Implant-Abutment Connection Designs for Anterior Crowns: Reliability and Failure Modes

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Objectives: *To investigate the effect of implant-abutment connection types on reliability and failure modes of anterior single-unit crowns.*

Methods: *Fifty-four implants were divided in 3 groups (n = 18 each): external hexagon (EH), internal hexagon (IH), and Morse taper (MT) connection. Abutments were screwed to the implants, and maxillary central incisor metal crowns were cemented and subjected to step-stress accelerated life testing.*

Results: *The beta values derived from use-level probability Weibull calculations for groups IH (2.52), EH (1.67), and MT (0.88) indicated that fatigue influenced the failure only of IH and EH groups. The reliability for a mission of 100,000 cycles at 175 N was 0.99 (0.98–1.00), 0.84 (0.62–0.94) and 0.97 (0.87–0.99) for the EH, IH, and MT, respectively. The characteristic strength was not significantly different between EH (290 N) and IH (251 N) but significantly higher for MT (357 N). For IH and EH groups, failure involved screw fracture, and the MT implants primary failure mode was abutment fracture.*

Conclusions: *Reliability was higher for the EH and MT relative to IH groups, whereas the characteristic strength was significantly higher for implants with MT connection. (Implant Dent 2013;0:1–6)*

Key Words: dental implants, reliability, Weibull, fractography

The success of dental implant therapy should be evaluated from both esthetic and mechanical perspectives.[1] Considering that both esthetics and biomechanics are affected by the achievement and maintenance of osseointegration,[2] engineering parameters of the implant, such as macrogeometry and type of implant-abutment connection, are under constant development.[1,3–10]

The external hexagon (EH) system was initially designed to provide a rotational torque transferring mechanism suited for surgical placement of the implant into the osteotomy. Although providing ways for prosthesis indexing and antirotational capabilities, the extension of use of EH from full-mouth splinted reconstructions to single-unit prosthesis leads to concerns regarding the mechanical challenges imposed by loads mainly borne by the abutment screw.[11] Internal connections such as internal hexagon (IH) and Morse taper (MT) were further developed so that loads could be dissipated along the implant walls in contact with the abutment surface, also providing a shield for the abutment screw.[12] MT includes an interference fit connection type in a conical geometry of the abutment and the corresponding surface of the implant well.[13]

The choice of implant-abutment connection design (external or internal) and prostheses fixation mode (cemented vs screwed) may affect either biological or technical complication rates, especially in single crowns, which are not splinted and subjected to multidirectional loading that challenges the connection components and restoration structural integrity.[1,14–16] It has been reported that the single-unit implant-supported restoration represents the scenario where the incidence of screw loosening or fracture is the highest, especially in external connections.[4,17,18] In addition, the design of the implant-abutment connection may also influence the biological response of hard and soft tissues.[18,19]

In an attempt to reduce prosthetic and biological complications, different implant-abutment connection designs

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have been developed and are available for use. However, the literature concerning the mechanical behavior of EH, IH, and MT implant-abutment connections is still sparse and may be contradictory.[20] Most studies concerning the mechanical behavior of implant connections have been limited to static numerical simulations,[14,21,22] and only a few have considered the role of fatigue in the mechanisms of failure.[14,21,22] Finite element analysis, for instance, has shown improved stability for the abutment and the lowest stress concentration in the abutment screw for MT connections[23] relative to EH and IH. Conversely, a recent study comparing the EH, IH, and MT implants showed that EH presented significantly higher fatigue resistance than IH and MT.[20]

The main challenge in the development of implant-abutment connection designs relies on reducing/eliminating the incidence of mechanical failures in the implant-prosthetic devices and improving the response of bone and soft tissues.[18,24,25] Thus, the evaluation of reliability and failure modes could provide insight into the mechanical behavior of different configurations of implant-abutment connections.[1,18,26–28]

This study aims to evaluate the reliability and failure modes of maxillary central incisor metal crowns on EH, IH, and MT implant-abutment connection configurations when subjected to step-stress accelerated life testing (SSALT). The null hypothesis was that there would be no difference in reliability or failure modes between the different implant-abutment connections of implants from the same manufacturer when subjected to SSALT.

