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Ferrule Design Does Not Affect the Biomechanical Behavior of Anterior Teeth Under Mechanical Fatigue: An *In Vitro* Evaluation

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Clinical Relevance

The presence of the ferrule and the uniformity of the ferrule might not affect the fracture resistance and failure mode of fiber-post retained composite restorations of anterior teeth.

SUMMARY

Objectives: To investigate the survival and failure mode of fiber-post resin restorations over preparations with different ferrule designs when submitted to a fatigue load test.

Methods and Materials: Fifty bovine incisors were selected and divided into five groups (n=10) according to ferrule design: a no-ferrule group, a 2-mm circumferential ferrule group, a 2-mm buccal ferrule group, a 2-mm lingual ferrule group, and a 2-mm buccal and lingual ferrule group. The fiberglass post was cemented and the composite core was built up and prepared, followed by cementation of a full composite crown. The samples were subjected to a cyclic fatigue test with loading applicator at 135°; a staircase approach was used until fracture. Survival (cycles to fracture) and failure modes were recorded. Survival data were analyzed with the log-rank test, while Kruskal-Wallis and Fisher exact tests were used to analyze failure mode data (α=0.05).

Results: The median number of cycles to fracture ranged from 215,000 to 236,153. The log-

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rank test showed no statistically significant difference in survival rates among the groups (p=0.82). Regarding failure mode, three types were observed: I, post and/or core fracture; II, root fracture in the cervical third; and III, root fracture in the middle third. No statistical difference was observed among the groups (Kruskal-Wallis test, p=0.147).

Conclusion: The ferrule design had no effect on fatigue resistance or failure mode of endodontically treated incisor teeth restored with a fiber post, composite core buildup, and composite crown.

INTRODUCTION

The amount of remaining, sound coronal tissue has been reported as an important factor affecting the biomechanical behavior of post-retained restoration of endodontically treated teeth.[1] When a considerable amount of remaining coronal dentin is preserved, a 360° collar surrounding the parallel walls of dentin and extending coronally to the shoulder of the preparation can be used. This is called the ferrule effect,[2] which protects the root from fractures by reducing the stress concentration generated by masticatory function.[3]

A recent systematic review and meta-analysis of *in vitro* studies demonstrated the protective effect that a complete circumferential ferrule provides to endodontically treated teeth.[4] It enhances fracture resistance and, depending on its height, prevents unrepairable or catastrophic failures, which determines the tooth's extraction.[5] Unfortunately, it is not always possible to prepare the complete circumferential ferrule when restoring endodontically treated anterior teeth, mainly because of significant tooth structure loss, especially in the proximal areas. However, a partial ferrule might be better than the complete absence of a ferrule.

Previous studies assessing the effect of a partial ferrule upon the biomechanical properties of endodontically treated teeth have shown controversial results.[6-13] Some studies have reported that a partial ferrule, on the lingual/palatal side of the root, results in higher fracture resistance when compared with a complete circumferential ferrule.[6-9] A recent investigation has demonstrated that a complete 2-mm ferrule provides higher fracture resistance than a ferrule missing on a single proximal; however, this missing wall can be compensated for if more than 3 mm of the height of the remaining walls can be preserved.[10] Another recent finite element study has also demonstrated that a uniform ferrule tends to be more favorable than a localized higher ferrule in anterior endodontically treated teeth.[11] Conversely, others have reported that ferrule location had no significant effect on fracture resistance. It should be noted, however, that the presence of a ferrule is always associated with a more favorable failure mode.[12,13]

In addition to conflicting results, another issue must be taken into account when analyzing these studies. All studies using static loading test arrangements test the maximum load capability of the tooth.[14] However, static loading is poorly correlated to clinical situations and hence not clinically relevant. On the other hand, tests in which a subcritical dynamic (cyclic) load is applied yield the fatigue phenomenon, which better reproduces biomechanical clinical situations. Some *in vitro* studies have reported a positive effect of ferrule on the biomechanical behavior of post-restored teeth under a fatigue load.[15-17] However, until now, there have been no studies—to the best of the present authors' knowledge—that have investigated ferrule design under any dynamic loading protocol.

