Effects of Abutment Height and Type of Cement on Bond Strength of Monolithic Zirconia Single Crowns Luted to One-Piece Zirconia Implants

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Purpose: To test the bond strength of one-piece zirconia implants with either standard or reduced height using different luting agents and pretreatments of the inner surfaces of ceramic crowns. **Materials and Methods:** A total of 20 monolithic zirconia CAD/CAM–fabricated single crowns per luting agent group were cemented onto 20 one-piece zirconia implants with either 5-mm (n = 10) or 4-mm (n = 10) abutment height using 13 different luting agents. After water storage, the crowns were removed using a specially developed test fixture in a universal testing machine. The maximum force (N) was recorded, and the force per area (MPa) was calculated. The statistical evaluation was performed using univariate analysis of variance. **Results:** A mean of 4.19 MPa (SD 2.90) at 5-mm height and 3.89 MPa (SD 2.85) at 4-mm height was obtained for all luting agents. The highest values were achieved for a resin-modified glass-ionomer cement, with 12.37 MPa (4 mm) and 12.00 MPa (5 mm). The lowest values were shown for a long-term temporary material, with 0.73 MPa (4 mm) and 1.07 MPa (5 mm). Only a polycarboxylate cement ($P < .001$) and a glass-ionomer cement ($P = .006$) showed statistically significant differences in favor of the reduced abutment height. Reduced abutment height did not significantly reduce bond strength for any of the materials examined. **Conclusion:** Implants with a reduced abutment height are clinically suitable. Pretreatment of the crowns' inner surfaces with ceramic primer showed to be advantageous. *Int J Prosthodont 2022;35:XX–XX. doi: 10.11607/ijp.7110*

According to current standards in clinical treatment, implant rehabilitation is the method of choice for replacing missing teeth unless it is contraindicated by the clinical situation and/or the patient´s medical history. With growing demand for implant-based solutions in dentistry, the continuous development of new implant constructions and materials has become an important component of dental research.

Over the past decades, implants made of titanium have been considered the gold standard in the selection of materials. However, despite all their positive characteristics—like mechanical strength, biocompatibility, and clinically excellent survival rates—the gray color of the material can be challenging in esthetically relevant areas,[1,2] as the grayish shimmering of the implant leads to dissatisfaction among patients and dentists, particularly in combination with thin overlying mucosal tissue.[3,4] The

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accumulation of titanium particles in surrounding tissue and even in regional lymph nodes after implant placement has also been described. A correlation between the amount of particles and the time since implantation has been observed.[5,6] Although little clinical evidence has been reported, hypersensitivity and local symptoms due to titanium implants have been described.[1,7] Patient demand for metal-free alternatives to reduce the foreign body sensation and to optimize the esthetic outcome has also increased in recent years.[3] With the development of modern high-performance ceramics, new alternative implant materials are now available. In particular, polycrystalline yttrium-stabilized zirconium oxide (3Y-TZP), with its excellent mechanical properties, is the most frequently used material for ceramic implants.[8] In addition to the well-described biocompatibility of this material, its low affinity for plaque formation plays an important role in the reduction of peri-implant inflammatory processes, thus promoting osseointegration of the implant.[9] Most zirconia implants currently available are one-piece systems made of Y-TZP. Even though long-term study results are rare, initial clinical results are satisfactory, showing survival rates of 95.6% after 1 year[10] and 95% after 5 years,[11] which are comparable to titanium implants. The same applies to marginal bone loss, which can also be a parameter for successful implant treatment. With an average rate of 0.79 mm of bone loss after 1 year, there is no significant difference compared to titanium implants.[10] Two-piece zirconia implant systems are also available but show higher average loss rates due to a lack of osseointegration. The main reason is likely the gap between abutment and implant as a potential source of risk for inflammation.[12]

Implant-supported restorations can be either screw retained or cemented, and the retention modalities show no significant differences in survival rates after 5 years. Cemented restorations in particular have several advantages, such as a cost-effective and simple workflow, excluded loss of the nonexistent implant screw, and also improved and simplified results in esthetics and occlusion due to the absence of a screw channel.[13] However, cemented restorations are more prone to biologic complications, as the presence of an adhesive gap increases the risk of peri-implant inflammation of the surrounding tissue. Special attention must be paid to the remaining luting material in the peri-implant sulcus after cementation, as this can lead to bone loss.[14,15] Complete healing of the peri-implant tissue can be expected with subsequent removal of excess material.

