Abstract: This study aimed to investigate the effect of frequency on shear fatigue strength (SFS). The SFS of a resin composite bonded to dentin was determined using three self-etch adhesive systems: G-ænial Bond, Scotchbond Universal, and Optibond XTR. The staircase method of fatigue testing was used to determine the SFS at frequencies of 5, 10, and 20 Hz for 50,000 cycles. The failed bonding sites observed were classified based on the type of bond failure as follows: adhesive failure, cohesive failure in composite, cohesive failure in dentin, or mixed failure (partially adhesive, partially cohesive). A modified t-test with Bonferroni correction was used to analyze the SFS data, and a complex chi-square test was used to analyze the fracture modes. The SFS of OX was significantly greater than that of GB at both 5 and 10 Hz. However, no significant differences in SFS were found among the three frequencies (5, 10, and 20 Hz) in the three self-etch adhesive systems. Furthermore, no significant differences in bond failure mode were observed among the three frequency rates in all the three adhesives used. (J Oral Sci 58, 539-546, 2016)

Keywords: dentin bonds; fatigue strength; frequency; self-etch adhesives.

Introduction

The adhesive bonding of resin composite materials to mineralized tooth structures is an important component affecting the long-term performance of resin composite restorations. Evaluation of the bond strengths of various adhesive systems to the tooth substrate has been one of the primary investigative avenues in this assessment. Bond strength evaluations involve the testing of adhesive systems on both enamel and dentin substrates, since each calcified structure is important for retaining the composite resin restorations in vivo. In addition, differences in structural, physiologic, and mechanical properties between the enamel and dentin influence the adhesion of resin materials to these substrates.

Advanced techniques for the adhesive bonding of dental materials to mineralized tooth structures are being continually assessed by refining protocols to more closely mimic conditions in the oral cavity, and maintaining strict control in the laboratory to conduct studies that yield relevant results. Fatigue strength studies have demonstrated value in measuring adhesive bond strengths in vitro that can then help guide clinicians with predictive applications on the performance of composite restorations in vivo. Investigators must control many variables in the design of fatigue strength testing protocols, two of which include frequency and number of cycles. Relating frequency and number of cycles to human chewing continues to be a challenge for researchers when conducting fatigue tests. Erickson et al. (1) reported difficulties in showing correlations between the number of cycles and load levels in the laboratory fatigue testing of adhesive systems and actual functioning dentition.
The chewing frequency reportedly ranges from 1 to 2 Hz (2-6). The number of occlusal contacts per day from chewing and swallowing has been estimated at 1,800 per day or 10^5 over a period of 2 months (3). Therefore, determining a frequency rate and the number of cycles for clinical relevance during the laboratory fatigue testing of adhesive materials is difficult, particularly when testing efficiency and costs of both equipment and personnel are taken into consideration.

Earlier fatigue studies reported by Erickson et al. (7) and Barkmeier et al. (8) on enamel bonds with adhesive systems and resin composite used the staircase methodology described by Draughn (9) with frequencies ranging 0.25-2 Hz and 40,000 to 10^5 cycles. A more recent study (10,11) used 10 Hz and 50,000 cycles for fatigue testing of both enamel and dentin bonds. The investigators evaluated the enamel and dentin bonds using a phosphoric acid pre-etch prior to the application of self-etch adhesives and a resin composite. Wiskott et al. (12) acknowledged that in spite of some shortcomings, the acceleration of fatigue testing is necessary to alleviate time constraints. Their group reported using frequencies of 1, 5, 10, and 15 Hz for evaluation of the fatigue resistance of soldered joints. In an effort to conduct laboratory fatigue testing (micro-rotary fatigue) of tooth to composite bonds in a realistic length of time (around 7 h), De Munck et al. (13) used 10^5 cycles and a frequency of 4 Hz. These authors also noted that higher frequencies may lead to heating within the samples being tested. Takamizawa et al. (14) investigated the influence of frequency on the fatigue strength of enamel bonds utilizing both 5 and 20 Hz frequencies, and 50,000 cycles, and found no significant difference in fatigue strengths between the two frequencies. There is a wide variation in the frequency rates and number of cycles reported in the literature for fatigue testing of dental materials. A challenge for researchers conducting fatigue strength evaluations in the laboratory is the fact that lower frequency testing methods prolong the assessment. As De Munck et al. (13) stated, the quest is to maximize laboratory efficiency while trying to mimic clinical conditions.

