Dental implants have been successfully used to restore complete and partially edentulous arches.1-3 Furthermore, many in vivo studies have shown high success rates over 5 to 10 years, ranging from 95% to 97% for single-implant restorations.4-6 As a result of its well-documented biomechanical properties,1,7,8 titanium (Ti) became the standard material for implant abutments. However, metal components often shine through the mucosa giving a grayish shade.9 In addition, when Ti abutments are restored with ceramic crowns, the underlying metal abutment may affect the color of the restoration.2,10-12

To meet the increased demands for highly esthetic results, new generations of ceramic abutments have been developed. Still, ceramics are inherently brittle, making them susceptible to tensile stresses.13 This limits the widespread application of ceramics as implant abutments. Zirconia (ZrO₂) ceramics, as a result of transformation toughening, exhibit high flexural strength (900 to 1200 MPa), compression strength (2000 MPa), and fracture toughness (6 MPa·m⁰.⁵) as well as excellent biocompatibility and improved esthetics.14-17 Zembic et al18 showed excellent survival rates for single-implant ceramic crowns supported by ZrO₂ abutments and estimated 5-year survival and failure rates

Materials donated by FairImplant (Bönningstedt, Germany) and Ivoclar Vivadent AG (Schaan, Liechtenstein).

**ABSTRACT**

**Statement of problem.** The whitish color of zirconia (ZrO₂) abutments offers favorable esthetics compared with the grayish color of titanium (Ti) abutments. Nonetheless, ZrO₂ has greater opacity, making it difficult to achieve natural tooth color. Therefore, lithium disilicate (LaT) abutments have been suggested to replace metal abutments.

**Purpose.** The purpose of this in vitro study was to evaluate the fracture strength and failure mode of single-tooth implant restorations using ZrO₂ and LaT abutments, and to compare them with titanium (Ti) abutments.

**Material and methods.** Five different types of abutments, Ti; ZrO₂ with no metal base; ZrO₂ with a metal base (ZrT); LaT; and LaC combination abutment and crown (LcT) were assembled on 40 Ti implants and restored with LaT crowns. Specimens were subjected to quasistatic loading using a universal testing machine, until the implant-abutment connection failed. As bending of the metal would be considered a clinical failure, the values of force (N) at which the plastic deformation of the metal occurred were calculated, and the rate of deformation was analyzed. Statistical analysis was done using the Mann-Whitney U test (α=.05).

**Results.** Group ZrO₂ revealed the lowest resistance to failure with a mean of 202 ±33 N. Groups ZrT, LaT, and LaC withstood higher forces without fracture or debonding of the ceramic superstructure, and failure was due to deformation of metal bases, with no statistically significant differences between these groups regarding the bending behavior.

**Conclusions.** Within the limitations of this in vitro study, it was concluded that LaT abutments have the potential to withstand the physiological occlusal forces that occur in the anterior region and that ZrO₂ abutments combined with Ti inserts have much higher fracture strength than pure ZrO₂ abutments. (J Prosthet Dent 2017;117:499-506)
comparable to metal abutments supporting metal ceramic crowns. Conversely, ZrO2 aging and sensitivity to low-temperature degradation could reduce strength and toughness.\textsuperscript{16,17}

Excellent esthetics can be achieved by manufacturing abutments entirely of ZrO2, yet weak and fracture-prone points can develop at the connection, especially with internal conical types.\textsuperscript{19,20} Moreover, the precision of the pure ZrO2 abutment connection interface has been questioned, as ceramics cannot be machined as precisely as metals.\textsuperscript{21} Such inaccuracy can promote screw loosening and microbial infections, which may lead to marginal bone loss.\textsuperscript{22}

A Ti insert can overcome the brittleness of ZrO2 and improve the fracture resistance of the abutment.\textsuperscript{23} In a recent study, when 5 different ZrO2 abutments were tested for fracture strength, ZrO2 abutments with Ti inserts demonstrated a greater fracture resistance than pure ZrO2 abutments.\textsuperscript{24}

