. Peak and accumulated drilling torques were calculated. Accumulated drilling torque was defined as the simple sum of the torque values recorded at 0.05-second intervals throughout the drilling process. Peak and accumulated drilling torque values were compared among the three density-distribution models.

Statistical analysis

Statistical analyses were performed using GraphPad Prism version 7 (GraphPad Software, Inc.; La Jolla, CA, USA). One-way analysis of variance (ANOVA), followed by Tukey's multiple comparisons test. Data are presented as mean and standard deviation (M [SD]). Statistical significance was set at $P < 0.05$.

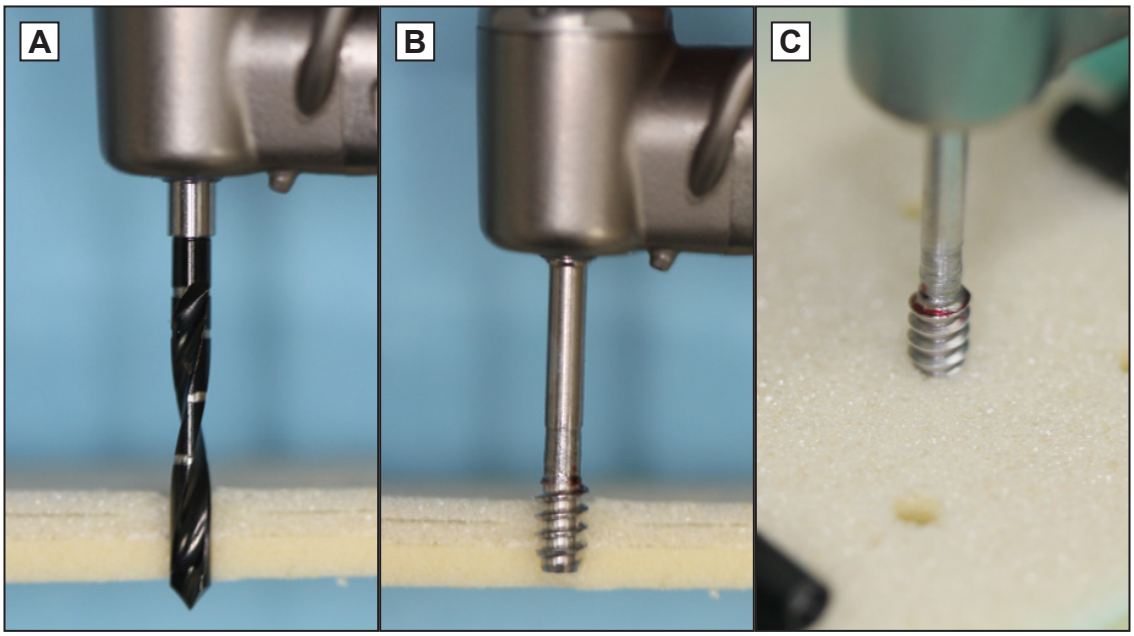

Figure 2. Experimental procedure: A = initial osteotomy preparation using a 2.0-mm twist drill; B = drilling using the 2.7-mm torque-measurement drill; C = torque measurement during drilling.

