THE JOURNAL OF PROSTHETIC DENTISTRY

CLINICAL RESEARCH

An evaluation of fluid distribution at the implant site during implant placement by using a computational fluid dynamics model

Shanshan Hu, DDS,[a] Lunliang Duan, DE,[b] Qianbing Wan, DDS, PhD,[c] and Jian Wang, DDS, PhD[d]

ABSTRACT

Statement of problem. Heat reduction during implant site preparation is critical. However, studies that assess fluid distribution at the implant site by using saline irrigation as the cooling method during osteotomies are lacking.

Purpose. The purpose of this study was to evaluate the effect of various parameters on fluid distribution at the implant site by using a computational fluid dynamics numerical model and thus predict the cooling effect at the drill site.

Material and methods. The computational fluid dynamics code Flow-3D was adopted to simulate implant site preparation. A 10-mm-deep implant site was prepared by using a 2.2-mm pilot drill, with 4 °C saline sprayed onto the drill from an external injection hole. Different drilling procedures were performed with irrigation volumes of 20, 40, 60, and 80 mL/min at various drill speeds (600, 800, 1000, 1200 rpm) and feed rates (0.5, 1.0, 1.5, 2.0 mm/s), and the fluid distribution under various circumstances was respectively investigated and compared. Data were analyzed by using 1-way ANOVA or the Friedman test according to the normality of the data distribution ($P>.05$).

Results. Below the irrigation volume of 60 mL/min, the saline inside the implant site increased with the irrigation volume ($P<.001$), but further increase in irrigation volume to 80 mL/min had no significant influence on the fluid distribution ($P>.05$). The obtained fluid had an inverse relationship with the drill speed under the irrigation volumes 20 and 40 mL/min ($P<.001$), and deeper areas received less cooling under 20 mL/min ($P<.001$). However, no significant differences were observed under 60 and 80 mL/min ($P>.05$). In addition, the variation of feed rate had no significant effect on the mean fluid fraction for all the tested groups ($P>.05$).

Conclusions. The fluid distribution at the implant site could be affected by the irrigation volume and drill speed but was not correlated with the feed rate. (J Prosthet Dent 2019;122:142.e1-e9)

During bone drilling, an unavoidable necrotic zone of bone will develop around the inserted implant.[1] The width of the necrotic zone is directly proportional to the magnitude of heat generated during surgery.[2] A resorption of the adjacent bone of 10% might occur if the temperature exceeds 47 °C for 1 minute and 20% to 30% if the temperature exceeds 47 °C for 5 minutes.[1,2] An even lower temperature increase (4.3 °C) has been reported to reduce the rate and quality of the newly formed bone after implant site preparation.[3] As a result, this heat-induced injury would endanger the primary healing and osseointegration of dental implants, leading to early implant failure.[4]

Thermal bone injury must be minimized during the drilling procedure, and several in vivo and in vitro studies have investigated factors that influence heat generation during implant site preparation.[3,5-13] Heat generation is related to multiple factors, including drill speed, feed rate, drill diameter, and irrigation.[3,5-8] Among these, adequate saline irrigation is mandatory to avoid thermal damage

This study was supported by National Natural Science Foundation of China (81601613; 81771122) and Science & Technology Support Program Sichuan Province (2016FZ0085).

[a]Doctoral student, State Key Laboratory of Oral Diseases, National Clinical Research Center for Oral Diseases, West China Hospital of Stomatology, Sichuan University, Chengdu, PR China.
[b]Doctoral student, Department of Bridge Engineering, Southwest Jiaotong University, Chengdu, PR China.
[c]Professor, Department of Prosthodontics, West China Hospital of Stomatology, Sichuan University, Chengdu, PR China.
[d]Professor, Department of Prosthodontics, West China Hospital of Stomatology, Sichuan University, Chengdu, PR China.

Clinical Implications

During implant site preparation, to receive adequate cooling, clinicians may consider increasing the irrigation volume to a certain level, for example, the 60 mL/min in this experimental design. However, excessive amounts of irrigation were also not necessary and may limit the visibility of the surgical site. Moreover, a relatively larger irrigation volume should be adopted when drilling with increased speed.

during implant drilling.[7,8] However, most studies have only evaluated the use of irrigation with drilling procedures performed without irrigation or just focused on comparing different irrigation methods.[9-11] Two studies have investigated the effects of the amount of irrigation on heat generation, but their conclusions are inconsistent.[12,13] Therefore, the effect of irrigation volume remains to be elucidated.

Designing an ideal experiment for determining bone temperature during implant osteotomy is challenging. First, in experimental studies, the temperature rise has been mostly measured by using a thermocouple positioned adjacent to the drill site.[14] However, the thermocouple could be placed no closer than 0.5 mm from the edge of the drilled hole, and the temperature measured by the thermocouple did not provide a true indication of the peak temperature in the immediate vicinity of a drilled hole.[15] Other studies used infrared thermography to detect temperature rise, but it could only measure temperature fluctuations in the superficial cortical bone areas and disregarded the heat generation in the deeper cancellous bone, leading to controversial outcomes.[8,9,11] Moreover, that experimental method only enabled the temperature to be determined at specific points and could not provide information related to the temperature distribution in the entire surgical field.[16] Therefore, others have suggested the use of finite element analysis for simulating the temperature field during the drilling process as a good way to investigate the effects of the drilling parameters on the bone temperature.[6,15-17] However, the cooling effect of the saline irrigation was not simulated while using the finite element analysis in these studies.[6,15-17]

Computational fluid dynamics (CFD) is a branch of fluid mechanics which uses numerical methods and algorithms to analyze and solve problems involving fluid flow by means of computer-based simulations.[18,19] Although initially developed for industrial and engineering practice, in recent years, CFD has also been applied in the biomedical field.[20-22] In contrast with experiments, CFD modeling could provide details about the fluid distribution in areas where experimental measurements are difficult to perform, especially in microscale and dynamic flow situations.[23,24]

In the present study, a 3D dynamic CFD model was constructed to investigate the effects of various parameters on fluid distribution at the implant site. The parameters included the irrigation volume, drill speed, and feed rate. The purpose of this study was to evaluate the fluid distribution at the drill site under different circumstances and thus to predict the cooling effect at the drill site during implant site preparation. The null hypothesis was that the irrigation volume, drill speed, and feed rate would have no influence on the fluid distribution at the implant site.