MATERIALS AND METHODS

Experimental Design

Fifty-four implants of 4.0 mm diameter and 10 mm length with the same external macrogeometry were used for this study (Implacil de Bortoli, Ltda., Sao Paulo, Brazil). They were divided according to the implant-abutment connection design as follows: EH, IH, and MT (Table 1).

Table 1. Characteristics of the Groups Used in This Study

Groups	EH (n = 18)	IH (n = 18)	MT (n = 18)
Design of implant-abutment connection (Implacil de Bortoli, Ltda)	Conical implant with external hexagon connection	Conical implant with internal hexagon connection	Conical implant with internal conical connection

Sample Preparation

Implants with EH, IH and MT design were secured to their respective prefabricated abutments (Implacil de Bortoli, Ltda) and torqued according to the manufacturer's instructions (25 N·cm). Then, they were vertically embedded in poly-methyl-methacrylate resin (Orthodontic Resin; Dentsply Caulk, Philadelphia, PA) leaving 1 mm of the implant-abutment finishing line exposed above the potting surface.

All groups were restored with standardized central incisor metallic crowns cast in Co-Cr alloy (Wirobond 280; BEGO, Bremen, Germany). To reproduce the anatomy of the crowns (n = 54 total), an impression was taken from the first waxed pattern and used by the technician as a guide during waxing of the remaining crowns. Before cementation, crowns were sandblasted with aluminum oxide (particle size ≤ 40 μm, using 276 KPa compressed air

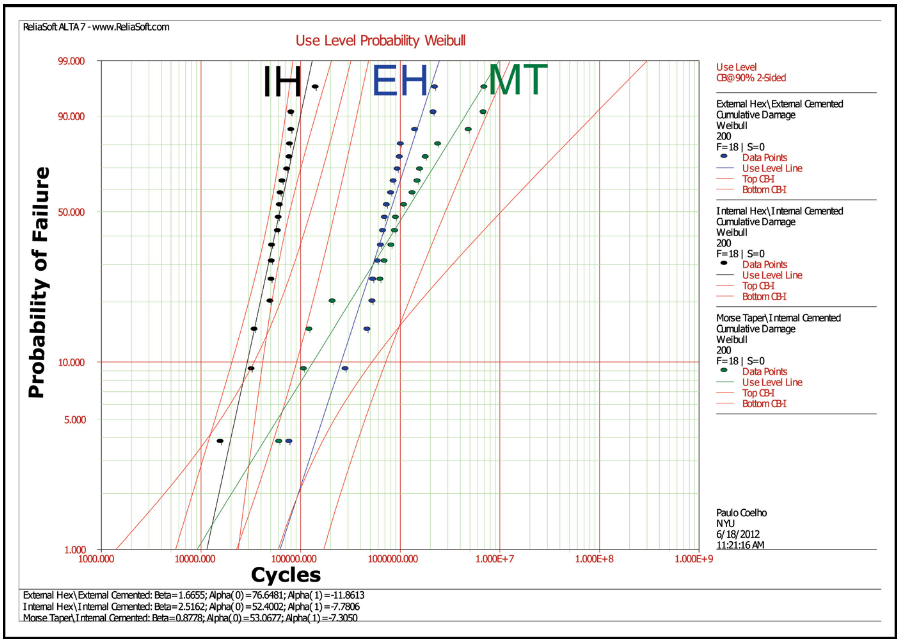

Fig. 1. Use-level probability Weibull for tested groups showing the probability of failure as a function of number of cycles given a mission of 100,000 cycles at 175 N.

Table 2. Calculated Reliability for a Mission of 100,000 Cycles at 175 N Load

	EH	IH	MT
Mission of 100,000 cycles at 400 N			
Upper	1.00	0.94	0.99
Mean	0.99	0.84	0.97
Lower	0.98	0.62	0.87
Beta			
Upper	2.56	3.91	1.68
Mean	1.67[a]	2.52[a]	0.88[b]
Lower	1.08	1.62	0.46

Equal letters (a and b) represent statistically homogeneous groups.