There is still limited information in the literature regarding the effect of frequency on the fatigue testing of bond endurance of resin composites to dentin using new generation self-etch adhesive. The aim of the present study was to determine the effect of frequency on the shear fatigue strength of resin composite bonded to dentin. The null hypotheses was that there would be no significant difference (α = 0.05) in the fatigue strength of the dentin bonds at frequencies of 5, 10, and 20 Hz.

### Material and Methods

#### Study materials

Table 1 illustrates the materials used in this study. The self-etch adhesives used were: G-ænial Bond (GB; GC Corporation, Tokyo, Japan), Scotchbond Universal (SU; 3M ESPE Dental Products, St Paul, MN, USA), and OptiBond XTR (OX; Kerr Corporation, Orange, CA, USA). The resin composite used for the bonding procedure was Z100 Restorative (3M ESPE Dental Products).

#### Specimen preparation

A total of 75 carries free human molars were extracted, de-identified, and used in this study. The teeth were stored in distilled water containing 0.5% chloramine T for up to 4 weeks after extraction. The experimental protocol was reviewed and approved by the Ethics Committee for Human Studies at the Nihon University School of Dentistry, Tokyo, Japan (EP2015-06). The bonding sites on dentin were prepared by sectioning the molars...
mesiodistally, and then removing roughly two-thirds of the apical root. The tooth sections were mounted on aluminum rings (25 mm diameter) with Triad DuaLine (DENTSPLY International, York, PA, USA). The dentin bonding surfaces were ground using a sequence of carbide polishing papers (Struers Inc., Cleveland, OH, USA) finishing with a 4,000 grit paper under water cooling.

Stainless steel metal machined rings with inner and outer diameters of 2.4 and 4.8 mm, respectively, and a length of 2.6 mm were used to condense resin composite (Z100 Restorative) onto the dentin surfaces for shear bond strength (SBS) and shear fatigue strength (SFS) tests. The resulting resin composite cylinder in the ring was approximately 2.36 mm in diameter and 2.5 mm in length; the metal ring was left in place.

Shear fatigue strength (SFS) tests
The staircase method of fatigue testing, described by Draughn (9) and Dewji et al. (15), was used for the SFS testing in this study. For each condition, 25 specimens were used to measure SFS on the dentin. The adhesive agents were applied to the flat ground dentin surfaces according to manufacturers’ directions. A releasing agent (3% solution of paraffin and hexane) was then placed on the surface of the metal rings contacting the adhesive agent on the bonding sites. The metal rings were then positioned over the bonding sites and secured in place by clamping in a custom fixture (Fig. 1).

Z100 resin composite was confined into the rings and cured for 40 s with a light curing unit (Spectrum 800 Curing Unit, DENTSPLY Caulk, Milford, DE, USA) set at 600 mW/cm². Before SFS testing, the bonded assemblies were stored for 24 h in distilled water at 37°C. The load was applied to the metal rings at a position immediately adjacent to the tooth surface, using a metal rod with a chisel-shaped end. The ring was kept in place for the bond strength tests (Fig. 1). The lower load limit for SFS testing was set near zero (0.4 N). The initial maximum load applied was 50-60% of the SBS previously determined for each of the three adhesive systems (10). Initial maximum load was based on those applied in previous studies (1,9,15). Frequencies of 5, 10, or 20 Hz were used to apply the load on the samples using an ElectroPuls E1000 machine (Instron Worldwide Headquarters, Norwood, MA, USA) in a sine wave pattern for 50,000 cycles or until failure occurred (Fig. 2). The load was adjusted upward on survival or downward on failure by approximately 10% of the initial load. Adapting the calculation described by Draughn (9), SFS for a particular frequency was taken to be the stress value that was likely to produce failure in 50% of cases over 50,000 cycles. Failed samples were observed by means of an optical microscope (MZ16; Leica Microsystems Ltd., Heerbrugg, Switzerland) at ×20 magnification. The type of bond failure was then categorized as follows: adhesive failure, cohesive failure in composite, cohesive failure in dentin, or mixed failure (partially adhesive, partially cohesive). The judgement was made based on the percentages of the substrate types (dentin-adhesive-composite) observed on the de-bonded surface. The failure modes of SFS and SBS in the present study were compared with the failure patterns of SBS from a previous study belonging to our group (10).