MATERIAL AND METHODS

The geometry of the 2.2-mm pilot drill (Straumann) was scanned by cone beam computed tomography (KaVo Dental GmbH) and reconstructed by using a medical imaging processing software program (MIMICS 17.0; Materialise). The alveolar bone was modeled as a cylindrical workpiece with a 10-mm diameter and 11-mm height by using a computer-aided design software program (AutoCAD v20.0.51.0; AutoDesk). The developed geometry model comprising the workpiece (bone) and the drill is shown in Figure 1A. The drill was initially placed at the top of the bone to facilitate standardization under different situations.

The 3D geometric model was imported into the Flow-3D codes (Flow Science Inc), and the functions of “Fluid sources,” “Gravity and non-inertial reference frame,” “Moving and simple deforming objects,” and “Viscosity and turbulence” in the Flow-3D codes were initialized. The saline was assumed to be an incompressible and homogeneous Newtonian fluid. The flow motions were modeled by solving the Reynolds-Averaged Navier-Stokes (RANS) equation,[25] and the standard k-ε turbulence model[26] was adopted to achieve the closure of the governing equations. Meanwhile, the volume of fluid (VOF) method was used to track the free surface.[27] The fractional area-volume obstacle representation technique was applied in the process of mesh generation, and the mesh type is nonconforming. In the numerical model, the size of cells was 0.015 cm, and the total flow domain was meshed with 1 817 200 hexahedral elements (Fig. 1B). Moreover, the gravity factor was along the negative z-axis (Fig. 1A).

In this study, a 0.9% solution of 4 °C saline with a density of 1.0 g/cm^3 was used during the irrigation. The viscosity of the 4 °C saline was 1.55×10^{-3} Pa·s, measured by using a rotational viscosimeter (Hengping Co, Ltd) at room temperature. The implant drilling procedures with various irrigation volumes (20, 40, 60, 80 mL/min), drill speeds (600, 800, 1000, 1200 rpm),

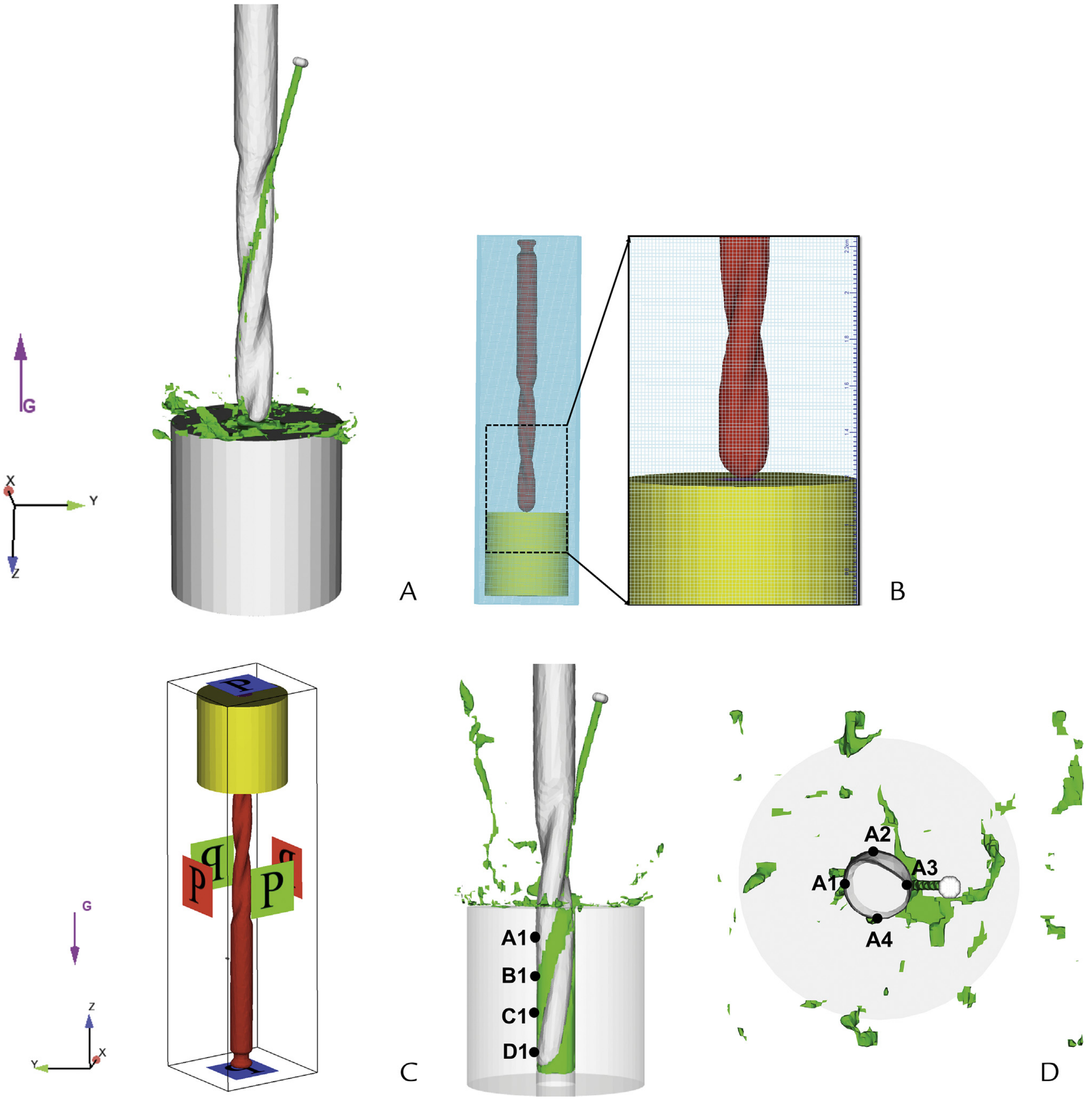

Figure 1. A, Implant site preparation and saline irrigation model. B, Mesh distribution of model. C, Boundary conditions of model. D, Location of measured points at depth of 2 mm (A1), 4 mm (B1), 6 mm (C1), and 8 mm (D1) and location of A1-A4 along the periphery of the drill.

and feed rates (0.5, 1.0, 1.5, 2.0 mm/s) were investigated. A 10-mm-deep implant site was prepared under all circumstances using a 2.2-mm pilot drill, with irrigation sprayed onto the drill from an external injection hole (0.5 mm in diameter) (Fig. 1A). In the CFD model, the drill was assumed to be the moving object. Meanwhile, the value of the translation velocity along the z-axis and the angular velocity were set according to the feed rates and drill speeds, respectively. The mass source was used to simulate the fluid injected from the external hole, and the irrigation volume was specified by setting the fluid normal velocity of the mass source. In addition, the sink motion velocity along the vertical direction of the mass source was set to be the same as the value of the translation velocity along the z-direction of the drill to make its motion consistent with the drill. As a result, the movement of the saline coolant together with the drill in clinical practice could be modeled based on the aforementioned procedures.