Glass ceramics have proven to be more esthetic than ZrO2, which has poor translucency and is unnaturally white and opaque.\textsuperscript{25-27} Lithium disilicate is the strongest and toughest of the glass ceramics available. It has moderate flexural strength (360 to 440 MPa)\textsuperscript{28} and fracture toughness (2.5 to 3 MPa-m\textsuperscript{0.5})\textsuperscript{29} and excellent translucency and shade matching.\textsuperscript{27,30} Higher translucency was observed for lithium disilicate (LaT) than for ZrO2--based ceramic systems.\textsuperscript{26,31}

In esthetically challenging treatments, tooth-colored LaT offers better and more natural esthetics than white ZrO2 abutments. LaT abutments may be suitable as an esthetic alternative to ZrO2 if proved to be clinically reliable.\textsuperscript{32,33}

LaT abutments may be used as a combination abutment bonded to a Ti insert supporting a ceramic crown (lithium disilicate) or as a combination abutment and crown, where the abutment and crown are fabricated in 1 piece that will be bonded to a Ti insert and screwed to the implant. The screw access hole is subsequently closed with composite resin.\textsuperscript{32-34}

Because cemented crowns are difficult to remove after a complication, such as screw loosening, the combination abutment crown allows easy access to the screw through the composite resin. Additionally, residual cement may lead to perimplant tissue inflammation.\textsuperscript{35,36} These hazards could be eliminated with the use of the combination abutment crown.

The authors are aware of few articles or case reports describing the use of LaT ceramic as an implant abutment material.\textsuperscript{32-34} Additionally, limited laboratory or clinical studies have compared the mechanical properties of ZrO2 abutments with ZrO2 abutments supported by a Ti insert using internal conical connection and have shown better results for the ZrO2 abutments with inserts.\textsuperscript{19,24,37}

Laboratory tests can be done in a short time and are reproducible, with the possibility of standardizing test parameters.\textsuperscript{38} Well-designed laboratory tests can be effective indicators of the applicability and performance of materials and their likely clinical success before widespread clinical use is recommended. The purpose of this in vitro study was to (1) evaluate the fracture resistance of single-tooth implant-supported ceramic restorations using ZrO2 and LaT abutments and to compare them with conventional Ti abutments and to identify the mode of failure of the restorations; (2) evaluate the effect of a Ti insert on the fracture strength of ZrO2 abutments; and (3) evaluate the differences in mechanical properties between the 2 methods of using LaT as an abutment material.

The null hypothesis of the study was that no differences would be found in resistance to fracture among the different abutment materials or the different forms of using ZrO2 or LaT abutments.

### MATERIAL AND METHODS

Forty Ti implants (FairTwo, grade 4 Ti, lot: 135395; FairImplant) with a diameter of 4.2 mm, a length of 11.5 mm, and an internal conical connection and platform-switched design were used in this study. For randomization, numbers were assigned to the implant specimens. Then, numbers were randomly drawn to distribute the specimens into 5 groups of 8 implants each according to the abutment material and type (Ti; pure ZrO2; ZrO2 with Ti insert [ZrT]; LaT; and LaT combination abutment crown [LcT]) as shown in Table 1 with their group codes. The implants were restored with 40 single implant-supported ceramic crowns made from lithium disilicate glass ceramic (IPS e.max CAD, lot: T44702; Ivoclar

<table>
<thead>
<tr>
<th>Group</th>
<th>Abutment</th>
<th>Crown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>Titanium\textsuperscript{a}</td>
<td>Lithium disilicate\textsuperscript{c}</td>
</tr>
<tr>
<td>ZrO2</td>
<td>Zirconia (no metal insert)\textsuperscript{b}</td>
<td>Lithium disilicate\textsuperscript{c}</td>
</tr>
<tr>
<td>ZrT</td>
<td>Zirconia (with metal insert)\textsuperscript{b}</td>
<td>Lithium disilicate\textsuperscript{c}</td>
</tr>
<tr>
<td>LaT</td>
<td>Lithium disilicate (with metal insert)\textsuperscript{b}</td>
<td>Lithium disilicate\textsuperscript{c}</td>
</tr>
<tr>
<td>LcT</td>
<td>Lithium disilicate combination abutment and crown (with metal insert)\textsuperscript{b}</td>
<td>Lithium disilicate\textsuperscript{c}</td>
</tr>
</tbody>
</table>