Scanning electron microscopy (SEM) observations
Representative resin/dentin interfaces of each tested adhesive, and the failure sites of de-bonded specimens of each frequency condition were determined by SEM (ERA-8800FE, Elionix Ltd, Tokyo, Japan). For ultrastructural observations of the resin/dentin interface, specimens were prepared in the same manner as that for the bond strength test described earlier. The bonded
specimens were mounted with epoxy resin (Epon 520, Nissin EM, Tokyo, Japan) and then longitudinally sectioned using a precision low speed saw (Isomet 111280, Buehler, Lake Bluff, IL, USA). Abrasive discs (Fuji Star Type DDC, Sankyo Rikagaku Co., Saitama, Japan) were used to polish the sectioned surfaces, followed by the use of diamond pastes down to 0.25-μm particle size (DP-Paste, Struers, Ballerup, Denmark) to achieve a high gloss. After the SFS testing, five representative de-bonded specimens were selected from among those that displayed adhesive failure. They were ultrasonically cleaned (L&R Solid State Ultrasonic T-14B, South Orange, NJ, USA) in distilled water for 3 min, and then the resin side was prepared directly for evaporation coating. SEM samples of resin/dentin interfaces were dehydrated using ascending grades of tert-butyl alcohol and a critical-point dryer (Model ID-3, Elionix) in the standard way (10). The samples were then subjected to argon-ion beam etching (EIS-200ER, Elionix) for 40 s with the ion beam (accelerating voltage 1.0 kV, ion current density 0.4 mA/cm²) directed perpendicular to the polished surfaces. Finally, gold was used to coat the SEM specimens in a vacuum evaporator, Quick Coater (Type SC-701, Sanyu Denchi Inc, Tokyo, Japan). Observations were conducted using an operating voltage of 10 kV.

Statistical analysis
A modified $t$-test with Bonferroni correction was used for the SFS data at a significance level of $\alpha = 0.05$ (custom Excel worksheet for Draughn (9) staircase method). For analysis of the fracture mode of SBS and SFS, a complex chi-square test was used by means of the Sigma Plot software system (Ver. 11.0; SPSS Inc., Chicago, IL, USA) at a significance level of $\alpha = 0.05$.

Results

SFS tests
The results of the SFS tests are shown in Table 2; previously reported (10) SBS values are also included in the table. The rank orders of the bond values for SBS and SFS were the same for the three adhesive systems tested in this study.

The modified $t$-test with Bonferroni correction did not reveal any significant differences ($P > 0.05$) in SFS for the three self-etch adhesives between the three frequencies used (5, 10, and 20 Hz). However, significant differences in SFS were noted among the three adhesives at the same frequency. The SFS of OX was significantly greater ($P < 0.05$) than GB at both 5 Hz and 10 Hz frequencies. No difference in SFS ($P > 0.05$) was observed among the three adhesive systems at the frequency of 20 Hz.

GB demonstrated higher SFS/SBS ratios than the other two adhesives at all three frequencies.

Failure mode analysis of de-bonded specimens
The percentages of different failure modes comparing those observed in SBS testing (10) with those observed in SFS testing under different frequency conditions are shown in Table 3. In the case of GB, all de-bonded specimens demonstrated adhesive failure, independent of the type of test. The complex chi-square test revealed that although no significant differences in SFS were observed among the different frequency groups for SU and OX, apart from one instance with OX at 10 Hz, significant differences were found between SBS and SFS.

| Table 2 Shear bond strength (SBS) and Shear fatigue strength (SFS)-MPa (SD) | Adhesive | SBS (SD) | 5 Hz SFS (SD) | Ratio SFS/SBS | 10 Hz SFS (SD) | Ratio SFS/SBS | 20 Hz SFS (SD) | Ratio SFS/SBS |
|---|---|---|---|---|---|---|---|---|
| GB | *31.1 (3.8)$^b$ | 16.6 (2.7)$^a$ | 0.53 | 16.9 (1.8)$^{a,A}$ | 0.54 | 17.4 (2.3)$^{a,A}$ | 0.56 |
| SU | *42.6 (4.0)$^a$ | 20.4 (4.6)$^{a,A}$ | 0.48 | 19.8 (2.5)$^{a,A}$ | 0.46 | 18.4 (2.3)$^{a,A}$ | 0.43 |
| OX | *50.9 (4.9)$^a$ | 25.4 (4.1)$^{a,A}$ | 0.50 | 25.0 (3.0)$^{a,A}$ | 0.49 | 21.3 (5.3)$^{a,A}$ | 0.42 |

