Survival and failure modes: platform-switching for internal and external hexagon cemented fixed dental prostheses

Anchieta RB, Machado LS, Hirata R, Coelho PG, Bonfante EA. Survival and failure modes: platform-switching for internal and external hexagon cemented fixed dental prostheses.


This study evaluated the probability of survival (reliability) of platform-switched fixed dental prostheses (FDPs) cemented on different implant–abutment connection designs. Eighty-four-three-unit FDPs (molar pontic) were cemented on abutments connected to two implants of external or internal hexagon connection. Four groups (n = 21 each) were established: external hexagon connection and regular platform (ERC); external hexagon connection and switched platform (ESC); internal hexagon and switched platform (ISC); and internal hexagon and switched platform (IRC). Prostheses were subjected to step-stress accelerated life testing in water. Weibull curves and probability of survival for a mission of 100,000 cycles at 400 N (two-sided 90% CI) were calculated. The beta values of 0.22, 0.48, 0.50, and 1.25 for groups ERC, ESC, IRC, and ISC, respectively, indicated a limited role of fatigue in damage accumulation, except for group ISC. Survival decreased for both platform-switched groups (ESC: 74%, and ISC: 59%) compared with the regular matching platform counterparts (ERC: 95%, and IRC: 98%). Characteristic strength was higher only for ERC compared with ESC, but not different between internal connections. Failures chiefly involved the abutment screw. Platform switching decreased the probability of survival of FDPs on both external and internal connections. The absence in loss of characteristic strength observed in internal connections favor their use compared with platform-switched external hexagon connections.

From a treatment-planning perspective, implant-supported fixed dental prostheses (ISFDPs) are among the first treatment options for the replacement of more than one missing tooth in posterior regions (1–3). Clinical studies have indicated a success rate of at least 86% after 10 yr of clinical service (4, 5), with ISFDPs presenting similar success rates to those of tooth-supported fixed dental prostheses (FDPs) (6). When supported by implants, the most commonly reported complications are chipping of the porcelain veneer and loosening or fracture of abutment screws (4).

Several factors may influence the long-term success of implant-supported restorations (1–3). From a mechanical perspective, the implant–abutment connection design seems to influence the complication rates of single-unit crowns (7–9) and to affect the short- and long-term soft- and hard-tissue response (3, 10). Thus, to improve the clinical behavior of implant and prosthetic devices, a variety of implant–abutment configurations has been developed (3, 11, 12).

Single-unit restorations on external connections are more prone to abutment screw complications, such as loosening and fracture, when compared with similar restorations on internal connections (8), as the stability of the former relies primarily on the short hexagon and abutment screw (13, 14). It has been suggested that the internal connection is mechanically superior to the external hexagon as a result of improved load distribution deep within the implant internal walls, leading to better stress shielding of the abutment screw (15). The presence of some internal wall engagement has been reported to create a stiff, unified body that better resists oblique loading (14, 16).

Apart from the implant–abutment connection geometry, the horizontal relationship between implant and abutment margins at their junction has been the subject of investigations for its potential to affect marginal bone levels (17). There is growing evidence that the degree of marginal bone-level maintenance is proportional to the amount of mismatch between abutment and implant, where abutments of decreased diameter, in relation to the
implant, favor marginal tissue health (18–20). However, one aspect still unresolved is the amount of mismatch in platform switching required to maintain bone level or lead to minimal loss while not being detrimental to the overall system’s mechanical performance. In evaluations of the same implant–abutment connection geometry, a mismatch of 0.5 mm did not affect the probability of survival (3) compared with a matching platform, whereas a mismatch of 1 mm led to a significant decrease in the probability of survival (21). Numerical simulations (22–24) and in vivo studies (19, 25) have also shown that alternative implant–abutment configurations, such as switching platform, reduced the stress concentration in some implant components as well as in the peri-implant bone.