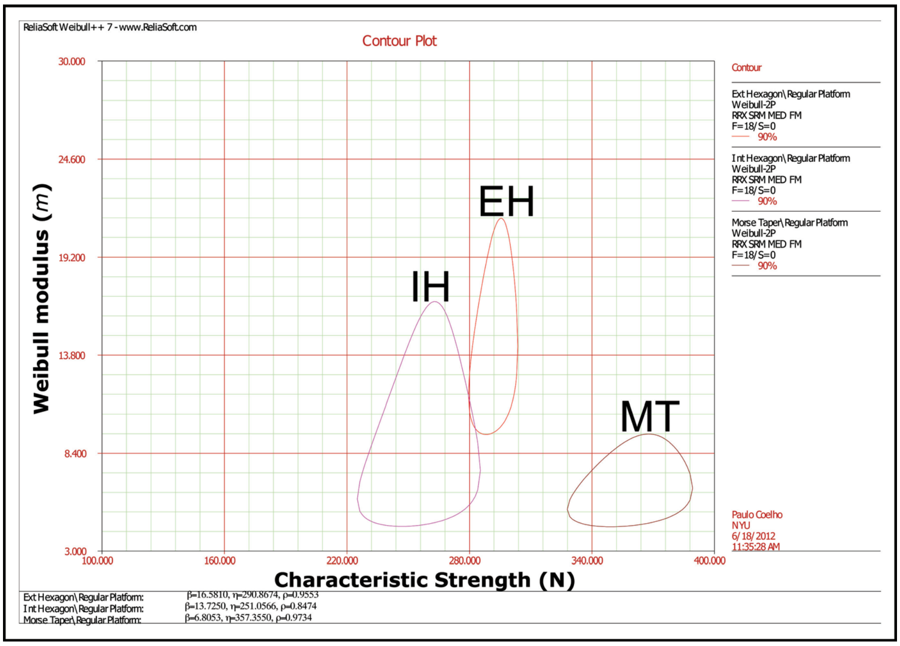

Fig. 2. Contour plot (Weibull modulus vs characteristic strength) for group comparisons. Note the overlap between IH and EH.

pressure), cleaned with ethanol, dried with air free of water and oil, and then cemented (Rely X Unicem; 3M ESPE, St Paul, MN). The final dimensions for EH, IH, and IC were the same.

Mechanical Testing and Reliability Analysis

To test the implant-abutment connection in a challenging scenario, mechanical testing was undertaken with all specimens placed at a 30-degree axial inclination, as per ISO 14801:2007, where the indenter contacted the crown surface and applied the prescribed load within the step profile. The intent was to provide a bending component during loading, which may occur during intercuspal position but more commonly present in protrusive or laterotrusive mandibular movements, namely anterior guidance.[29] Based on the mean load to failure of previous studies, SSALT profiles were determined.[1,18,27,28] This fatigue testing approach consists of testing the samples at stress levels higher than used stress to facilitate failures in a timely manner. The results of these tests are then analyzed so that a profile of the failure behavior of the specimens at used stresses can be determined based on the behavior of the samples at the accelerated stresses.[26]

The profiles were designated mild, moderate, and aggressive, with the number of specimens assigned to each group in the ratio 3:2:1, respectively. Therefore, of the 18 samples per group, 9 were allocated in the mild, 6 in the moderate, and 3 in the aggressive profiles. Mild, moderate, or aggressive profile refer to the increasingly stepwise rapidness in which a specimen is fatigued to reach a certain level of load, meaning that specimens assigned to a mild profile will be cycled longer to reach the same load of a specimen assigned to either moderate or aggressive profile.[26] The rationale for using at least 3 profiles for this type of testing was based on the need to distribute failures across different step loads, allowing better prediction statistics, narrowing confidence bounds. The prescribed fatigue method was SSALT under water at 9 Hz with a servo-all-electric system (TestResources 800L, Shakopee, MN), where the indenter contacted the crown surface and applied the prescribed load within the step profile.

The specimens were evaluated at the completion of each fatigue step-stress cycle or final failure (determined by setting the machine to stop when a compression lower limit of approximately 0.5 mm was reached). Criteria used for failure were bending or fracture of the fixation screw, partial fracture or total fracture of the abutment, and fracture of an implant.