\textsuperscript{a}CopraTi-4: grade 4 Ti blanks (Whitepeaks; lot no. T4001). \textsuperscript{b}Wieland Zenostar (Wieland Dental; lot no. S23252). \textsuperscript{c}IPS e.max CAD (Ivoclar Vivadent; lot no. T44702).
Vivadent AG), simulating a maxillary right central incisor of 11 mm in length and 8.5 mm in width. Figure 1 shows the components of groups ZrT, LaT, and LcT.

The implants were embedded in a 3-component, autopolymerizing polyester resin (Technovit 4000, lot: 010294; Heraeus Kulzer) to imitate the elastic reaction of the surrounding bone during loading. The resin covered the implant body up to the first thread. Brass tubes were used as molds and served to hold the specimen during testing.

All abutments were attached to the implants with Ti screws (lot: 961209; FairImplant). The torque wrenches were calibrated (Torque Tester; Crane Electronics), and the screws were tightened to 25 Ncm. After 10 minutes, the screws were retightened to prevent screw loosening. The screw holes were filled with foam pellets and gutta percha.

All abutments and crowns were custom-manufactured according to a scanned modified Ti abutment and a crown wax pattern. For means of standardization, using computer-aided design/computer-aided manufacture (CAD) technology, the scanned design was used to mill all restorations. The dimensions of the crowns and abutments are shown in Figure 2. A minimum thickness of 0.5 mm for the abutment was applied. A chamfer finish line with rounded internal angles was used to provide improved mechanical retention and marginal fit.

Before adhesive cementation of the restorations, proper surface treatment of each material was done according to the manufacturers’ instructions (Table 2). Subsequently, all surfaces were primed for at least 60 seconds using a universal primer for ceramics and metal (Monobond Plus, lot: S14727; Ivoclar Vivadent AG).

Ti inserts (grade 4 Ti inserts, lot: 399275; FairImplant) were adhesively cemented to the ceramic suprastructures (ZrO2 in group ZrT and LaT in groups LaT and LcT), using an autopolymerizing luting composite resin (Multilink Hybrid Abutment, lot: T35016; Ivoclar Vivadent AG) under a constant load of 7.4 N. Excess cement was removed, and a glycerin gel (Liquid strip, lot: T29465; Ivoclar Vivadent AG) was applied to prevent the formation of an oxygen-inhibited layer.

For adhesive cementation of the crowns to abutments, a dual-polymerizing adhesive resin cement (Multilink Automix, lot: T29844; Ivoclar Vivadent AG) was used under a constant load of 50 N. After excess cement was removed, a glycerin gel (Liquid strip; Ivoclar Vivadent AG) was applied to the abutment-crown interface. Light polymerization (Elipar 2500; 3M ESPE) was then applied for 20 seconds from the labial and palatal sides.

In group LcT, the screw hole was sealed with composite resin (Tetric EvoCeram, lot: T09635; Ivoclar Vivadent AG), which was applied in increments, and each
was light polymerized for 20 seconds. The restorations were stored in distilled water at 37°C for 72 hours before testing to ensure that the resin cement had completely polymerized.

Fracture strength measurements were carried out using a universal testing machine (Z010; Zwick). Loads were applied with an angle of 30 degrees to the long axis of the implants to simulate a clinical occlusal force application representing a class I occlusion with a 150-degree interincisal angle. The point of force application was 3 mm below the incisal edge, using a 0.5-mm-thick tin foil (Zinnfolie; Dentaurum) to ensure even application. Force was applied using a preload of 5 N and a cross-head speed of 2 mm/min until failure, which was perceived as the fracture, a sudden reduction in force, or deformation of 3 mm. The failure loads were recorded with software (testXpert II V3.3; Zwick).