To date, the majority of studies related to the probability of survival and failure patterns, or stress concentration of implant/abutment systems have been reported for single crowns (3, 11, 12). The performance of ISFDPs (where abutment splinting may have a more prominent effect than the abutment material) or fixation method has been less explored. A recent fatigue study performed by our group showed that the fixation method had a significant impact on the survival of ISFDPs, with a lower percentage of survival for screwed restorations compared with cemented restorations (26), which is in agreement with a systematic review (27). On the other hand, it is unknown whether the performance of cemented three-unit FDPs with mismatched implant–abutment platforms is influenced by the implant–abutment connection design. Therefore, the present study aimed to evaluate the survival and the failure modes of three-unit ISFDPs with external hexagon connection either with matched or mismatched implant–abutment platforms, using stress accelerated life-testing (SSALT), and to compare the results with data generated on internal connection counterparts tested under the same conditions (26). The hypothesis tested was that no differences in survival and failure modes would be found between prostheses with these configurations considering that the three-unit ISFDPs with a molar pontic are splinted.

Material and methods

Experimental design

The group combination of implant–abutment connection design and horizontal configuration of the implant–abutment platform used for the three-unit posterior ISFDP (n = 21 per group) were as follows: implants with external hexagon connection and regular platform (ERC); implants with external hexagon connection and switched platform (ESC); implants with internal hexagon connection and regular platform (IRC); and implants with internal hexagon connection and switched platform (ISC) (26) (Fig. 1, Table 1). The external geometry and dimensions of the implants between groups were identical.

Sample preparation

Two implants were connected to two abutments and vertically embedded in polymethyl-methacrylate resin (Orthodontic Resin; Dentsply Caulk, Philadelphia, PA, USA) leaving 1 mm of implant–abutment finishing line exposed above the potting surface. The resin block with embedded implants and abutments was used for the production of all samples. All groups were restored with a standardized three-unit metal ISFDP (first molar pontic) obtained by milling and produced from one single .stl file, which fabricated a series of identical samples (Co-Cr alloy, Wiroombond 280; Bego, Bremen, Germany). To keep variables constrained to our study aims, no veneering porcelain was layered onto the prostheses. The prefabricated abutments (Ti-6Al-4V) (Emfils; Colosso Evolution system, Itu, SP, Brazil) were torqued (Tohnichi BTG150CN-S; Tohnichi America, Northbrook, IL, USA) according to the manufacturer’s instructions (30 Ncm), with the respective abutment screws (Ti-6Al-4V Emfils; Colosso Evolution system). Before cementation, the intaglio surface of the prostheses was blasted with aluminum oxide (particle size ≤40 μm, using 276 kPa compressed air pressure), cleaned with ethanol, dried with air free of water and oil, and then cemented (Rely X Unicem; 3M ESPE, St Paul, MN, USA).

Mechanical testing and probability of survival analysis

To test the implant–abutment connection in a challenging scenario, mechanical testing was undertaken with all
specimens placed at a 30° axial inclination, with the indenter contacting the lingual slope of the buccal cusp of the pontic. The intent was to provide a bending component during loading (28). Three specimens of each group underwent single load to failure (SLF) testing, using a universal testing machine equipped with a tungsten carbide indenter and 10,000 N load cell at crosshead speed of 1 mm min⁻¹ (INSTRON 5666 machine; Instron, Canton, MA, USA). The mean load to failure was calculated for each group. Based upon the mean load to failure, SSALT profiles were determined. This fatigue-testing approach consists of testing the samples at stress levels higher than use-stress in order 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 use-stresses can be determined based on the behavior of the samples at the accelerated stresses (28–31).

The profiles were designated as mild, moderate, and aggressive, and the number of specimens were assigned in a ratio of 3:2:1, respectively, in each group. For example, of the 18 samples in each group, nine were allocated to the mild profile, six to the moderate profile, and three to the aggressive profile. These profiles refer to the increasingly step-wise 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 for longer to reach the same load of a specimen assigned to either moderate or aggressive profiles (28–31). Fatigue testing was then performed at 9 Hz using a servo-all-electric system (TestResources 800L; TestResources, Shakopee, MN, USA).

The specimens were evaluated at the completion of each fatigue cycle. Criteria used for failure were: bending or fracture of the fixation screw, and/or bending, partial fracture, or total fracture of the abutment or implant.