Based on the step-stress distribution of the failures, use-level probability Weibull curves (probability of failure vs cycles) with use stress of 175 N and 90% 2-sided confidence intervals were calculated and plotted (Alta Pro 7; ReliaSoft, Tucson, AZ), using a power law relationship for damage accumulation. Reliability for a mission of 100,000 cycles at 175 N (90% 2-sided confidence interval) was calculated for comparison between the groups. The Weibull modulus 2-sided 90% confidence intervals were calculated using the Fisher matrix method.[26] For the parameters calculated in this study, the 90% confidence interval range were calculated as follows:

$$IC = E(G) \pm Z_{\alpha}\,\mathrm{sqrt}(\mathrm{Var}(G)) \quad (1)$$

where IC is the confidence bound, $E(G)$ is the mean estimated reliability for the mission calculated from Weibull statistics, z_{α} is the z value concerning the given IC level of significance, and Var (G) is the value calculated by the Fisher information matrix.[30,31]

Table 3. Failure Modes After Mechanical Testing (SSALT) According to the Used Failure Criteria

	EH (n = 18)	IH (n = 18)	MT (n = 18)
Implant	10 = fracture (hexagon) 6 = fracture (body) 2 = intact	18 = intact	18 = intact
Abutment	18 = intact	18 = intact	7 = fracture 7 = bending 4 = intact
Abutment screw	12 = fracture 6 = intact	18 = fracture	4 = fracture 14 = intact

Failure Analysis

The failed samples were inspected in polarized light (MZ-APO stereomicroscope; Carl Zeiss MicroImaging, Thornwood, NY) and classified according to the proposed failure criteria for comparisons between groups. To identify fractography markings and to characterize failure origin and propagation direction, the most representative failed samples of each group were inspected under a scanning electron microscope (SEM) (S-3500N; Hitachi, Osaka, Japan).[1,32]

RESULTS

The step-stress use-level probability Weibull plot and summary statistics at a 175-N load are presented in Figure 1 and Table 2, respectively. The step-stress accelerated fatigue permits estimates of reliability at a given load level. The calculated reliability with 90% confidence intervals for a mission of 100,000 cycles at 175 N showed that the cumulative damage from loads reaching 175 N would lead to 99% implant-supported restoration survival in the EH, 84% in the IH, and 97% in the MT groups.

The mean beta (β) values (confidence interval range) and associated upper and lower bounds derived from use-level probability Weibull calculation (probability of failure vs number of cycles) were 1.67 (1.56–1.08), 2.52 (3.9–1.62), and 0.88 (0.46–1.68) for groups EH, IH, and MT, respectively. These values indicated that fatigue was not an accelerating factor only for failures of group MT, whereas EH and IH presented failure distributions that were influenced by damage accumulation. The β (called the Weibull shape factor) describes failure rate changes over time where $\beta < 1$: failure rate is decreasing over time, commonly associated with "early failures" or failures that occur because of egregious flaws; $\beta \sim 1$: failure rate that does not vary over time, associated with failures of a random nature; and $\beta > 1$: failure rate is increasing over time, associated with failures related to damage accumulation.[18]

The load-at-failure data during step stress for each sample were then used to calculate a probability Weibull

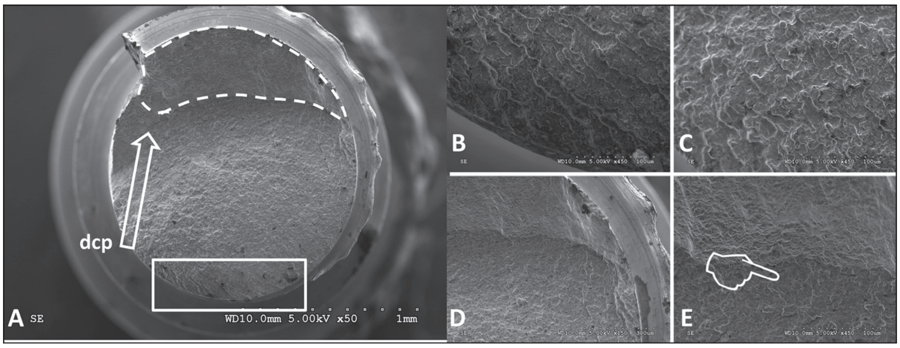

Fig. 3. Representative fractured screw after SSALT of group (IH): (**A**) SEM micrograph (50×) showing a fracture occurring in the abutment screw viewed from its long axis. The white dotted area shows a compression curl, which evidences fracture origin at the opposing tensile side (white box) and indicates the direction of crack propagation (dcp) (white arrow). **B** and **C**, Higher magnification (450×) of the boxed area presented in (**A**). **D** and **E**, Higher magnifications (150× and 450×, respectively) of the fractured surface showing the dimpled surface appearance because of microvoid coalescence (pointer).