After failure, each specimen was examined visually and under an optical microscope (Carl Zeiss) to determine the mode of failure. Radiographs were made of the specimens (in mm for each 100-N increase in force) using a universal testing machine (Z010; Zwick) with the Bonferroni-Holm correction for multiple testing.

To reveal differences in the bending behavior of metal bases, the deformation in each abutment was determined for forces equivalent to 100, 200, 300, and 400 N. The deflection of the specimens (in µm) for each 100-N increase in force was measured and analyzed. Normality distribution was tested using the Shapiro-Wilk test, which revealed that the data were not normally distributed. Therefore, statistical analyses of the test results were made with the Kruskal-Wallis test, followed by multiple pairwise comparisons of the groups using the Mann-Whitney U test (α=.05). Significance levels were adjusted with the Bonferroni-Holm correction for multiple testing.

RESULTS
The mean fracture load for 1-piece ZrO₂ abutments was 218.5 ±14.4 N. These abutments exhibited 1 type of failure that was fracture of the ceramic and was located predominantly at or slightly above the level of the implant axis (Fig. 4A).

A visual assessment of failed specimens of the Ti abutments (group Ti) and all abutments with Ti insert (groups ZrT, LaT, and LcT) showed a homogenous mode of failure. They presented bending at the screw and internal connection of the Ti abutment or insert without ceramic displacement or fracture. Figure 4B shows a representative LaT abutment. None of the abutments in the 4 groups fractured or showed mobility after testing. However, radiographs (Fig. 4C, D) showed no fracture in the screw or the metal. Figure 5 shows the measurements used to determine the deformation of metal in these 4 groups. The results of the deformation of the specimens for each 100-N increase in force are given in Table 3. A significant difference was found between the Ti abutments and the 3 groups with Ti inserts, whereas the Ti abutments showed significantly higher deformation than the Ti inserts for all measurements (100 to 200 N, 200 to 300 N, and 300 to 400 N). However, groups ZrT, LaT, and LcT with the Ti inserts did not show any significantly different deformation behavior.

DISCUSSION
The null hypothesis was partially rejected, as no differences were found between LaT abutments with the 2 designs and the combination ZrO₂ abutments. However, pure ZrO₂ abutments showed lower resistance to fracture than combination ZrO₂ abutments. To eliminate other possible factors influencing the fracture strength, only the material of the abutment was varied, while all other factors such as crown and luting materials were kept constant.

Maximal occlusal forces reported in the anterior region were in the range of 150 to 235 N with a mean of 206 N. Such loads were tolerated by specimens from

| Table 2. Surface treatment of all materials used |
| --- | --- | --- |
| Material | Restoration | Surface Treatment |
| Titanium | Titanium abutments (group Ti) | Airborne-particle abrasion with 50-µm alumina particles at 250 kPa until dull surface was achieved* |
|  | Titanium inserts (groups ZrT, LaT, LcT) | |
| Zirconia | Zirconia abutments (group ZrO₂) | Airborne-particle abrasion with 50-µm alumina particles at 100 kPa, until black marker coating was completely removed* |
|  | Zirconia superstructure (group ZrT) | |
| Lithium disilicate | Abutments (group LaT) | Etching for 20 s with 4.5% hydrofluoric acid (IPS Ceramic Etching Gel, lot: T40413; Ivoclar Vivadent AG) |
|  | Combination abutment and crown (group LcT) | |
|  | Crowns of groups (Ti, ZrO₂, Zr/T, LaT) | |

*After airborne-particle abrasion, parts ultrasonically cleaned in 99% isopropanol for 3 minutes and dried. †After etching, parts cleaned with water spray and dried with oil-free air.

Figure 3. Specimen of control group (Ti) during quasistatic loading. Force applied at 30 degrees to implant axis.
groups Ti, ZrT, LaT, and LcT but not by specimens from group ZrO2.