Therefore, the objective of this study was to assess the effect of ferrule design on the fatigue resistance and failure mode of endodontically treated bovine incisors restored with fiberglass posts, composite core buildups, and all-composite crowns. The tested hypothesis was that ferrule design does not affect the fatigue resistance and the failure mode of endodontically treated incisors restored with fiberglass posts, composite core buildups, and all-composite crowns.

METHODS AND MATERIALS

Fifty bovine incisors with similar dimensions were randomly selected and cleaned with a hand scaler. The dimensions and shapes of the bovine roots used were similar to those found in human maxillary central incisors.[18] The teeth were analyzed using 4× loupe magnification (Stemi 2000-C, Carl Zeiss, Gottingen, Germany) and were free of fractures or cracks. The buccal-lingual and mesiodistal widths were measured, and the mean widths of teeth were calculated. Teeth presenting widths deviating more than 10% from the average were replaced. The crowns were removed, resulting in 17-mm-long roots, which were numbered from 1 to 50 (by the generation of five random sequences of 10 numbers[19]) and allocated to be prepared according to ferrule design. The incisors were thus divided into five groups: NF, teeth with no ferrule (15-mm-length

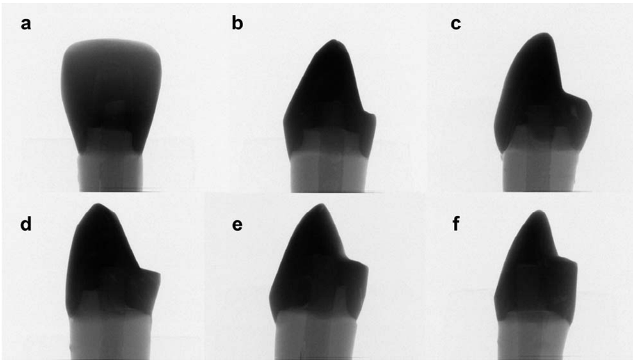

Figure 1. *Images of specimens used in the present study obtained by micro computed tomography illustrating the ferrule designs. (a): Complete ferrule, buccal view. (b): Complete ferrule, lateral view. (c): Ferrule on the buccal and lingual sides. (d): Ferrule only on buccal side. (e): Ferrule only on lingual side. (f): No ferrule.*

root); CF, teeth with a 2-mm circumferential complete ferrule; BF, teeth with a 2-mm ferrule only on the buccal side of the root; LF, teeth with a 2-mm ferrule only on the lingual side of the root; and BLF, teeth with a 2-mm ferrule only on the buccal and lingual sides of the root.

Root canal treatment was performed starting with No. 2 and 3 Gates Glidden drills (Dentsply Maillefer, Ballaiges, Switzerland) in the cervical and middle thirds of roots and with K-files (Dentsply Maillefer, Ballaiges, Switzerland) in the apical third of the root, limited to 1 mm short of the apex. The canals were rinsed with a 2.5% sodium hypochlorite solution and filled with gutta-percha points (Dentsply Maillefer) and calcium hydroxide–based cement (Sealer 26; Dentsply, Petrópolis, RJ, Brazil) using a lateral condensation technique. Each root was then embedded in a self-polymerized acrylic resin (VIPI Flash, VIPI, Pirassununga, Brazil) cylinder. Roots in the NF group were embedded 2 mm below the cervical limit, while the others were embedded 4 mm below. The periodontal ligament was simulated by using polyether impression material[20] (Impregum Soft; 3M ESPE, St Paul, MN, USA).