Same small case letter in SBS and SFS vertical columns indicates no difference at 5% significance level. Same capital letter between SFS horizontal rows indicates no difference at 5% significance level. *SBS values from previous report (10).

| Table 3 Failure mode analysis of de-bonded dentin specimens | Adhesive | SBS | SFS | SFS | SFS |
|---|---|---|---|---|---|
| | | 5 Hz | 10 Hz | 20 Hz | |
| GB | [100/0/0/0]$^A$ | [100/0/0/0]$^A$ | [100/0/0/0]$^A$ | [100/0/0/0]$^A$ | NS |
| SU | [20/20/46.7/13.3]$^b$ | [66.7/0/6.7/26.6]$^C$ | [75/0/8.3/16.7]$^C$ | [76.5/5.9/0/17.6]$^C$ | |
| OX | [0/33.3/40/26.7]$^D$ | [41.7/0/8.3/50]$^E$ | [23.0/0/38.5/38.5]$^E$ | [64.3/0/0/35.7]$^E$ | |

Same capital letter indicates no difference at a significance level of 5%. NS: Not significantly different ($P < 0.05$).

Failure mode [adhesive failure/cohesive failure in resin composite/cohesive failure in dentin/mixed failure] percentage of each failure mode

†Failure mode of SBS from previous report (10).
SEM observations

Representative SEM images are shown in Figs. 3 to 11. Resin/dentin interface exhibited good adaptation regardless of the adhesive system for all the adhesives tested in this study. The adhesive layers of the single-step self-etch adhesives were thinner than those of the two-step self-etch adhesive OX. SU and GB formed an adhesive layer of 6-8 µm (Figs. 3a, 4a), whereas OX formed an adhesive layer of approximately 10-12 µm (Fig. 5a). For SU and GB, a thin transitional layer that does not seem to be a hybridization of the tooth and resin monomer was formed at the interface between the cured adhesive layer and the dentin substrate (Figs. 3b, 4b). On the other hand, approximately 0.5 µm of dentin hybrid layer was observed between dentin structure and adhesive layer with OX (Fig. 5b).

The resin composite side of the de-bonded specimens after the SFS tests are exhibited in Figs. 6 to 11. For GB, low magnification images revealed the presence of adhesive failures (Figs. 6a, 7a); however, in the high magnification images, cracks, cleavages, beach marks, and partial resin tags (arrows) were observed in all the frequency groups (Figs. 6b, 7b). In the case of SU, adhesive and cohesive failures in the resin composite were observed in low magnification images (Figs. 8a, 9a), whereas high magnification images (Figs. 8b, 9b) revealed the presence of cracks, cleavages, beach marks, and partial resin tags, as was seen with GB. Partial cohesive failure in the dentin and resin composite was observed in low magnification images for OX, regardless of the frequency used (Figs. 10a, 11a). At higher magnifications, cohesive failures in the dentin and resin composite were more clearly observed (Figs. 10b, 11b) with OX than with the other two adhesives.

Discussion

Investigators continually strive to develop new evaluation techniques to simulate in vivo conditions for testing dental materials. Additionally, improving existing techniques is necessary for advancement in the research environment.

Fatigue is defined as the behavior of a material to fail at stresses that are lower than their maximum monotonic loading stress when subjected to cyclic loading (16).
Fatigue strength is the apparent strength of a material for a desired “life” (i.e., the number of loading cycles applied) (17). Degradation of the bonded interface can occur as a result of acid attack from oral bacteria (18), hydrolytic degradation of the adhesive (19), enzymatic degradation of the dentinal hybrid layer by MMP’s (matrix metalloproteinases) (20), and fatigue of the adhesive resin (10,11).
In the present study, we examined associations between the results obtained from fatigue testing of dentin bonds using different frequencies. The ability to examine the bond durability of resin adhesive systems at higher frequencies certainly has its advantages in the efficiency of fatigue testing. Significant differences ($P < 0.05$) in SBS among the three adhesive systems have been reported previously (10). The rank order of the SFS at all three frequencies (5, 10, and 20 Hz) was the same as that of SBS. It can be inferred that individual mechanical properties, such as the thickness of the adhesive layer, application procedure, and adhesive composition, may influence SBS and SFS values. However, the results did not demonstrate a significant difference ($P > 0.05$) in SFS between the three frequencies used (5, 10, and 20 Hz) for the three self-etch adhesive systems. Therefore, the null hypothesis that there would not be a significant difference in the fatigue strength of the dentin bonds at 5, 10, and 20 Hz was not rejected.