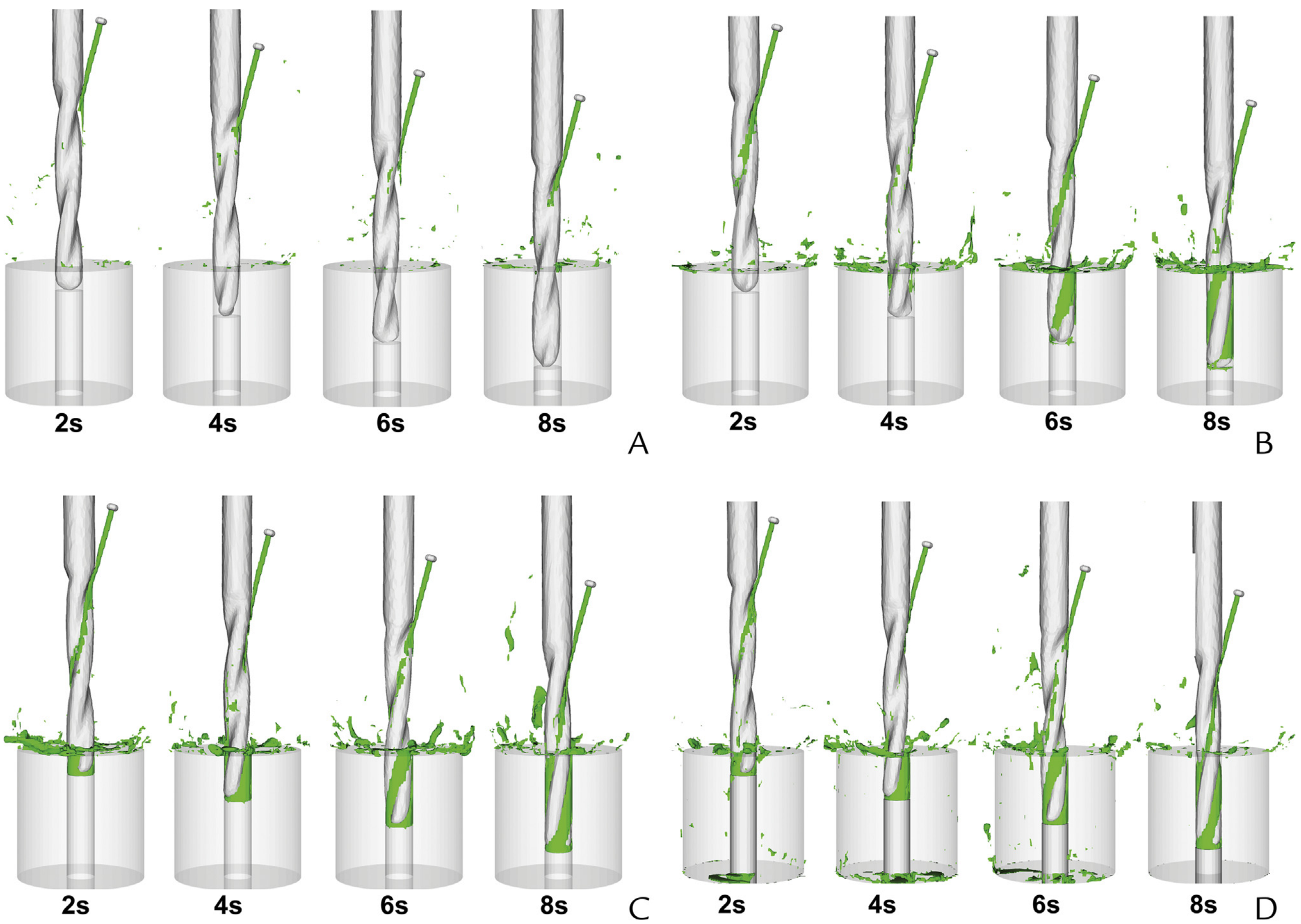

Figure 2. Fluid distribution at defined depths with different irrigation volumes under drill speed of 1000 rpm and feed rate of 1.0 mm/s. A, 20 mL/min. B, 40 mL/min. C, 60 mL/min. D, 80 mL/min.

The sketch of the boundary conditions in the CFD model is illustrated in Figure 1C. As shown, the boundary condition type of the 6 planes of the mesh block was set as the specified pressure (Fig. 1C), which meant the relative pressure was zero. Moreover, the surfaces of the bone and drill were all defined as wall boundary conditions based on the assumptions that the surfaces of the bone and the drill were all rigid, smooth, and impermeable. In this study, the minimum time step (the minimum difference value between two adjacent time points) was set to be 10^{-7} s throughout the whole calculations, and the generalized minimal residual method (GMRES) was applied to solve the water pressure. Computations were carried out on a Windows 7 Computer workstation with 2 CPU and 128 GB RAM. A series of computations were performed with various irrigation volumes, drill speeds, and feed rates. The fluid distribution, the volume of fluid at the drill site, and mean fluid fraction (the quantity of water per unit of volume in each cell) at depths of 2, 4, 8, and 10 mm (point A, point B, point C, and point D in Fig. 1D) were measured and compared under different conditions. In addition, at each defined depth, 4 points (point A1-A4, point B1-B4, point C1-C4, and point D1-D4 in Fig. 1D) were selected, and the values of their corresponding mean fluid fraction were also tested.