Teeth with a length of 17 mm were demarcated 2 mm below the cervical limit to enable the preparation of a 2-mm circumferential ferrule with a diamond bur No. 4137 (KG Sorensen, Barueri, SP, Brasil). The cervical tooth preparation was performed by using a half diameter of the diamond bur, resulting in a 1-mm-thick round cervical limit and 2-mm ferrule height. A flat end diamond bur No. 3131 (KG Sorensen, Barueri, SP, Brazil) was used to reduce the ferrule buccally, palatally, or biproximally, according to the desired design. BF group teeth had their ferrule reduced on their lingual side, LF group teeth had it reduced on their buccal side, and BLF group teeth had it reduced on both proximal sides (Figure 1). After ferrule preparation, the gutta-percha filling was partially removed with warm endodontic pluggers (SS White Duflex, Rio de Janeiro, Brazil), leaving 5 mm of gutta percha apically. The Largo drill No. 5 (Dentsply-Imp, Indústria e Comercio Ltda, Petrópolis, RJ) and Exacto specific drill No. 3 (Angelus, Londrina, PR, Brazil) were used for post space preparation. A prefabricated fiberglass post (Exacto No. 3, Angelus, Londrina, PR, Brazil) was etched with hydrogen peroxide[21] and cemented into the root canal with self-adhesive resin cement (RelyX Unicem 2, 3M ESPE). Composite resin cores (Filtek Z-350, 3M ESPE) were built up and standardized for each tooth as described by da Silva and others.[18] All teeth were prepared with a 1.5-mm axial reduction and 6° of axial convergence using a diamond bur No. 4138 (KG Sorensen), so all teeth remained with a 6.0-mm-height composite core. A high-speed handpiece with air-water spray was used in all preparations.

Impression of the coronal portion of the specimen was taken using a two-step technique involving condensation silicone impression material (Clonage, DFL, Rio de Janeiro, Brazil). After one hour, the impressions were poured with type IV stone (GC Fujirock EP, GC America, Alsip, IL, USA). Standardized composite crowns with a circumferential thickness of approximately 1.5 mm and a lingual stop of 1 mm to facilitate the load application were fabricated directly over the stone molds with a light-cured nanohybrid composite (Filtek Z-350 XT 3M) using the modified technique described by Krejci and others.[22] The composite crowns were then air abraded using 50-μm aluminum oxide particles (aluminum oxide; Pasom, Mairiporã, SP, Brazil) for 10 seconds, treated with a one-bottle silane coupling agent (Silano, Angelus Science and Technology, Londrina, Brazil) for one minute, and, finally, adhesively luted to the preparation using a self-adhesive resin cement (RelyX Unicem, 3M ESPE).[23]

For mechanical cycling, the specimens were submitted to an accelerated fatigue-testing protocol.[24,25] They were loaded one at a time in an MTS servo-hydraulic testing machine (Bionix, servohydraulic test system) at an angle of 135° to the long axis of each tooth. Cyclic isometric loading was applied on the palatal surface of the crown using a round-shaped metallic tip (Figure 2). A frequency of 2 Hz was used, starting with a load of 50 N for 5000 cycles (preconditioning phase), followed by stages of

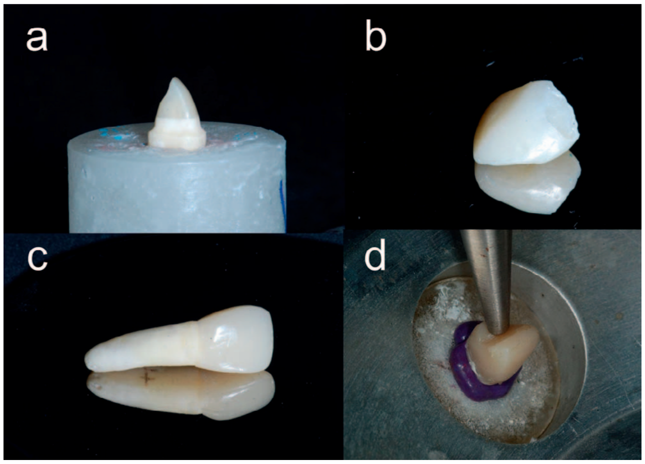

Figure 2. *Specimen build up and testing. (a): Specimen with complete ferrule and core in composite inserted into resin cylinder. (b): All-composite crown. (c): Restored tooth. (d): Loaded application over the lingual surface of specimen.*

100 N, 150 N, 250 N, 350 N, 450 N, and 550 N at 70,000 cycles each. For the survival analyses, the number of cycles it took for the specimens to fail were recorded. After each set of 70,000 cycles, the specimens were evaluated for the presence of cracks in the root and/or the restoration by a calibrated operator (50× magnification, DM2500, Leica Microsystems, Wetzlar, Germany). If there was still no failure observed, the specimen was loaded again for the next 70,000-cycle round. For each root, the test was carried out until failure. When failure occurred, the specimens were analyzed under a stereomicroscope (50× magnification, DM2500, Leica Microsystems) to determine the failure mode.[26] The failures were classified as I, post and/or core fracture; II, root fracture in the cervical third; III, root fracture in the middle third; IV, root fracture in the apical third; and V, vertical root fracture. In addition, the failure mode was dichotomized; specimens presenting types I and II were classified as reparable or favorable, whereas specimens that presented class III, IV, or V were classified as irreparable or unfavorable fractures.