When selecting a suitable restorative material, all-ceramic systems made of lithium disilicate or zirconium oxide are the materials of choice. Due to advances and material innovations in the field of CAD/CAM technology, monolithic fabricated restorations are preferred over veneered all-ceramic superstructures.[12] Monolithic restorations are usually cemented or adhesively seated due to a lack of available ceramic implant systems that allow screw fixation of restorations.

Furthermore, dentists are often challenged by a lack of vertical space, making the prosthetic restoration of natural teeth or implant abutments complex and difficult. The influence of various preparation parameters of natural teeth on the retention and survival of dental restorations has been well described in the literature.[16,17] Precise guidelines and regulations for the height of abutments are so far missing in standard German textbooks, but the necessary height of prepared teeth is well covered. Both Reitemeier et al and Strub et al require an axial wall height of at least 3 mm after preparation in order to ensure sufficient mechanical retention of the future dental restoration.[18,19] When reducing the axial wall height, the surface area available for bonding is minimized, which is also important for the retention of dental restorations.[17] Additional accessories, such as boxes and grooves, can compensate for unfavorable preparation parameters, but are contraindicated when using CAD/CAM–fabricated restorations, as these demand strict avoidance of undercuts and sharp edges.[20] Therefore, the problem of adequate retention requires proper selection of the luting agent and good knowledge of the available materials and their contents to compensate for eventual deficiencies of the preparation. While bonding with conventional materials is based on mechanical friction between the surfaces and the cement, adhesive luting agents in combination with a ceramic primer can adhere directly to both surfaces (tooth/abutment and inner surface of the restoration) to increase retention.[21] In addition to established materials, new developments should also be considered within the scope of an investigation.

The aim of this study was to evaluate the effects of reducing the abutment height of one-piece zirconia implants and to assess the influence of different luting agents and different surface-conditioning methods on the retention of monolithic zirconia single crowns.

MATERIALS AND METHODS

The specimens were divided into 16 test groups (n = 20) depending on the selected luting agent and the conditioning method for the inner surface of the ceramic crown (Table 1). In each test group, 10 zirconia one-piece implants with a standard abutment height of 5 mm and 10 zirconia one-piece implants with a reduced abutment of 4 mm were used, resulting in 320 test specimens. All implants (Zirkolith Z5m implants, Z-Systems) were made of TZP-A BIO-HIP ceramic (Metoxit). Compared to the abutments with reduced height, the standard abutments had a reduced upper diameter but an enlarged bonding surface due to

Table 1 Materials Used and the Different Conditioning Methods for the Inner Surface of the Ceramic Crowns

Material	Manufacturer	Type of application	Light-curing/application of glycerine gel	Pretreatment of ceramic crowns
HIS	Harvard Dental International	Automix syringe	Light-curing 20 s per side	Al_2O_3 50 µm, 10 s Cleaning with ethanol
DUR	3M	Automix capsule	–	Al_2O_3 50µm, 10 s Cleaning with ethanol
PHZ	Kulzer	Manual mixture of powder and liquid	–	Al_2O_3 50 µm, 10 s Cleaning with ethanol
BQM	Voco	Automix syringe	Liquid Strip Transparent, Ivoclar Vivadent Light-curing 20 s per side	Al_2O_3 50 µm, 10 s Ceramic Bond, Voco Cleaning with ethanol
BOP	Voco	Automix syringe	Liquid Strip Transparent Light-curing 20 s per side	Al_2O_3 50 µm, 10 s Cleaning with ethanol
P21	Kuraray Noritake	Manual mixture of two pastes	Oxyguard II, Kuraray Noritake	Al_2O_3 50 µm, 10 s Cleaning with ethanol
PV5	Kuraray Noritake	Automix syringe	Light-curing 20 s per side	Al_2O_3 50 µm, 10 s Clearfil Ceramic Primer Plus Cleaning with ethanol
PUO	Kuraray Noritake	Automix syringe	Light-curing 20 s per side	Cleaning with ethanol
PGO	Kuraray Noritake	Automix syringe	Light-curing 20 s per side	Al_2O_3 50 µm, 10 s Cleaning with ethanol
BSE	Voco	Automix syringe	Light-curing 20 s per side Liquid Strip Transparent	Al_2O_3 50 µm, 10 s Cleaning with ethanol
REX	3M	Automix capsule	–	Al_2O_3 50 µm, 10 s Cleaning with ethanol
SCP	Ivoclar Vivadent	Automix syringe	Liquid Strip Transparent	Al_2O_3 50 µm, 10 s Ivoclean, Ivoclar Vivadent Cleaning with ethanol
PSA	Kuraray Noritake	Automix syringe	–	Al_2O_3 50 µm, 10 s Cleaning with ethanol
AQM	Voco	Manual mixture of powder and liquid	–	Al_2O_3 50 µm, 10 s Cleaning with ethanol
KEC	3M	Automix capsule	–	Al_2O_3 50 µm, 10 s Cleaning with ethanol
FUJ	GC Europe	Automix syringe	–	Al_2O_3 50 µm, 10 s Cleaning with ethanol