To comprehend the degradation mechanisms of dentin bonds, analysis of the failure process of the resin-dentin interface is essential. Intraoral restorations are subjected to repeated loading over the lifetime of the restoration, a period of years, which apply stresses of all kinds, tensile, compressive, and flexural, to the adhesive bond between the resin and the tooth. Therefore, repeated sub-critical loading during normal function as in SFS is more realistic than critical loads as in SBS. From the results of de-bonded failure analysis using the complex chi-square test, the three adhesives tested in this study did not show any significant differences in SFS at frequencies of 5, 10, and 20 Hz. However, significant differences between SBS and SFS were observed with SU and OX. Based on SEM observations of the resin/dentin interface, the single-step self-etch adhesives SU and GB showed similar morphological features, which were clearly different from those of the two-step self-etch adhesive OX. In addition, SEM observations exhibited different trends in failure pattern among the adhesives, but no clear visible differences were observed for each of the three individual self-etch adhesive systems at 5, 10, or 20 Hz frequencies. Therefore, these results indicate that the type of adhesive system or bond strength test used may influence the failure pattern of the de-bonded specimens; in addition, load frequency of SFS may also influence the failure pattern to a lesser extent.

The primary advantage of using higher frequencies is that more tests can be completed within a given amount of time. Other researchers have reported the inherent value of using lower loading frequencies in laboratory fatigue studies involving the failure of dental implants and denture teeth (21-23). Karl & Kelly (21) and Lee et al. (22) investigated the fatigue failure of titanium implants using 2 and 30 Hz frequencies. The occurrence of fatigue loading failure was significantly greater at 2 than at 30 Hz, and this was attributed to strain rate differences between the two frequencies (22). Rippe et al. (24) evaluated the effect of fatigue testing frequency on the bond strength of glass fiber posts bonded to prepared canals in bovine root dentin. The four groups in their study included one control (no mechanical cycling) and three cycling frequencies of 2, 4, and 8 Hz. The specimens were cross-sectioned and bonded posts were then subjected to a push-out test. In this test system, the frequency did not appear to affect the bond strength between bovine root dentin and the fiber post. Thus, the possibility of using higher frequencies in mechanical fatigue testing without impairing reliability was suggested in the study. In another study, Kelly et al. (25) examined fatigue loading on veneered glass-infiltrated alumina core ceramic discs (VITA In-Ceram ALUMINA) using 2, 10, and 20 Hz frequencies for 1 million cycles. They reported that the fatigue effect was small between 2 and 20 Hz and concluded that 20 Hz could be used for comparative testing. Although it is difficult to compare monolithic substances such as implant fixtures and ceramic materials with complex compound dentin bonded specimens, it appears that when using SFS testing models employed in this and early studies (14), higher frequencies (such as 10 and 20 Hz) do not markedly influence fatigue strength values and failure patterns.

The present study examined the bond durability to dentin, using three self-etch adhesives with a resin composite. The results demonstrated that frequencies of 5, 10, and 20 Hz produced the same SFS rank order of the adhesives, and that no significant differences in SFS were found in the adhesives between the three frequencies used. Although similar results may be achieved at a higher frequency, this study was limited only to the dentin and may not be applicable to other substrates or materials.

Frequencies of 5, 10, and 20 Hz, and 50,000 cycles produced similar results in fatigue strength for each of the three individual self-etch adhesives used for bonding a resin composite to dentin. In addition, failure analysis using the complex chi-square test showed that there was no significant difference in SFS among the three frequencies for the three adhesives tested in this study. These results suggest that frequencies as high as 20 Hz can be used to expedite fatigue testing of dentin bonds of resin composite materials using self-etch adhesives.
Conflict of interest
The authors declare no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