Survival rates were estimated by Kaplan-Meier, and the log-rank test was used to detect any differences between groups. The Kruskal-Wallis test was used to detect any failure pattern differences, while Fisher exact test was used to test if the ferrule design was associated with failure mode (favorable or unfavorable). RStudio software (2016) version 1.0.136 was used, and the significance level was set at $\alpha=0.05$ for all analyses.

Table 1: *Median Number of Cycles to Failure and Corresponding Survival Rate*

Group	Median (95% LCI)	Survival Rate, % (SE)
No ferrule	215,220 (145,008)	40% (0.15)
Without ferrule	215,000 (215,000)	40% (0.15)
Buccal ferrule	236,153 (215,000)	50% (0.15)
Lingual ferrule	215,002 (215,000)	40% (0.18)
Bucco-lingual ferrule	215,000 (191,134)	40% (0.15)
Complete ferrule	215,220 (145,008)	40% (0.15)

Abbreviations: LCI, lower bound confidence interval (since all tests went on until a fracture occurred, the upper bound of the confidence interval is not calculated); SE = standard error.

RESULTS

Table 1 shows the median number of cycles to fracture for all groups, as well as their corresponding survival rates. Kaplan-Meier survival estimates for each group are presented in Figure 3. Differences were not statistically significant (log-rank test, $p=0.82$). Only three types of failures (types I, II, and III) were observed. Figure 4 shows the distribution according to ferrule design. Differences were not statistically significant (Kruskal-Wallis test, $p=0.147$). Furthermore, ferrule design was not associated with a difference in proportion between reparable/irreparable failures (Fisher exact test, $p=0.48$). Qualitative analyses of failure mode showed that most root fractures occurred on the proximal side of the root. Some fractures seemed to start at the proximal side, extended 2 to 3 mm apically, then changed direction toward the buccal side of the root and ended at the opposite proximal side (Figure 5).

DISCUSSION

Regarding the biomechanical behavior of endodontically treated bovine incisors with post-retained restorations, we found that an incomplete ferrule design does not affect the fatigue resistance and failure mode. Therefore, both hypotheses of this study were accepted.

To the best of our knowledge, this was the first study to use an accelerated fatigue testing protocol and survival analyses to investigate the effect of incomplete ferrule designs on mechanical resistance of post-retained restorations. It has been stated that this methodology results in stronger correlation between *in vitro* fatigue testing findings and clinical outcomes than others using static loading.[27,28] In addition to being well-related to clinical conditions, the accelerated fatigue method has other advantag-

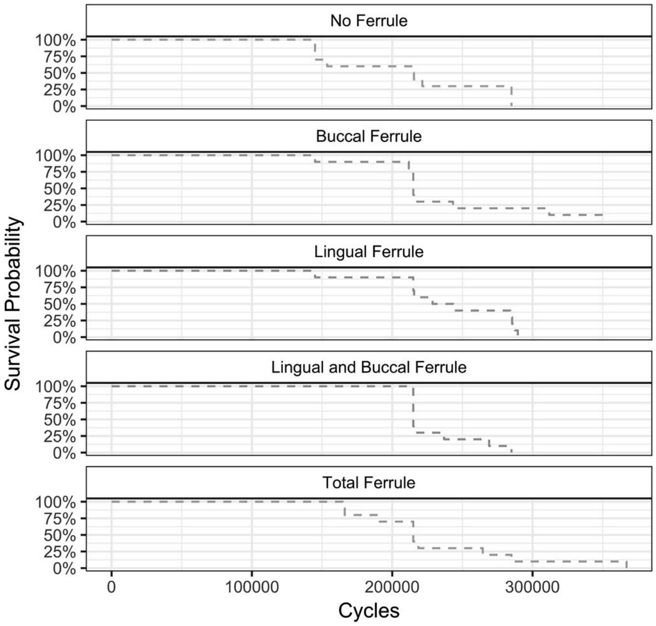

Figure 3. *Kaplan-Meier survival estimate. Note the similarity of curves among the experimental groups.*

es: it shortens the test time and, consequently, decreases costs. Furthermore, it can simulate the accelerated life cycle of the restored tooth, which could be impossible with other fatigue-testing methods because the tooth or post restoration might not fail if loaded below its endurance limit.[23]