Based upon the step-stress distribution of the failures, use-level probability Weibull curves (probability of failure vs. number of cycles) with use-stress of 400 N and two-sided 90% CIs were calculated and plotted (Synthesis 9, Alta 9; ReliaSoft, Tucson, AZ, USA) using a power law relationship for damage accumulation. Survival for a mission of 100,000 cycles at 400 N (two-sided 90% CI) was calculated for comparison between the groups. The Weibull modulus two-sided 90% CIs were calculated using the Fisher Matrix method (28). For the mission survival and β parameters calculated in the present study, the 90% CI ranges were calculated as follows:

\[ IC = E(G) \pm Z_{\alpha/2}\sqrt{\text{Var}(G)}, \]

where IC is the confidence bound (CB), \( E(G) \) is the mean estimated survival for the mission calculated from Weibull statistics, \( Z_{\alpha/2} \) is the Z value concerning the given IC level of significance, and \( \text{Var}(G) \) is the value calculated using the Fisher Information matrix (29–31).

### Failure analysis

The failed samples were inspected in polarized light (MZ-APO stereomicroscope; Carl Zeiss MicroImaging, Thornwood, NY, USA) 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 (Model S-3500N; Hitachi, Osaka, Japan) (13, 32).

### Results

The mean values for SLF were 1,200 ± 230 N for ERC, 1,266 ± 352 N for ESC, 741 ± 212 N for IRC, and 1,038 ± 58 N for ISC.

The step-stress use-level probability Weibull plot and summary statistics at a 400 N load are presented in Fig. 2A and Table 3, respectively. The beta (\( \beta \)) values, mean (CI), and associated upper and lower bounds derived from use-level probability Weibull calculation (probability of failure vs. number of cycles), of 0.22 (0.08–0.58), 0.48 (0.22–1.02), 0.50 (0.12–2.09), and 1.25 (0.69–2.26) for ERC, ESC, IRC, and ISC, respectively, indicate that fatigue was not an accelerating factor for ERC, ESC, and IRC, but that failure of ISC was influenced by damage accumulation. The beta value (or Weibull shape factor) describes failure-rate changes over time (\( \beta < 1 \) indicates that failure rate is decreasing over time, commonly associated with ‘early failures’ or failures that occur because of egregious flaws; \( \beta > 1 \) indicates that failure rate that does not vary over time, associated with failures of a random nature; and \( \beta > 1 \) indicates that failure rate is increasing over time, associated with failures related to damage accumulation) (29, 33).

Load-at-failure data during SSALT for each sample were then used to calculate a probability Weibull distribution. A graphical method that demonstrates whether
these data sets are from different populations (based upon non-overlap of confidence bounds) is the Weibull parameter contour plot [Weibull modulus \((m)\) vs. Characteristic Strength \((\eta = \text{Eta})\)] presented in Fig. 2B. Differences were detected between external hexagon groups ERC and ESC, for which a significantly higher characteristic strength was observed for matched platforms compared with switched platforms. Although data for IRC and ISC groups did not reach statistical significance, a trend for higher characteristic strength and Weibull modulus was observed for internal switched platforms relative to regular platforms. When intergroup comparisons were made, internal connections, either switched or regular, overlapped both external connections (ERC and ESC). The probability

Weibull calculations showed \(m = 6.37\) for ERC, \(m = 7.88\) for ESC, \(m = 4.47\) for IRC, and \(m = 9.22\) for ISC, and Characteristic Strength of \(\eta = 773.5\) N for ERC, \(\eta = 561.1\) N for ESC, \(\eta = 521.7\) N for IRC, and \(\eta = 691.9\) N for ISC (Fig. 2B, Table 2).

The step-stress accelerated fatigue tests permit estimates of survival at a given load level. The calculated survival with 90% CI for a mission of 100,000 cycles at 400 N showed that the cumulative damage from loads reaching 400 N would lead to 98% implant-supported restoration survival in IRC, 95% in ERC, 74% in ESC, and 59% in ISC (Table 3).