The pure ZrO2 abutments in this study had a mean ±SD fracture resistance of 218.5 ± 14.4 N. This value is considered to be in the range of the physiological maximum occlusal forces in the anterior region, indicating a risk of failure when this type of abutment is used clinically. The mode of failure of the pure ZrO2 abutments was fracture of the ceramic at the connection. No fracture or bending of the implant or abutment screw occurred. This is consistent with the results of other studies.39,52-55

In this study, Ti, combination ZrO2 and both types of LaT abutments could bear loads more than the reported physiological occlusal forces in the anterior regions. Although they became deformed, combination ZrO2 and LaT abutments successfully resisted fracture and could tolerate forces in the range of 900 N. Still, these values cannot be stated as the definitive fracture strength of the materials as there was reduction of force and the test was

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Figure 4. A-D, Failure mode of specimens from groups Ti, ZrO2, ZrT, and LcT. A, Fracture specimen. Image shows fracture line slightly above implant shoulder, which is a typical fracture of ZrO2 abutments (original magnification ×40). B, Typical failure mode of specimens with LaT abutments (groups LaT and LcT) bending of Ti insert to buccal direction. C, Radiographic image shows group Ti specimen after failure. D, Radiographic image shows group ZrT specimen after failure.
stopped because of plastic deformation of the Ti inserts, which is deemed as failure. In addition, failure of combination ZrO₂ and LaT because of fracture or debonding between the metal and ceramic did not occur in this study. Thus, all specimens of these groups showed more resistance to loading than the minimum required fracture resistance for anterior restorations.

The mean fracture strength of the LaT ceramics are reported to be lower than that of ZrO₂, yet statistical analysis of this study revealed no significant difference between the use of both materials as combination abutments. The failure occurred as a result of deformation of the Ti inserts and screws, which are similar in both types of abutments, whereas the ceramic suprastructure remained intact. The purpose of this study was to test the failure of the abutments in respect to clinical situation. As a result, testing was stopped after 3 mm of deformation of the abutments, even if ceramic fracture did not occur. However, if the loading tests had been continued, a difference in the fracture resistance of ZrO₂ and LaT might have been noticed. Similarly, no differences between abutments and combination abutment and crown made from LaT were observed, as again, the failure occurred at the Ti inserts and not at the ceramic suprastructure. It can be assumed that the adhesive cementation strengthened the connection between the abutment and the crown.

Clearly, the application of a secondary Ti insert positively influences the performance of ZrO₂ abutments by replacing the brittle ZrO₂ with metal at the weakest part. Furthermore, the difference between the fracture mode of the ZrO₂ and ZrT groups was prominent. This result corresponds to that of previous studies. The Ti insert and the ZrO₂ abutments were airborne–particle abraded, and both parts were adhesively bonded using a composite resin, as recommended clinically and by some studies.

The cervical region of the abutments is subjected to high stress concentrations; therefore, the implementation of a Ti insert is important to replace the brittle ceramic with metal. Hence, the LaT abutments were exclusively assembled with Ti inserts. This also complies with the manufacturer’s instructions.

During screw tightening, some favorable degree of elastic deformation occurs in the Ti, which is known as the settling effect. Loads higher than the yield limit of the Ti will cause plastic deformation of the abutment, which may result in fracture of the screw as it is the weakest component of the implant-abutment connection. This explains the deformation of the Ti abutment and Ti inserts in this study. The bending behavior of Ti inserts in specimens from the ZrT, LaT, and LcT groups was similar. However, the Ti abutments exhibited higher bending than the Ti inserts at the same load values. According to the manufacturer’s explanation, the Ti abutments used were milled from blanks in a dental laboratory to produce the customized design of the abutment requested; meanwhile, the Ti inserts were prefabricated in the factory with higher precision equipment.

Several factors contribute to differences in the results and mode of failures between studies. Slight differences in the composition of the Ti and the ZrO₂ tested may be a reason for the different values between studies. Additionally, the load-bearing capacity of the implant restorative system depends on the implant-abutment connection. The performance of Ti abutments, when loaded, for systems with conical connections seems to be inferior to that of external hexagon connections.