References
1. Erickson RL, De Gee AJ, Feilzer AJ (2006) Fatigue testing of enamel bonds with self-etch and total-etch adhesive systems. Dent Mater 22, 981-987.
2. Gillings BRD, Graham CH, Duckmanton NA (1973) Jaw movements in young adult men during chewing. J Prosthet Dent 29, 616-627.
3. Ruse ND, Shew R, Feduik D (1995) In vitro fatigue testing of a dental bonding system on enamel. J Biomater Res 29, 411-415.
4. Hiemae K, Heath MR, Heath G, Kazazoglou E, Murry J, Sapper D et al. (1996) Natural bites, food consistency and feeding behaviour in man. Arch Oral Biol 41, 175-189.
5. Buschang PH, Hayasaki H, Throckmorton GS (2000) Quantification of human chewing-cycle kinematics. Arch Oral Biol 45, 461-474.
6. Woda A, Mishellany A, Peyron MA (2006) The regulation of masticatory function and food bolus formation. J Oral Rehabil 33, 840-849.
7. Erickson RL, Barkmeier WW, Kimmes NS (2009) Fatigue of enamel bonds with self-etch adhesives. Dent Mater 25, 716-720.
8. Barkmeier WW, Erickson RL, Latta MA (2009) Fatigue limits of enamel bonds with moist and dry techniques. Dent Mater 25, 1527-1531.
9. Draughn RA (1979) Compressive fatigue limits of composite restorative materials. J Dent Res 58, 1093-1096.
10. Takamizawa T, Barkmeier WW, Tsujimoto A, Scheidel DD, Erickson RL, Latta MA et al. (2015) Effect of phosphoric acid pre-etching on fatigue limits of self-etching adhesives. Oper Dent 40, 379-395.
11. Takamizawa T, Barkmeier WW, Tsujimoto A, Scheidel DD, Watanabe H, Erickson RL et al. (2015) Influence of water storage on fatigue strength of self-etch adhesives. J Dent 43, 1416-1427.
12. Wiskott HW, Nicholls JI, Belser UC (1994) Fatigue resistance of soldered joints: a methodological study. Dent Mater 10, 215-220.
13. De Munck J, Braem M, Wevers M, Yoshida Y, Inoue S, Suzuki K et al. (2005) Micro-rotary fatigue of tooth-biomaterial interfaces. Biomaterials 26, 1145-1153.
14. Takamizawa T, Scheidel DD, Barkmeier WW, Erickson RL, Tsujimoto A, Latta MA et al. (2016) Influence of frequency on shear fatigue strength of resin composite to enamel bonds using self-etch adhesives. J Mech Behav Biomed Mater 62, 291-298.
15. Dewji HR, Drummond JL, Fadavi S, Punwani I (1998) Bond strength of Bis-GMA and glass ionomer pit and fissure sealants using cyclic fatigue. Eur J Oral Sci 106, 594-599.
16. Kappert PF, Kelly JR (2013) Cyclic fatigue testing of denture teeth for bulk fracture. Dent Mater 29, 1012-1019.
17. Kruzic JJ, Ritchie RO (2008) Fatigue of mineralized tissues: cortical bone and dentin. J Mech Behav of Biomed Mater 1, 3-17.
18. Mutluay MM, Zhang K, Ryou H, Yahyazadehfar M, Majd H, Xu HH et al. (2013) On the fatigue behavior of resin-dentin bonds after degradation by biofilm. J Mech Behav Biomed Mater 18, 219-231.
19. Feitosa VP, Leme AA, Sauro S, Correr-Sobrinho L, Watson TF, Sihoreti MA et al. (2012) Hydrolytic degradation of the resin-dentin interface induced by the simulated pulpal pressure, direct and indirect water ageing. J Dent 40, 1134-1143.
20. Hebling J, Pasley DH, Tjäderhane L, Tay FR (2005) Chlorhexidine arrests subclinical degradation of dentin hybrid layers in vivo. J Dent Res 84, 741-746.
21. Karl M, Kelly JR (2009) Influence of loading frequency on implant failure under cyclic fatigue conditions. Dent Mater 25, 1426-1432.
22. Lee CK, Karl M, Kelly JR (2009) Evaluation of test protocol variables for dental implant fatigue research. Dent Mater 25, 1419-1425.
23. Kappert PF, Kelly JR (2013) Cyclic fatigue testing of denture teeth for bulk fracture. Dent Mater 29, 1012-1019.
24. Rippe MP, Wandscher V, Bergoli CD, Baldissara P, Valandro LF (2011) Effect of cycle frequency of mechanical fatigue on bond strength. Dent Mater 27, Suppl 1, e17-18.
25. Kelly JR, Rungruangamun P, Hunter B, Vailati F (2010) Development of a clinically validated bulk failure test for ceramic crowns. J Prosthet Dent 104, 228-238.