**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. Failure modes are described in Table 4. For all groups, failure predominantly involved abutment screw fracture. Two representative fractographic analyses are presented in Figs 3 and 4 for external hexagon implant groups, whereas for internal hexagon implant groups the same patterns have been reported elsewhere (26). The abutments remained intact in ERC and ESC groups after mechanical testing. A higher percentage of abutment fractures was found for IRC and ISC groups compared with ERC and ESC groups. However, implant fractures occurred nearly twice as frequently in ERC and ESC.

**Table 2**

<table>
<thead>
<tr>
<th>Variable</th>
<th>ERC</th>
<th>ESC</th>
<th>IRC</th>
<th>ISC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull modulus ((m))</td>
<td>6.37</td>
<td>7.88</td>
<td>4.47</td>
<td>9.22</td>
</tr>
<tr>
<td>Characteristic strength ((\eta))*</td>
<td>773.5</td>
<td>561.1</td>
<td>521.7</td>
<td>691.9</td>
</tr>
</tbody>
</table>

*Characteristic Strength values are given in N.

ERC, external hexagon connection and regular platform; ESC, external hexagon connection and switched platform; IRC, internal hexagon connection and regular platform; ISC, internal hexagon connection and switched platform.

**Table 3**

<table>
<thead>
<tr>
<th>Reliability over 100,000 cycles at 400 N load [26]</th>
<th>Groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>ERC</td>
</tr>
<tr>
<td>Mean</td>
<td>0.95 A</td>
</tr>
<tr>
<td>Lower</td>
<td>0.86</td>
</tr>
<tr>
<td>Beta</td>
<td>0.22</td>
</tr>
</tbody>
</table>

The same letters represent statistically homogeneous groups.

ERC, external hexagon connection and regular platform; ESC, external hexagon connection and switched platform; IRC, internal hexagon connection and regular platform; ISC, internal hexagon connection and switched platform.
Table 4

Description of the failure modes for each sample (%) of the groups tested

<table>
<thead>
<tr>
<th>Components</th>
<th>Groups</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IRC</td>
</tr>
<tr>
<td>Single failure mode</td>
<td></td>
</tr>
<tr>
<td>Screw</td>
<td>33.33</td>
</tr>
<tr>
<td>(13 S, 1 Sb)</td>
<td>(10 S)</td>
</tr>
<tr>
<td>Mixed failure mode</td>
<td></td>
</tr>
<tr>
<td>Screw and implant</td>
<td>38.9</td>
</tr>
<tr>
<td>(14 S, 10 I)</td>
<td>(17 S, 1 Sb, 12 I)</td>
</tr>
<tr>
<td>Screw and abutment</td>
<td>27.77</td>
</tr>
<tr>
<td>(10 S, 6 A)</td>
<td>(2 S, 2A)</td>
</tr>
<tr>
<td>Screw, implant, and abutment</td>
<td>0</td>
</tr>
<tr>
<td>(0)</td>
<td>(6 S, 4 A, 3 I)</td>
</tr>
</tbody>
</table>

Values represent the percentage (number) of fractures.
A, abutment fracture; ERC, external hexagon connection and regular platform; ESC, external hexagon connection and switched platform; I, implant fracture; IRC, internal hexagon connection and regular platform; ISC, internal hexagon connection and switched platform; S, screw fracture; Sb, screw bending.

Fig. 3. Representative scanning electron microscopy images of an abutment screw fracture in the external hexagon connection and regular platform (ERC) group. (A) Low-magnification view showing the start of a compression curl (black arrows), which allowed the identification of direction of crack propagation shown by white arrows. The yellow arrow shows the opposite tensile site as the fracture origin. (B, C) Higher-magnification views of the fracture origin. (D, E) Detailed views of the compression curl, which represents a feature of flexural fractures. In summary, failures initiated at the lingual surface and propagated toward the buccal surface of the prostheses, where the compression curl is located.

Fig. 4. Representative scanning electron microscopy images of an abutment screw fracture in the external hexagon connection and switched platform (ESC) group. (A) The low-magnification view shows a pattern similar to that reported for the external hexagon connection and regular platform (ERC) group. Black arrows point to the compression curl, which allowed the identification of direction of crack propagation shown by white arrows. The yellow arrow depicts the opposite tensile site as the fracture origin. (B, C, D, E) Higher-magnification views of failure origin and crack propagation path, and of the compression curl.
groups compared with IRC or ISC groups (Table 4). Observation of the polarized-light and scanning electron microscopy images of the fractured surface of the abutment screws allowed the consistent identification of fracture markings, such as compression curl, and the identification of fracture origin and the direction of crack propagation (Figs 3 and 4).