Statistical analysis was performed by using a statistical software program (IBM SPSS Statistics, v22.0; IBM Corp). The Shapiro-Wilk test was adopted to test the normality of distribution. Parametric data were tested with 1-way ANOVA, followed by the Tukey honestly significant difference test for between-group comparisons (α=.05). In addition, the Friedman test was used to assess the nonparametric data, and post hoc analysis between groups was performed using the Wilcoxon signed ranks test (α=.05).

RESULTS

Irrigation volumes of 20, 40, 60, and 80 mL/min were investigated with a drill speed of 1000 rpm and feed rate of 1.0 mm/s. Figure 2 showed the overall fluid distribution with different irrigation volumes. In addition, the variation of volume of fluid at the implant site

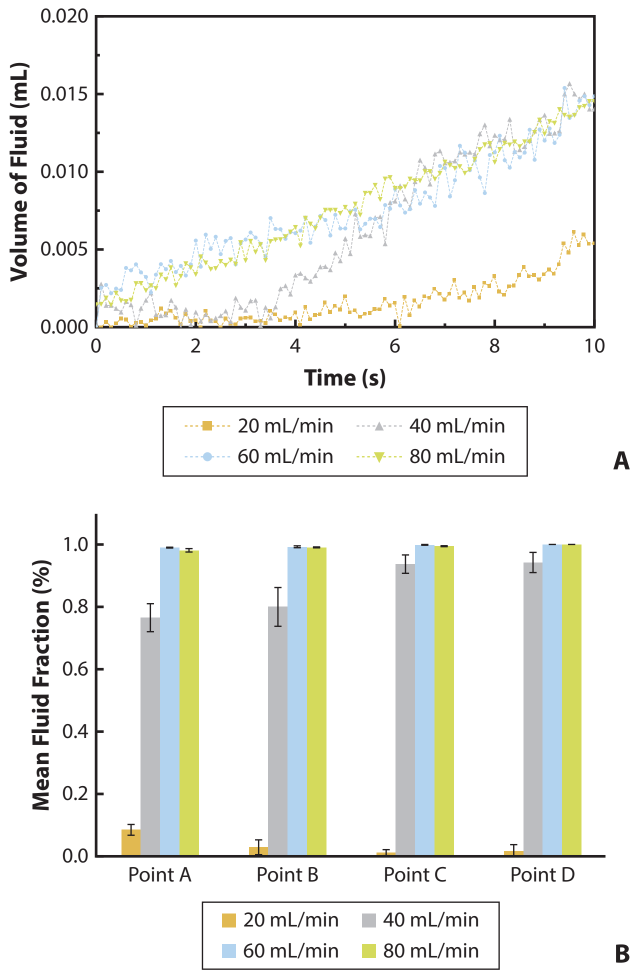

Figure 3. A, Variations of volume of fluid at implant site. B, Mean fluid fraction at defined depths. Different irrigation volumes under drill speed of 1000 rpm and feed rate of 1.0 mm/s.

and the mean fluid fraction at various depths are shown in Figure 3A, B to quantify the fluid distribution at the implant site. Statistically significant differences were found among the 4 groups for both the volume of fluid (P<.001) and mean fluid fraction (P<.001). Specifically, the 20 mL/min group obtained significantly less fluid at the implant site than other groups (P<.001). For the 40 mL/min group, although the fluid volume was statistically less than the 60 mL/min and 80 mL/min groups (P<.001), it was less only at the beginning of the implant placement process and increased rapidly later to be comparable with that of 60 mL/min and 80 mL/min (Fig. 3). However, when the irrigation volume reached 60 mL/min, a further addition of irrigation volume (80 mL/min) led to no significant differences in the volume of fluid at the implant site (P>.05). Moreover, the variation of the dynamic flow developed at the implant site during the drilling process with an irrigation volume of 80 mL/min is also shown in Supplemental Video 1 (available online).

Drill speeds of 600, 800, 1000, and 1200 rpm were used with different irrigation volumes, and the feed rate was fixed at 1.0 mm/s. The variations in the volume of fluid at depths of 2, 4, 8, and 10 mm with different drill speeds are illustrated in Figure 4, and the mean fluid fraction, in Figure 5. When the irrigation volume was 20 mL/min or 40 mL/min, the volume of fluid decreased with increasing drill speed, and the differences were statistically significant with various drill speeds (P<.001) (Fig. 4A, B). However, when the irrigation volume was above 60 mL/min, no significant differences were found for all tested drill speeds (P>.05) (Fig. 4C, D). For the mean fluid fraction, the same variation trend and statistical results were observed with different irrigation volumes. In addition, the deeper area of the implant site received less saline coolant when the irrigation volume was 20 mL/min, and the differences were statistically significant (P<.001) (Fig. 5).

The effect of feed rates on the fluid distribution was also explored, and the results are shown in Figure 6. Feed rates of 0.5, 1.0, 1.5, and 2.0 mm/s were assessed with various irrigation volumes, and the drill speed was fixed at 1000 rpm. According to the results, the variation in the feed rate had no statistically significant impact on the mean fluid fraction for all tested groups with different drill speeds and irrigation volumes (P>.05).

DISCUSSION

Multiple factors have been reported to be closely related to heat production, and irrigation is obligatory during osteotomy.[3,5-13] However, an ideal experiment for determining bone temperature during implant osteotomy is difficult, and experimental methods cannot provide information related to fluid distribution or the dynamic flow developed at the implant site. Consequently, using a CFD numerical model, the present study made an initial attempt to investigate the effects of various parameters on real-time fluid distribution at the implant site. As the results suggested, the null hypothesis that the irrigation volume, drill speed, and feed rate would have no influence on the fluid distribution at the implant site was rejected.