HIS = Harvard Implant Semi-Permanent; DUR = Durelon; PHZ = Phosphatzement; BQM = Bifix QM; BOP = Bifix Qm, sandblasting, no primer; P21 = Panava 21; PV5 = Panavia V5; PUO = Panavia V5, no sandblasting, no primer; PGO = Panavia V5, sandblasting, no primer; BSE = Bifix SE; REX = RelyX Unicem; SCP = SpeedCEM Plus; PSA = Panavia SA Cement Plus; AQM = Aqua Meron; KEC = Ketac Ceram; FUJ = Fujicem; .

Fig 1 Ceramic crown and one-piece zirconia implant. The ceramic crown was deliberately overcontoured (1.5–2 mm) in the marginal area to prevent the assembled implant-crown complex from sliding out of the test fixture during the debonding process in the universal testing machine.

Fig 2 Specimen fixed to the lower mounting box of the universal testing machine.

the different heights of the abutments with the same taper (7 degrees) and the same lower diameter (4.4 mm). To prevent rotation, the abutment design had two parallel surfaces with grooves on opposite sides (Fig 1). A total of 20 monolithic CAD/CAM–fabricated zirconia single-tooth crowns (Ceramill Zolid HT+ Pre-shades, Amann Girrbach) were produced by a dental laboratory (Joachim Maier Dental Design). Designed as a maxillary premolar, the marginal area of the crown was deliberately overcontoured (1.5 to 2 mm) to prevent the assembled implant-crown complex from sliding out of the test fixture during the debonding process in the universal testing machine (Z010, Zwick Roell; Fig 1).

Prior to cementation, all abutments were cleaned with alcohol and then dried with oil-free air. Any further pretreatment of the surface was not required by the manufacturer. The cementation area of the one-piece implants (abutment part) showed no optical or tactile surface roughness. The abutment surface was not sandblasted at any time (this applies to pretreatment for bonding as well as all necessary steps of the specimens' preparation for reuse). Before cementation, the abutment surface was cleaned with alcohol. After debonding, the cement residues were carefully removed with a laboratory cloth. In some rare cases, small remains were carefully sheared off with a scalpel, which did not damage the integrity of the abutment surface (light microscopic inspection).

The inside of the ceramic crowns was sandblasted with aluminum oxide particles (50 µm, 2 bar, 10 seconds, held at a distance of 10 mm), cleaned with ethanol in an ultrasonic bath (5 minutes), and dried with oil-free air. Depending on the luting material used, further pretreatment of the surface was applied where required (Table 1). The luting agents were mixed according to the manufacturers' instructions. Light curing and a glycerin gel were applied when indicated. The ceramic crowns were filled with the luting agent and then placed on the abutments using finger pressure, and excess marginal luting material was removed with a microbrush. All specimens were loaded with a force of 5 kg for the indicated setting time at room temperature (24°C) and then stored in a warming cabinet at 37°C in distilled water. After 24 hours, the specimens were fixed in the universal testing machine to detach the restorations from the implant abutments. For this purpose, an experimental test fixture was developed based on an established testing method for investigating the shear and tensile bond strength of dental materials,[22,23] which are simultaneously present with the use of anatomical crowns. In order to ensure pull-off forces in the axial direction, the upper part of each specimen was fixed in the testing machine using a mounting box with a bottom opening of 4.8 mm, analogous to the thickest part of the implant (Figs 2 and 3). The overcontoured margins of the crowns prevented

Fig 3 *(a)* The upper fixture is connected to the universal testing machine via two shekels. At the lower end of the upper fixture, there is an external thread that can be used to attach the mounting box with a hole in the bottom. *(b)* The implant part of the test specimen has a smaller diameter than the hole in the mounting box, which allows the implant part to slide through the bottom. The overcontoured crown has a larger diameter than the hole, making it impossible for the test specimen to slip through. The mounting box including the crown-implant test specimen can be connected to the upper part of the testing machine via the internal thread. *(c)* Only the implant part extends out of the box. *(d and e)* The implant part of the test specimen is then screwed into the internal thread of the lower mounting box. *(f)* This fixture is then connected to the universal testing machine via another two shekels.

the specimen from slipping through the hole in the bottom of the mounting box during crown removal (Fig 3b). The external threads of the implants were used to attach the implant to the lower holding device (Figs 3d to 3f).