Discussion
The postulated hypothesis that no differences in survival and failure modes would be found between three-unit posterior ISFDP with external or internal hexagon implant abutment connections, either with a matched or a switched platform, was partially accepted. The results showed that the probability of survival of ISFDP was directly affected by the horizontal configuration of the connection and not by the implant–abutment connection design per se. Regardless of connection being internal or external, platform switching resulted in an overall decrease in survival. Such results are in contrast to our previous findings for single crowns, for which platform switching in external hexagon implants presented the lowest survival, followed by external hexagon implants with matched platform, and finally by internal connections presenting equal results regardless of the horizontal configuration (21). Therefore, once splinted as a FDP, an important shift seems to occur in the restored system operating failure modes, and information previously reported for a variety of implant, abutment, and prosthesis single-unit configurations should not be translated to ISFDPs (1–3, 7, 9, 11, 13, 21, 28, 34–36).

Only the characteristic strength of external connections was negatively influenced by the use of the platform-switching concept. Perhaps the increased contact area between the implant and abutment results in improved stress distribution to the implant connection (24). On the other hand, switched-platform samples showed higher Weibull modulus ($m$). The $m$ value is an indicator of strength survival and/or the asymmetrical strength distribution as a result of flaws within the material (34, 37), meaning that samples with switched platforms presented smaller and/or fewer defects, leading to narrower load intervals required to failure during fatigue (37).

Although the survival was lower for the samples with a switched platform, the rationale for this concept is to minimize peri-implant bone loss after implant insertion (38–40). As shown in a recent meta-analysis, platform switching may preserve the inter-implant bone height and soft-tissue levels (20, 22). Platform switching has also been claimed to prevent marginal bone from stress concentration, mostly localized at the proximal areas between implants and abutments (22, 41, 42). Such a decrease in stress concentration at the bone may transfer the stress to the prosthetics components, which eventually overloads the abutment and its screw. This assumption warrants further investigation.

The failure modes were similar for all groups. Fractures of the abutment screw were more common in groups with internal hexagon implants. External hexagon implants presented complex failure modes, such as fractures of the abutment screw chiefly associated with fracture of the implant, which was less commonly observed in the internal hexagon groups. From a clinical perspective, failure modes, including fracture of the implant, are considered as catastrophic as they require surgical intervention for implant retrieval, and placement of a new fixture and prostheses, demanding high costs and long chair time. Although implant fracture is rare, its prevalence increases with clinical service, suggesting that fatigue-related damage accumulates and degrades the strength of the prostheses once they are in function (43, 44). Even in splinted ISFDPs with external hexagon connections, where stresses are mostly borne by the abutment screw, fractures of the implants have been reported clinically for splinted partial (45) and full-arch (46, 47) reconstructions.

Although there was no significant difference in survival and in characteristic strength between the platform-switched groups, the lower probability of survival observed for the internal hexagon connection was probably the result of its slightly higher mismatch (0.7 mm) compared with the external hexagon implant group (0.6 mm). The increased mismatch results in a decreased area for load distribution between the abutment and implant, which may result in a reduced mechanical performance (3, 21). Interestingly, the 0.6 mm switch in the external hexagon ISFDP was sufficient to evoke a significant reduction in characteristic strength, whereas a 0.7 mm mismatch did not alter the same parameter in the internal hexagon ISFDP. One possible explanation is that, as previously reported (8), internal connections present load distribution not limited to the abutment screw, but also to the inner implant walls, which makes it a more favorable scenario for platform switching compared with external hexagon implants, for which most load is borne by the abutment screw. Evidence for the clinical impact of this observation has been reported for single crowns; however, long-term clinical information on fixed dental prostheses with different implant–abutment connection designs is warranted.

In conclusion, this in vitro study showed that the probability of survival of ISFDPs was significantly reduced by platform switching, regardless of the implant–abutment connection design.

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