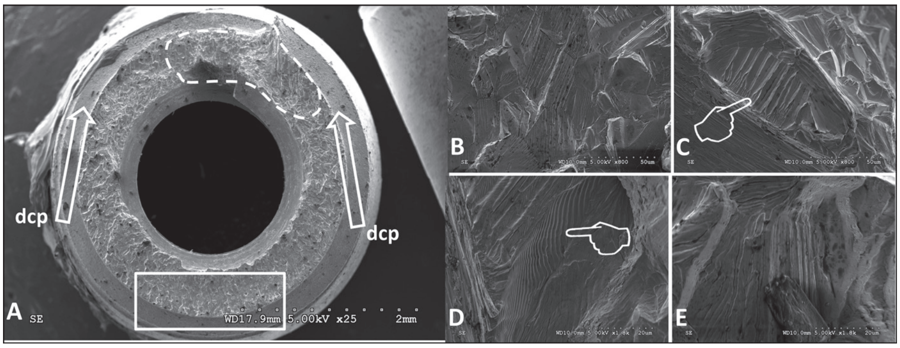

Fig. 4. Representative fatigue fractured implant from the external hexagon group: (**A**) SEM micrograph (25×) showing a fracture occurring in implant viewed from its long axis. The white dotted area shows a compression curl, which evidences fracture origin at the opposing tensile side (white box) and indicates the direction of crack propagation (dcp) (white arrow). **B** and **C**, Higher magnification (800×) of the boxed area and compression curl shown in (**A**) where fractographic marks such as fatigue striations are evident. **D** and **E**, Higher magnifications (1800×) of the fractured surface showing the direction of crack propagation (dcp) and fatigue striations (pointer).

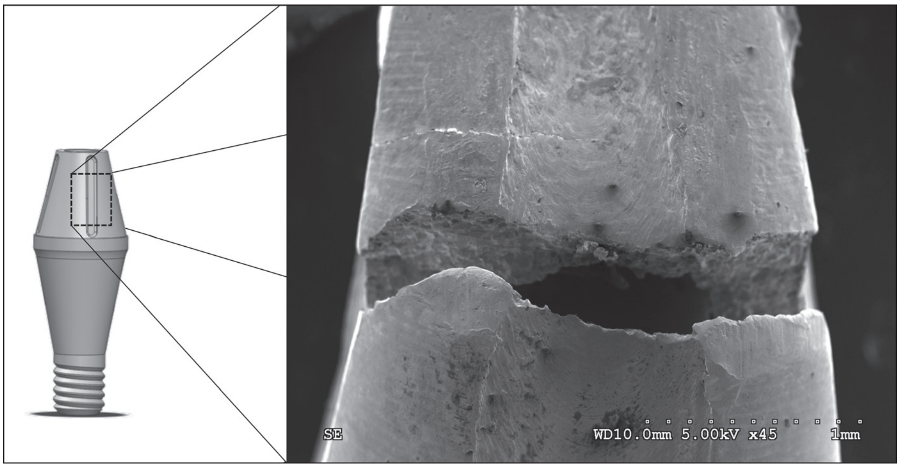

Fig. 5. Representative SEM micrograph (45×) of a fractured MT abutment.

distribution. An instructive graphical method to determine whether these data sets are from different populations (based on nonoverlap of confidence bounds) is the utilization of a Weibull parameter contour plot (Weibull modulus [m] vs characteristic strength [η]). As presented in Figure 2, the MT group presented a significantly higher characteristic strength compared with EH and IH groups, whereas no difference was observed between EH and IH groups. The Weibull modulus (m) was $m = 16.58$ for EH, $m = 13.72$ for IH, and, $m = 6.80$ for MT. The characteristic strength (η) was $\eta = 290.8$ N for EH, $\eta = 251$ N for IH, and $\eta = 357.3$ for MT (Fig. 2).