The specimens underwent no artificial aging with fatigue loading, which is a limitation of the study. Further studies comparing data of the fatigue resistance of LaT abutments as well as ZrO₂ with or without a Ti insert are required.

**CONCLUSIONS**

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

1. LaT and ZrO₂ abutments with metal inserts have the potential to withstand physiological occlusal

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Table 3. Traverse distance of deformation of metal at given forces (µm) and statistical differences

<table>
<thead>
<tr>
<th>Group</th>
<th>dl (100-200 N)</th>
<th>dl (200-300 N)</th>
<th>dl (300-400 N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti (n=8)</td>
<td>512 ± 2</td>
<td>635 ± 3</td>
<td>853 ± 4</td>
</tr>
<tr>
<td>ZrT (n=8)</td>
<td>156 ± 2</td>
<td>182 ± 2</td>
<td>195 ± 2</td>
</tr>
<tr>
<td>LaT (n=8)</td>
<td>173 ± 2</td>
<td>142 ± 2</td>
<td>207 ± 2</td>
</tr>
<tr>
<td>LcT (n=8)</td>
<td>141 ± 2</td>
<td>164 ± 2</td>
<td>189 ± 2</td>
</tr>
</tbody>
</table>

Different superscript letters indicate significant differences between groups. Mann-Whitney U tests (α = .05). Overall Kruskal-Wallis test (α = .001).
forces that occur in the anterior region and can therefore be recommended as an esthetic alternative for restoring single implants in the anterior region.

2. The fracture strength of LaT abutments is not influenced when they are used as a combination abutment or as a combination abutment and crown.

3. ZrO₂ abutments combined with Ti inserts have much higher fracture strength than pure ZrO₂ abutments. Therefore, care must be taken when using pure ZrO₂ abutments.

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13. The fracture strength of LaT abutments is not influenced when they are used as a combination abutment or as a combination abutment and crown.

14. ZrO₂ abutments combined with Ti inserts have much higher fracture strength than pure ZrO₂ abutments. Therefore, care must be taken when using pure ZrO₂ abutments.
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Noteworthy Abstracts of the Current Literature

Comparative accuracy of facial models fabricated using traditional and
3D imaging techniques

Lincoln KP, Sun AYT, Prihoda TJ, Sutton AJ

Purpose. The purpose of this investigation was to compare the accuracy of facial models fabricated using facial moulage impression methods to the three-dimensional printed (3DP) fabrication methods using soft tissue images obtained from cone beam computed tomography (CBCT) and 3D stereophotogrammetry (3D-SPG) scans.

Materials and Methods. A reference phantom model was fabricated using a 3D-SPG image of a human control form with ten fiducial markers placed on common anthropometric landmarks. This image was converted into the investigation control phantom model (CPM) using 3DP methods. The CPM was attached to a camera tripod for ease of image capture. Three CBCT and three 3D-SPG images of the CPM were captured. The DICOM and STL files from the three 3dMD and three CBCT were imported to the 3DP, and six testing models were made. Reversible hydrocolloid and dental stone were used to make three facial moulages of the CPM, and the impressions/casts were poured in type IV gypsum dental stone. A coordinate measuring machine (CMM) was used to measure the distances between each of the ten fiducial markers. Each measurement was made using one point as a static reference to the other nine points. The same measuring procedures were accomplished on all specimens. All measurements were compared between specimens and the control. The data were analyzed using ANOVA and Tukey pairwise comparison of the raters, methods, and fiducial markers.

Results. The ANOVA multiple comparisons showed significant difference among the three methods (p < 0.05). Further, the interaction of methods versus fiducial markers also showed significant difference (p < 0.05). The CBCT and facial moulage method showed the greatest accuracy.

Conclusion. 3DP models fabricated using 3D-SPG showed statistical difference in comparison to the models fabricated using the traditional method of facial moulage and 3DP models fabricated from CBCT imaging. 3DP models fabricated using 3D-SPG were less accurate than the CPM and models fabricated using facial moulage and CBCT imaging techniques.

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