According to the heat-transfer theory, the heat will always transfer from the higher temperature area to the lower temperature area.[28] Because the temperature of the bone is always higher than that of the 4 °C saline coolant, the heat will transfer from the bone wall to the saline, and the cooling effect will be proportional to the obtained volume of saline coolant at the implant site and the temperature difference. The use of irrigation has been reported to significantly reduce heat generation as compared with drilling procedures performed without irrigation, and irrigation at a lower temperature had a better cooling effect.[9-11] However, the authors are

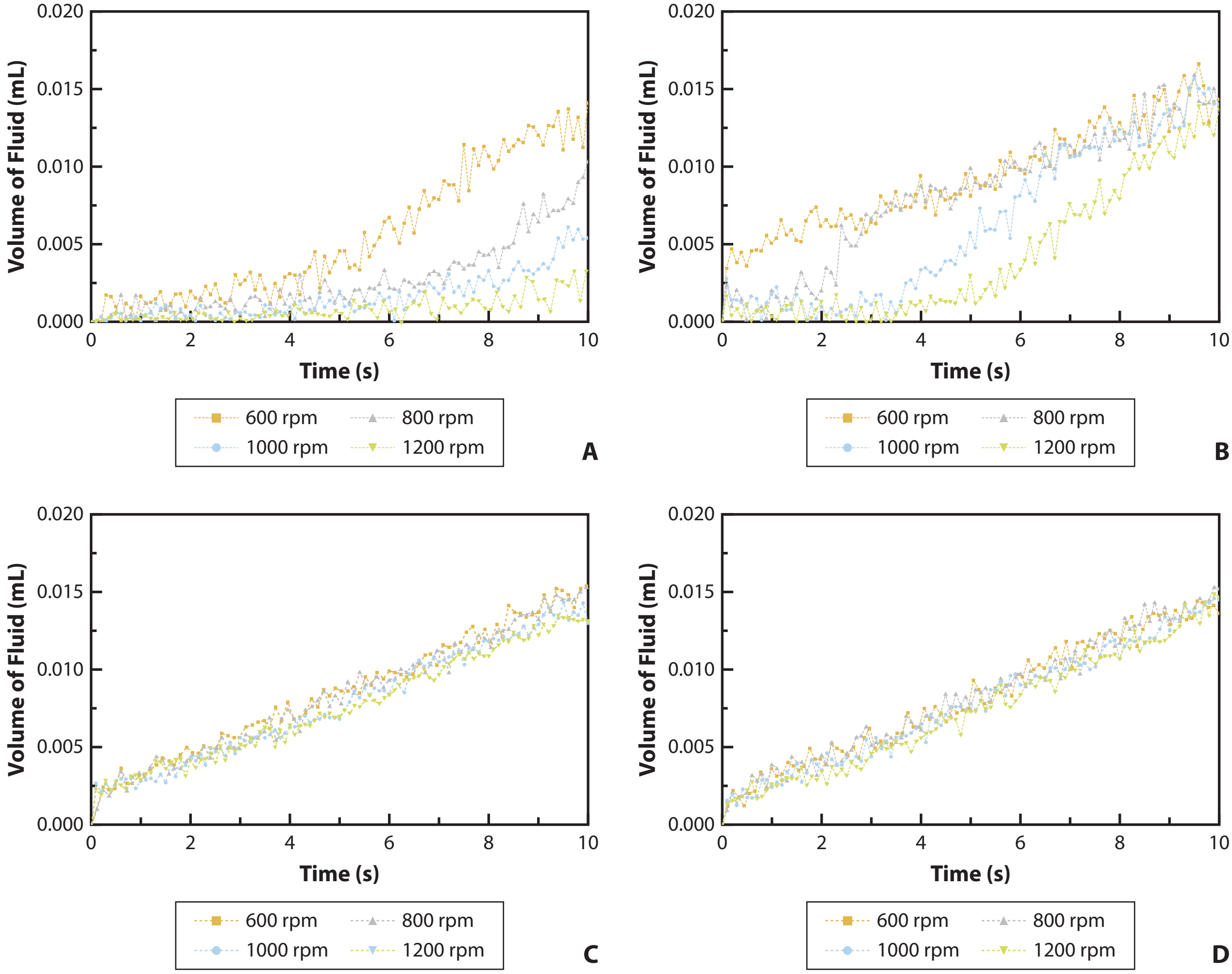

Figure 4. Variations of volume of fluid at implant site with different drill speeds under feed rate of 1.0 mm/s and different irrigation volumes. A, 20 mL/min. B, 40 mL/min. C, 60 mL/min. D, 80 mL/min.

unaware of a study evaluating the fluid distribution and volume of fluid at the implant site. Although Rashad et al[12] and Sindel et al[13] have investigated the effect of the amount of irrigation on the cooling effect by experimental measurement, their results were contradictory. Therefore, the effect of irrigation volume needed further investigation. As indicated by the present results, when the volume of the external irrigation was low, increasing the irrigation volume could help increase the volume of fluid inside the implant site (P<.001) and therefore could improve cooling (Figs. 3, 4); this is consistent with the study of Rashad et al[12] in which increased irrigation volume resulted in lower temperatures. However, after the irrigation volume increased to a certain value, for example, the 60 mL/min in this experimental design, a further increase in volume (80 mL/min) had no positive effect on the volume of fluid at the implant site (P>.05). Therefore, because excessive amounts of irrigation may limit the visibility of surgical site, clinicians should limit the irrigation volume to a certain level during implant site preparation.

Sindel et al[13] reported no significant difference in heat production when using 12 mL/min and 30 mL/min external irrigation volumes with a drill speed of 1000 rpm. The discrepancy between the results of the study by Sindel et al[13] and the present study can be explained as follows. First, as was shown by the present study, when the irrigation volume was 20 mL/min or 40 mL/min with a drill speed of 1000 rpm, the volumes of fluid at the implant site at the beginning of the drilling process were both quite small (Figs. 2, 3). However, in the study by Sindel et al,[13] only the highest temperature during implant drilling was measured by using a single thermocouple. The depth of the measured point was not specified. Therefore, if they only evaluated a point at the shallower part of the implant site, both the 12 mL/min and 30 mL/min irrigation groups may only have received a very small amount of saline coolant at the implant site,