Because most *in vitro* studies reported a positive effect of ferrule on the biomechanical behavior of post-restored teeth,[4,15-17] we expected to find a difference in survival at least between the complete circumferential ferrule and the no-ferrule groups. It can be speculated that the positive effect of ferrule was not demonstrated in the present study because of the reduced sample size used and the high data variability. However, data suggest that these factors may not be the main reason behind the findings of the present study. The observed effect size was very low for both the number of cycles to failure and the survival rate. For the former, the biggest median number of cycles to failure difference was 21,153 cycles, which occurred between the LF (236,153 cycles) and the CF and BLF groups (215,000) cycles. For the latter, the largest survival rate group difference was 10%. Other studies that reported statistically significant differences had much larger effect sizes. Ma and others[16] reported a statistical difference between no-ferrule, 0.5-mm ferrule, and 1-mm ferrule designs with an effect size that varied from 154,925 load fatigue cycles (mean difference between no-ferrule and 0.5-mm ferrule groups) to 262,659 cycles (mean difference between no-ferrule

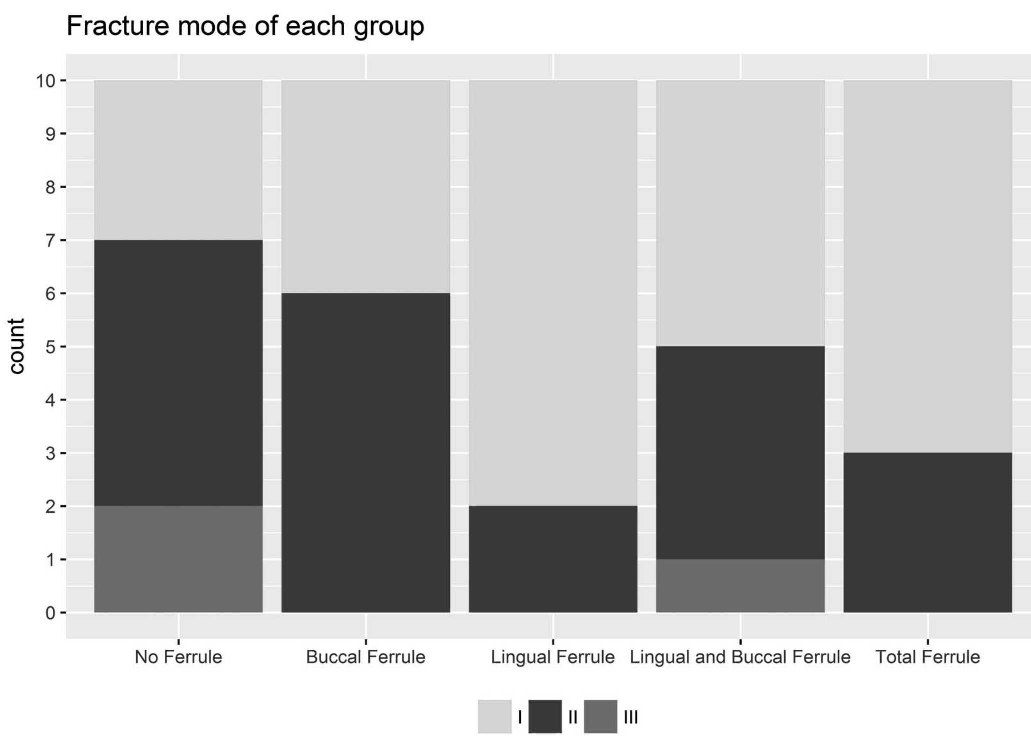

Figure 4. *Distribution of failure modes according to ferrule design. I, post and/or core fracture; II, root fracture in the cervical third; III, root fracture in the middle third.*