Failure Modes

All specimens failed after SSALT. When component failures were evaluated together, failures comprised the combination of abutment screw bending or fracture, abutment fracture, and implant fracture. Observed failure modes are described in Table 3. For EH and IH groups, failure predominantly involved abutment screw fracture. The abutments remained intact after mechanical testing for EH and IH groups. The MT group presented a higher number of abutment fractures in comparison with the EH and IH groups along with few failures in abutment screw. The highest number of implant failures occurred in the EH group at the hexagon. Observation of the polarized-light and SEM micrographs of the fractured surface of the abutment screws allowed the consistent identification of fractographic markings, such as compression curl with its opposite tensile side indicating the fracture origin, and the direction of crack propagation (Figs. 3–5).

DISCUSSION

It has been proposed that different implant-abutment connections will present advantages and disadvantages in clinical and laboratory practice.[9,15,16] Ultimately, their reliability is the parameter that will determine their success from an overall biomechanical performance as the highest number of failures of dental implant prosthetics arise from connection failures.[33] This study evaluated the reliability and failure modes of different implant connections from the same manufacturer. For this purpose, a fatigue testing method that results in failures that are remarkably similar to clinical failures was used.

The life-stress relationship model allows the extrapolation of a use-level probability density function from life data obtained at increased stress levels. These models describe the path of a particular life characteristic of the distribution from 1 stress level to another.[14] For the Weibull distribution, the scale parameter (η) is considered to be stress dependent.[14] Therefore, the life-stress model for data that fits the Weibull distribution is assigned to η.[14]

The current findings may be explained based on the association among stress distribution and systems' reliability around the weakest component of the implant-abutment connection: the abutment screw.[9,14–16] It can be speculated that higher levels of stress in the abutment screw lead to failures in implants with EH and IH configuration. Although no significant difference in reliability was found between the different implant connection designs, 2 important factors should be considered based on the failure modes: (1) from a clinical perspective, both the internally connected systems (IH and MT) resulted in the best scenario when the restorative overall system is considered; that is, implants never fractured and repair would be limited to prosthetic components; and (2) apart from the same reliability, the MT's failure was mainly dictated by damage accumulation rather than fatigue *per se*. In addition, significantly higher fatigue loads were needed for failure of MT compared with EH and IH groups. Because all previous considerations were performed considering a mean value of incisal bite force,[14,34] the cumulative damage from loads reaching 175 N would lead to acceptable percentage of restoration survival for the all specimens as per our simulation.

This means that, under functional occlusion conditions,[35] almost all tested specimens would present satisfactory fatigue endurance in the wet environment used in this study.

The results of the accelerated life testing suggest that the geometric inherent differences of each design did play a role in the use-level probability calculations, which showed that failure rates increased over time and were related to damage accumulation in the EH and IH system but not in the MT system (where the system strength was more likely to play a role on failure distribution as per the low beta value observed). Therefore, a fatigue-associated failure behavior was observed for the different tested systems with EH or IH connections, as evidenced by the resulting $\beta > 1$ (also called the Weibull shape factor).[28] The results of this study are in contrast with those recently presented, where fatigue resistance of EH, IH, and MT groups presented the same outcome,[20] and intrinsic differences in the implants and components geometry may have accounted for the different results.

The failure modes were different for all groups as each geometric configuration and manufacturing tolerances do result in different regions and level of stress concentration. Fractures of the abutment screw were more often observed in the IH group. Conversely, EH implant fractures were associated with complex fracture scenarios, such as fractures of the screw that at times were associated with failures in the body or implant hexagon. Different from the other groups, the MT presented more susceptibility to failure of the abutment, although occurring at significantly higher characteristic strength values than EH and IH, likely because of the larger contact area between the abutment and the implant internal walls relative to IH. In such a scenario, despite the larger area for stress dissipation during loading, as loading increases, the abutment integrity is challenged by the higher resistance provided by the implant wall thickness at the cervical region.[5] From a clinical perspective, the complex and multicomponent failures observed for the EH group may result in catastrophic implant loss. When a technical complication occurs, and they do seem to increase over time,[36] it is desirable that they remain limited to prosthetic restorative components rather than in the implant.

CONCLUSIONS

The postulated null hypothesis that different reliability and failure modes would be found for different implant-abutment connection designs when subjected to SSALT was partially accepted. Although the reliability was not different between EH, IH, and IC groups, the failure modes were different.

Disclosure

The authors claim to have no financial interest, either directly or indirectly, in the products or information listed in the article.

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