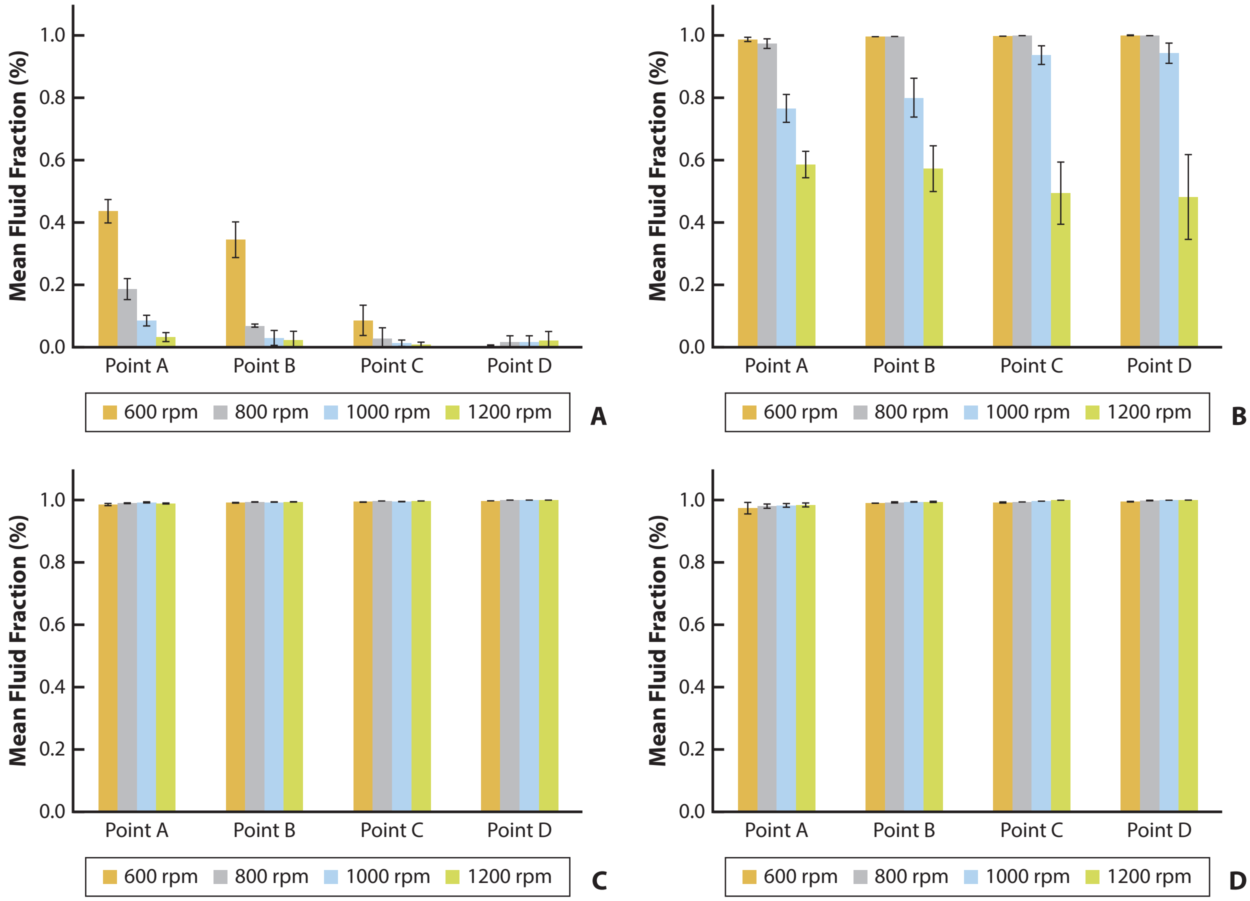

Figure 5. Mean fluid fraction at defined depths with different drill speeds under feed rate of 1.0 mm/s and different irrigation volumes. A, 20 mL/min. B, 40 mL/min. C, 60 mL/min. D, 80 mL/min.

which was not able to induce a detectable temperature change between the 2 groups. In addition, their thermocouple probe was inserted into the tissue at 3 mm from the drill insertion point.[13] Because the temperature at the point which is in direct contact with the cutting surface of the surgical drill is much higher, and because bone temperature decreases from the drill center to the periphery,[17,29,30] the measured temperature would be different at different distances from the drill. Even if there was a difference in temperature at the drill point of the 12 mL/min and 30 mL/min irrigation groups, that difference was likely insufficient to be detected by the thermocouple because the temperature decreased considerably at 3 mm from the drill point.[17]

Drill speed is another important determinant of heat generation at the implant drilling site. An inverse relationship between the drilling speed and heat production has been reported,[5,6] whereas some others have reported the opposite conclusion.[15,17,31] However, despite this controversy, for dental implant site preparation, the drill speed in clinical practice is more dependent on the implant system chosen and is always limited to 1200 rpm.[16] Therefore, instead of changing the drill speed to reduce heat generation, more attention should be given to how to improve the cooling efficiency by means of irrigation. The present study investigated fluid distribution with respect to different drill speeds, and the results indicated that a lower drill speed was associated with a larger volume of fluid at the implant site when the irrigation volume was 20 mL/min or 40 mL/min (P<.001) (Figs. 4A, B, 5A, B). According to Newtonian mechanics, in a rotating reference frame, all objects, regardless of their state of motion, are under the influence of a radially outward centrifugal force that is proportional to their mass, to the distance from the axis of rotation of the frame, and to the square of the angular velocity of the frame.[32] Therefore, a drill with an increased rotational speed generates a larger centrifugal force and thus less fluid is left along the drill groove before the drill enters the implant site, leaving less fluid there. However, as the external irrigation volume was sufficiently large, no significant differences were observed among various drill speeds (P>.05) (Figs. 4C, D, 5C, D). In consideration of this, a relatively increased irrigation volume should be adopted when drilling with increased speed during implant site preparation.