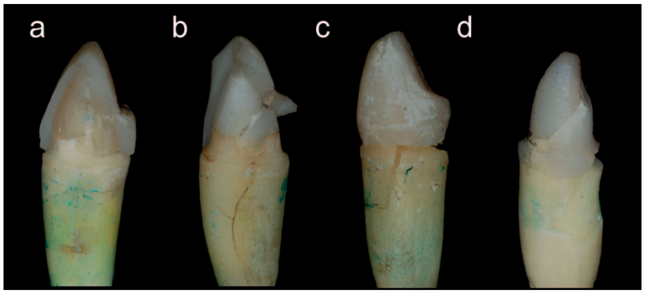

Figure 5. *Representative figures of fracture modes. (a): Fracture involving crown and core. (b): Fracture involving crown, core, and root, vertically until medium third. (c): Fracture of root starting at the proximal side and extending to buccal surface toward medium third. (d): Fracture of core with slight involvement of cervical third of root at lingual surface.*

and 1-mm ferrule groups). Libman and Nicholls[15] also reported a statistically significant effect of ferrule upon the fatigue resistance of post-restored teeth, with their smallest effect size being 70,511 cycles to failure (mean difference between 1-mm ferrule and 2-mm ferrule).

Another factor that may help to explain both the survival rate and the failure mode results is the use of adhesively luted all-composite crowns and fiberglass posts.[10] Fiberglass posts with a similar elastic modulus to dentin improve the stress distribution along the root, while more rigid post systems are usually associated with higher stress concentration areas—normally at the cervical area—that are prone to result in unfavorable failure modes.[29] Similarly, all-composite crowns have a similar elastic modulus to dentin, which may have further contributed to a better distribution of stress on the fiberglass post–restored tooth. An important advantage of fiber posts is the possibility of building up direct restoration with composite because this procedure reduces the cost of treatment when compared with using indirect restorations. Because this approach presents similar biomechanical behavior to indirect composite crowns, we chose to use indirect restorations in this study to standardize the restorative procedures and reduce the risk of bias. Therefore, we believe that using only restorative materials with a similar elastic modulus to dentin and adhesively integrated to the remaining tooth structure might strongly explain the findings observed in the present study. It is important to emphasize that an important advantage of using fiber posts is that they enable restoration of the extensively destroyed tooth using composite, and this approach reduces the number of sessions required to end the restorative procedure as well as the cost of treatment.

Because there is a lack of studies evaluating incomplete ferrule designs and adhesively luted composite crowns, comparisons with other studies is difficult. A recent systematic review and meta-analysis regarding the ferrule effect of both *in vitro* and clinical studies reported that the presence of ferrule was not related to higher survival of incisor and molar teeth, which is in accordance with our results.[4] On the other hand, premolar survival was positively influenced by the presence of ferrule in clinical studies. Another observation is that ferrule enhanced the fracture resistance of all types of teeth in several *in vitro* studies. Again, this discrepancy may be due to the fact that the *in vitro* studies used static loading, while the teeth were submitted to a cyclic load in our study, better simulating the clinical conditions. Other studies that also investigated incomplete ferrules on incisor teeth reported that a palatal ferrule effectively enhanced the teeth's fracture resistance (with better results than a circumferential ferrule).[6-8] Conversely, other studies reported no difference regarding ferrule designs.[12,13] It is important to emphasize that all these studies used a static loading setting, and these differences in experimental setup can strongly affect the results.

Despite being time-consuming and expensive, cyclic tests are important because they better simulate oral conditions. A possible limitation of our study design is the fact that the test was performed under dry conditions; the presence of humidity, which would make the conditions even closer to that of the oral environment, might influence the biomechanical behavior of endodontically treated teeth. Therefore, more mechanical fatigue studies—with different post systems and/or types of crowns, on different types of teeth, and under conditions closer to those of the oral cavity—are needed to better elucidate the effect of incomplete ferrule designs on the biomechanical behavior of post-retained restorations.

CONCLUSION

Within the limits of the present study, we conclude that the ferrule design does not affect the biomechanical behavior of endodontically treated incisor teeth restored with fiberglass post–retained restorations under cyclic loading.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of approval of the Federal University of Sergipe.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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