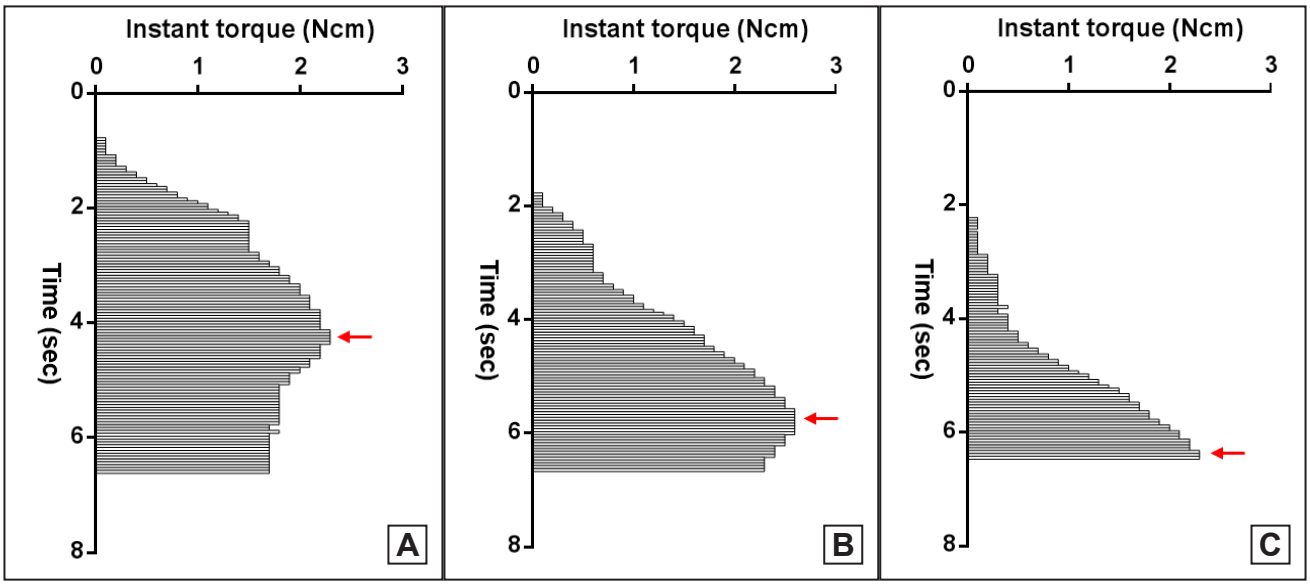

Figure 3. Representative drilling torque profiles for the three bone density distribution models.
A = D1-4-4 model, showing the earliest peak torque and relatively high torque values maintained thereafter.
B = D4-1-4 model, showing a peak torque reached later than that in the D1-4-4 model.
C = D4-4-1 model, showing minimal torque during the initial phase of drilling and the latest peak torque.
The arrows indicate peak drilling torque.

RESULTS

Figure 3 shows representative torque profiles recorded at 0.05-second intervals for each bone density-distribution model. The timing of peak torque varied with the position of the D1 layer; the peak torque occurred at approximately 4.0, 5.5, and 6.4 seconds in the D1-4-4, D4-1-4 and D4-4-1 models, respectively. The more superiorly the D1 layer was positioned, the earlier the peak torque occurred.

Peak drilling torque values were 2.3 (0.16) Ncm for D1-4-4, 2.4 (0.24) Ncm for D4-1-4, and 2.4 (0.26) Ncm for D4-4-1. One-way ANOVA showed no significant differences were observed among the D1-4-4, D4-1-4, and D4-4-1 groups ($P = 0.6317$; Figure 4A). In contrast, accumulated drilling torque values were 187.6 (SD 22.7) Ncm for D1-4-4, 125.7 (SD 28.1) Ncm for D4-1-4, and 78.4 (SD 13.8) Ncm for D4-4-1. Significant differences were observed among the D1-4-4, D4-1-4, and D4-4-1 groups ($P < 0.0001$; Figure 4B). Accumulated drilling torque decreased as the D1 layer was positioned deeper within the simulated bone model.

DISCUSSION

This study aimed to clarify the usefulness of evaluating bone conditions at implant sites by combining peak and accumulated drilling torque measurements obtained using a drill for measuring bone density. Evaluation based on drilling sensation is subjective and may vary according to the surgeon's experience [2,17-19]. In contrast, drilling torque measurement enables an objective, numerical evaluation of bone conditions during osteotomy preparation without relying on the surgeon's experience [2,8]. In this study, bone density was evaluated using not only conventional peak drilling torque but also accumulated drilling torque to determine whether these parameters provide complementary information regarding bone density distribution.

Experiments were conducted using polyurethane bone blocks with known density distributions. Three-layer models were prepared with a high-density, D1-equivalent layer positioned in the upper, middle, or lower layer. Peak drilling torque values were comparable among the three density-distribution models, regardless of the position of the D1 layer. In contrast, accumulated drilling torque was highest, intermediate, and lowest in the models with the D1 layer positioned in the upper, middle, and lower layers, respectively. These findings suggest that peak drilling torque primarily reflects the resistance encountered in the single densest region during drilling, whereas accumulated drilling torque reflects the resistance encountered throughout the drilling process. Accordingly, peak and accumulated drilling torque provide different but complementary information regarding bone conditions, and their