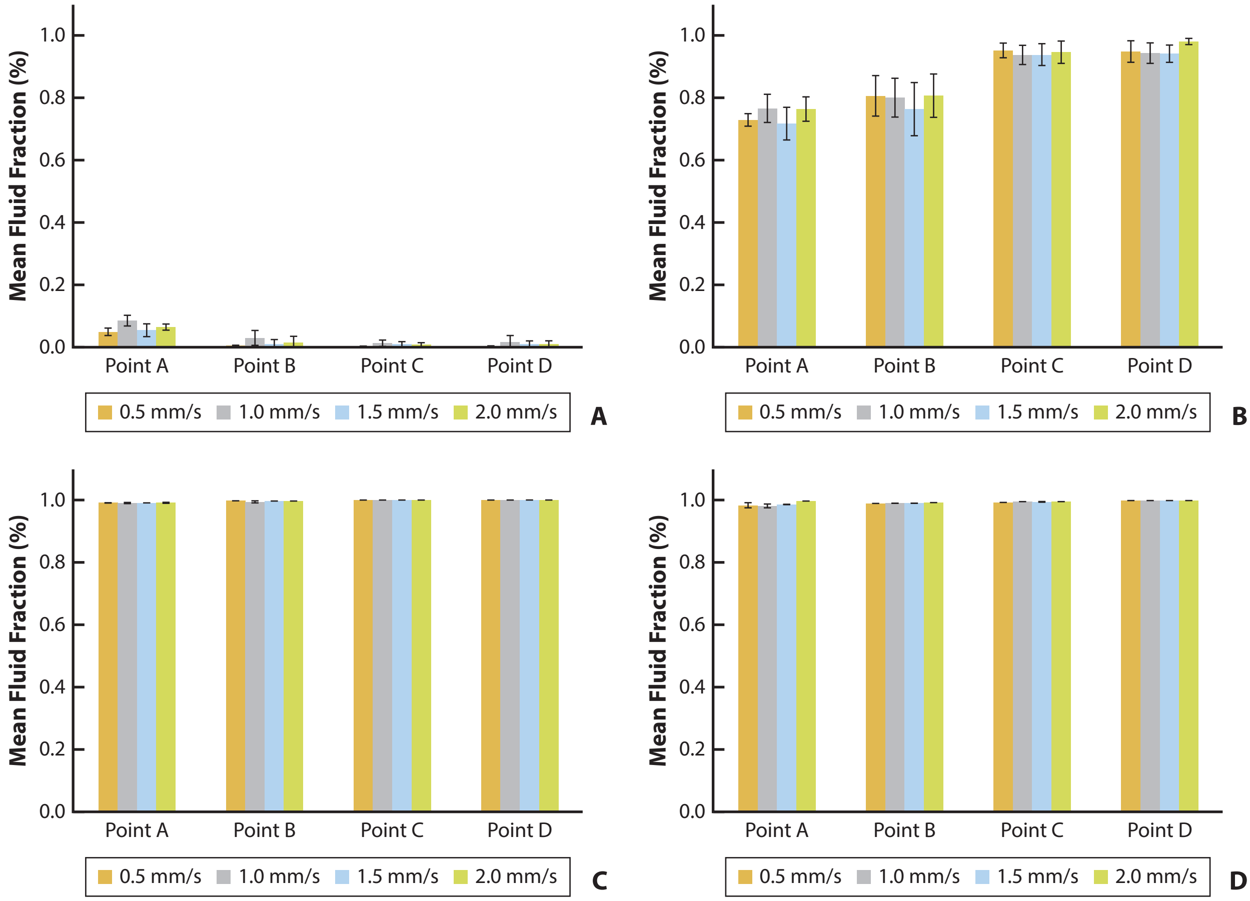

Figure 6. Mean fluid fraction at defined depths with different feed rates under drill speed of 1000 rpm and different irrigation volumes. A, 20 mL/min. B, 40 mL/min. C, 60 mL/min. D, 80 mL/min.

Recent publications have reported that deeper osteotomies induce increased heat generation.[11,33,34] The results of the present study also show that when the irrigation volume is low (20 mL/min), the mean fluid fraction decreases with the increase in drilling depths (Fig. 5A). This finding further demonstrates the importance of heat reduction in the deeper areas of the implant site. In addition, bone chips are less likely to escape from the deeper areas. Therefore, when making deep osteotomies, increasing the irrigation volume is extremely important to ensure an adequate cooling effect and prevent the clogging of bone chips in the deep area of the implant-preparation bed.

According to Sener et al,[11] heat generation is directly proportional to the duration of drilling during implant osteotomy. Therefore, because no significant differences in the cooling effect were found among the various feed rates ($P>.05$) (Fig. 6), shortening the overall drilling time by increasing the feed rate would benefit the local tissue and the patient. However, in reality, too fast feed rate is not recommended and may lead to tissue damage.

The findings of this study require additional evaluation. The present study only investigated a 1-step drilling procedure by using a pilot drill, and a graduated drilling sequence is lacking. In addition, the model has some limitations. For example, neither the removal of the cutting debris nor the bone density was simulated. Moreover, gravity variations according to the alignment of the implant drill and the patient's orientation in the chair were not taken into consideration. Further studies should be conducted to provide more comprehensive guidance.

CONCLUSIONS

Within the limitations of this CFD study, the following conclusions were drawn:

1. Below 60 mL/min, the amount of saline coolant inside the implant site was proportional to the irrigation volume but increase of the irrigation volume to 80 mL/min had no significant influence on the fluid distribution.
2. The volume of fluid at the implant site had an inverse relationship with the drill speed when the irrigation volume was 20 and 40 mL/min, and deeper areas received less cooling under 20 mL/min. However,

when the irrigation volume increased to a certain value (60 and 80 mL/min), the volume of fluid at the drill site was not influenced by the drill speed.

3. Fluid distribution at the implant site was not correlated with the feed rate regardless of the irrigation volume or the drill speed.