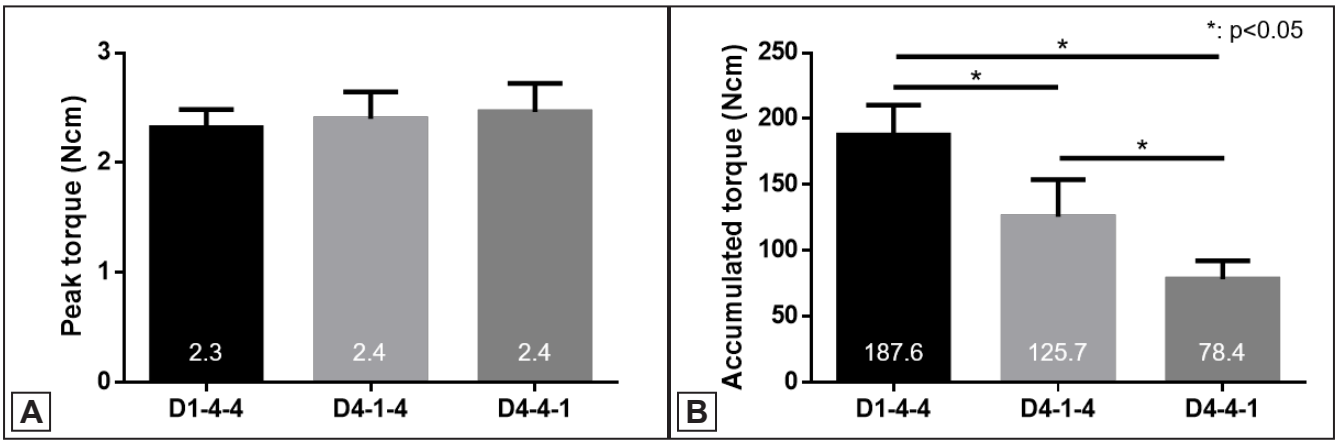

Figure 4. Peak and accumulated drilling torque values for the three bone density distribution models.
A = peak drilling torque values for the D1-4-4, D4-1-4, and D4-4-1 models. No significant differences were observed among the three groups.
B = accumulated drilling torque values for the three models. Accumulated drilling torque decreased as the D1 layer was positioned deeper within the simulated bone model.
*P < 0.05, Tukey's multiple comparisons test.

combined evaluation enables a more comprehensive assessment of bone density distribution than peak drilling torque alone.

We previously proposed a novel approach [12] for evaluating implant insertion torque by incorporating accumulated torque in addition to the conventional peak torque value. In this method, torque values are continuously recorded at 0.05-second intervals, and their sum is calculated as the accumulated torque value [12]. This parameter enabled a more detailed assessment of the resistance exerted by the surrounding bone throughout the insertion process. In the present study, accumulated drilling torque reflected both the contact area between the measurement drill and the bone and the duration of drilling. Consequently, when the D1 layer was located in the upper portion of the model, the high-torque state persisted for a longer period, resulting in higher accumulated drilling torque values. Conversely, when the D1 layer was located in the lower portion, the duration of the high-torque state was shorter, resulting in lower accumulated drilling torque values. These findings explain why accumulated drilling torque could distinguish differences in bone density distribution that could not be detected using peak drilling torque alone.

Previous studies [3,13] have demonstrated that torque-based measurements during drilling or implant insertion are associated with bone density. Iezzi et al. [3] showed that, under conditions corresponding to Misch bone qualities D1-D4 in bovine bone, peak and cumulative cutting torque values increased proportionally with bone density. Through histological evaluation, Di Stefano et al. [13] demonstrated that the insertion torque-depth curve integral was correlated with bone density during the assessment of primary implant stability. Tabassum et al. [20] used simulated bone blocks to clarify the relationship between cortical bone thickness and primary implant stability. In our previous study, torque during implant insertion was evaluated using both peak and accumulated values in simulated bone models with uniform density distributions [12]. Under these homogeneous conditions, peak and accumulated torque values were strongly correlated, indicating that both parameters reflected overall bone density similarly.

However, previous studies [3,13,20] evaluated homogeneous bone models or models with a dense cortical layer positioned in the upper portion and therefore did not specifically investigate differences in internal bone density distribution. In contrast, the present study systematically altered the position of the high-density layer while maintaining the same overall bone composition. Although peak drilling torque values remained unchanged, accumulated drilling torque values differed significantly according to the density distribution. To the best of our knowledge, this is the first study to demonstrate that combining peak and accumulated drilling torque can distinguish differences in internal bone density distribution that cannot be identified using peak drilling torque alone.

Because biological bone has a heterogeneous and complex internal structure, the presence and spatial distribution of high-density regions may affect primary implant stability. Previous studies [20-23] have reported that the initial stability of implants is strongly influenced by cortical bone thickness, presumably because the cortical bone located above the implant body provides mechanical stability. In contrast, bone regenerated following bone augmentation may exhibit

bone architecture different from that of native bone [24]. In this study, the peak torque occurred earlier when the high-density layer was located in the upper portion of the model. This finding suggests that the timing of peak torque, or the corresponding drilling depth, may provide information regarding the location of a high-density region. These findings suggest that the simultaneous evaluation of peak drilling torque, accumulated drilling torque, and the torque profile provides information regarding bone density distribution that cannot be adequately obtained using peak drilling torque alone. Rather than replacing conventional peak drilling torque measurements, accumulated drilling torque complements peak drilling torque by providing additional information regarding the spatial distribution of bone density.

The density distribution models used in this study comprised only two bone qualities, D1 and D4. Although simplified, these models enabled systematic evaluation of the influence of bone density distribution while minimizing the effects of other variables. These findings may contribute to the evaluation of bone quality and prediction of primary implant stability during implant placement.

Limitations

A limitation of this study is that the experimental models consisted of only two bone density levels, D1 and D4, and did not fully reproduce the heterogeneous structure of biological bone. Further studies using biological models and clinical investigations are needed to clarify the relationships among accumulated drilling torque, primary implant stability, and osseointegration.

CONCLUSIONS

This *in vitro* study demonstrated that accumulated drilling torque provided information regarding bone density distribution that was not detected by peak drilling torque alone. Accumulated drilling torque should not be regarded as a substitute for conventional peak drilling torque. However, the combined evaluation of peak and accumulated drilling torque may provide a more comprehensive assessment of bone density distribution at implant sites.

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The authors report no conflicts of interest related to this study.

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