REFERENCES

1. Eriksson RA, Albrektsson T. The effect of heat on bone regeneration: an experimental study in the rabbit using the bone growth chamber. J Oral Maxillofac Surg 1984;42:705-11.
2. Eriksson AR, Albrektsson T. Temperature threshold levels for heat-induced bone tissue injury: a vital-microscopic study in the rabbit. J Prosthet Dent 1983;50:101-7.
3. Iyer S, Weiss C, Mehta A. Effects of drill speed on heat production and the rate and quality of bone formation in dental implant osteotomies. Part II: relationship between drill speed and healing. Int J Prosthodont 1997;10:536-40.
4. Yoshida K, Uoshima K, Oda K, Maeda T. Influence of heat stress to matrix on bone formation. Clin Oral Implants Res 2009;20:782-90.
5. Iyer S, Weiss C, Mehta A. Effects of drill speed on heat production and the rate and quality of bone formation in dental implant osteotomies. Part I: relationship between drill speed and heat production. Int J Prosthodont 1997;10:411-4.
6. Chen YC, Tu YK, Zhuang JY, Tsai YJ, Yen CY, Hsiao CK. Evaluation of the parameters affecting bone temperature during drilling using a three-dimensional dynamic elastoplastic finite element model. Med Biol Eng Comput 2017;55:1949-57.
7. Krause WR, Bradbury DW, Kelly JE, Lunceford EM. Temperature elevations in orthopaedic cutting operations. J Biomech 1982;15:267-75.
8. Abouzgia MB, James DF. Temperature rise during drilling through bone. Int J Oral Maxillofac Implants 1997;12:342-53.
9. Benington IC, Biagioni PA, Briggs J, Sheridan S, Lamey PJ. Thermal changes observed at implant sites during internal and external irrigation. Clin Oral Implants Res 2002;13:293-7.
10. Strbac GD, Giannis K, Unger E, Mittlböck M, Watzek G, Zechner W. A novel standardized bone model for thermal evaluation of bone osteotomies with various irrigation methods. Clin Oral Implants Res 2014;25:622-31.
11. Sener BC, Dergin G, Gursoy B, Kelesoglu E, Slih I. Effects of irrigation temperature on heat control in vitro at different drilling depths. Clin Oral Implants Res 2009;20:294-8.
12. Rashad A, Sadr-Eshkevari P, Heiland M, Smeets R, Hanken H, Gröbe A, et al. Intraosseous heat generation during sonic, ultrasonic and conventional osteotomy. J Craniomaxillofac Surg 2015;43:1072-7.
13. Sindel A, Dereci Ö, Hatipoğlu M, Altay MA, Özalp Ö, Öztürk A. The effects of irrigation volume to the heat generation during implant surgery. Med Oral Patol Oral Cir Bucal 2017;22:506-11.
14. Augustin G, Zigman T, Davila S, Udilljak T, Staroveski T, Brezak D, et al. Cortical bone drilling and thermal osteonecrosis. Clin Biomech (Bristol, Avon) 2012;27:313-25.
15. Tu YK, Chen LW, Ciou JS, Hsiao CK, Chen YC. Finite element simulations of bone temperature rise during bone drilling based on a bone analog. J Med Biol Eng 2013;33:269-74.
16. Liu YF, Wu JL, Zhang JX, Peng W, Liao WQ. Numerical and experimental analyses on the temperature distribution in the dental implant preparation area when using a surgical guide. J Prosthodont 2018;27:42-51.
17. Chen YC, Hsiao CK, Ciou JS, Tsai YJ, Tu YK. Effects of implant drilling parameters for pilot and twist drills on temperature rise in bone analog and alveolar bones. Med Eng Phys 2016;38:1314-21.
18. Versteeg HK, Malalasekera W. An introduction to computational fluid dynamics. 2nd ed. Harlow: Pearson Education; 2007. p. 1-8.
19. Lecrivain G, Slaouti A, Payton C, Kennedy I. Using reverse engineering and computational fluid dynamics to investigate a lower arm amputee swimmer's performance. J Biomech 2008;41:2855-9.
20. Rmaile A, Carugo D, Capretto L, Aspiras M, De Jager M, Ward M, et al. Removal of interproximal dental biofilms by high-velocity water microdrops. J Dent Res 2014;93:68-73.
21. Park JB, Choi G, Chun EJ, Kim HJ, Park J, Jung JH, et al. Computational fluid dynamic measures of wall shear stress are related to coronary lesion characteristics. Heart 2016;102:1655-61.
22. Han X, Bibb R, Harris R. Engineering design of artificial vascular junctions for 3D printing. Biofabrication 2016;8:025018.
23. Boutsioukis C, Lambrianidis T, Kastrinakis E. Irrigant flow within a prepared root canal using various flow rates: a computational fluid dynamics study. Int Endod J 2009;42:144-55.
24. Boutsioukis C, Verhaagen B, Versluis M, Kastrinakis E, Wesselink PR, van der Sluis LW. Evaluation of irrigant flow in the root canal using different needle types by an unsteady computational fluid dynamics model. J Endod 2010;36:875-9.
25. Tilton JN. Fluid and particle dynamics. In: Perry RH, Green DW, Maloney JO, editors. Perry's chemical engineer's handbook. 8th ed. New York: McGraw-Hill; 2007. p. 13-4.
26. Rodi W. Turbulence models and their application in hydraulics-state-of-the-art review. 3rd ed. Rotterdam: A.A. Balkema; 1993. p. 27-30.
27. Hirt CW, Nichols BD. Volume of fluid (VOF) method for the dynamics of free boundaries. J Comput Phys 1982;39:201-25.
28. Incropera FP, DeWitt DP. Fundamentals of heat and mass transfer. 7th ed. New York: Wiley; 2011. p. 6-8.
29. Ercoli C, Funkenbusch PD, Lee HJ, Moss ME, Graser GN. The influence of drill wear on cutting efficiency and heat production during osteotomy preparation for dental implants: a study of drill durability. Int J Oral Maxillofac Implants 2004;19:335-49.
30. Harder S, Egert C, Wenz HJ, Jochens A, Kern M. Influence of the drill material and method of cooling on the development of intrabony temperature during preparation of the site of an implant. Br J Oral Maxillofac Surg 2013;51:74-8.
31. Alam K, Khan M, Muhammad R, Qamar SZ, Silberschmidt VV. In-vitro experimental analysis and numerical study of temperature in bone drilling. Technol Health Care 2015;23:775-83.
32. Feynman RP, Leighton RB, Sands M. The Feynman lectures on physics. Reading, MA: Addison-Wesley; 1965. chapter 19, p.11.
33. Strbac GD, Unger E, Donner R, Bijak M, Watzek G, Zechner W. Thermal effects of a combined irrigation method during implant site drilling. A standardized in vitro study using a bovine rib model. Clin Oral Implants Res 2014;25:665-74.
34. Oliveira N, Alaejos-Algarra F, Mareque-Bueno J, Ferres-Padro E, Hernandez-Alfaro F. Thermal changes and drill wear in bovine bone during implant site preparation. A comparative in vitro study: twisted stainless steel and ceramic drills. Clin Oral Implants Res 2012;23:963-9.

Corresponding author:
Dr Jian Wang
Department of Prosthodontics
West China School of Stomatology, Sichuan University
No.14, Section 3, South Peoples Rd
Chengdu 610041
PR CHINA
Email: ferowang@hotmail.com

https://doi.org/10.1016/j.prosdent.2018.12.015