Prior to debonding, the parameters of the universal testing machine were checked for analysis: crosshead speed of 0.5 mm/minute, preload of 5 N, a force limit of 10,000 N, and a force threshold of 20 N. The maximum

Table 2   Mean ± SD Bond Strength (MPa) and Retention Force (N) of the Different Luting Agents

Test series	n	Bond strength	Retention force
HIS	20	0.92 ± 0.36	53.50 ± 23.08
DUR	19	1.62 ± 1.02	89.96 ± 51.20
PHZ	20	2.98 ± 1.25	170.49 ± 68.02
BQM	20	1.67 ± 0.32	95.71 ± 16.47
P21	20	3.60 ± 0.51	207.75 ± 36.51
PV5	20	4.41 ± 0.97	253.70 ± 58,84
BSE	20	2.67 ± 0.84	153,99 ± 53.17
REX	20	3.71 ± 0.92	213.40 ± 55.45
SCP	20	4.30 ± 0.72	248.80 ± 51.36
PSA	20	5.40 ± 0.85	309.60 ± 46.81
AQM	20	3.68 ± 1.22	212.10 ± 70.60
KEC	20	5,20 ± 1.13	296.95 ± 54.98
FUJ	20	12.18 ± 1.82	700.95 ± 117.23

See Table 1 for abbreviations.

retention force at the time of debonding was recorded in Newtons (testXpert II, Zwick Roell). To receive the combined shear bond and tensile strength in megapascals, the surface area of the abutments was calculated based on the manufacturers' construction drawings. Based on these results (mm²), the recorded maximum force was used to calculate the force per area (N/mm² = MPa).

After debonding, the crowns and implants were meticulously cleaned. First, careful mechanical removal of larger cement residue was done with a scalpel. The abutments and crowns were then checked under the light microscope for any further cement residue. In case of remaining residue, the inside of the crown was completely cleaned by sandblasting with alumina particles (25 µm, 2 bar, held at a distance of 10 mm). For reuse, the surface of the abutments was treated with alcohol, laboratory cloths, and, in a few cases, with a scalpel, since there were only a few abutment surfaces with cement residue. A light microscope (see below) was used to ensure an entirely residue-free surface.

To qualitatively assess the fracture behavior of the luting agents, a light microscopic examination (magnification ×2.5) was carried out (Leica MS5). The fracture behavior was classified into two different categories: *(1)* adhesive fracture between two different surfaces, therefore either between the luting agent and the abutment or between the luting agent and the inner surface of the ceramic crowns; or *(2)* cohesive fracture within the ceramic or luting agent. In order to obtain a quantitative evaluation, the bonding surface was divided into different areas. The percentage of the total surface and the surface in the individual areas was calculated, resulting in an exact description of the individual fracture pattern in percent. This analysis was always performed first.

Afterwards, the specimens were cleaned for reuse as described above.

The data acquired were statistically analyzed with a suitable statistical software (SPSS version 25, IBM). Subsequent to the descriptive statistics and *t* test for two independent samples to evaluate the influence of the different abutment heights on the bond strength in the different test series, analysis of variance (ANOVA) was performed to determine the influence of surface pretreatment. In order to identify which subgroups showed a significantly different outcome, Tukey post hoc test was applied. The level of significance was set at α = .05 for all analyses.

RESULTS

All 320 implant-crown complexes were detached from each other. One specimen was excluded from data analysis due to incorrect fixation in the universal testing machine.

Influence of Different Luting Agents
The mean bond strength values (± SD) and the maximum retention force at the time of debonding (± SD) are shown in Table 2 for the 13 different luting agents independent of the different abutment heights. Materials from the group of glass-ionomer cements and self-adhesive luting agents showed the highest bond strength and retentive forces, followed by adhesive luting agents and conventional materials like polycarboxylate cement (Durelon [DUR], 3M) and phosphate cement (Phosphatzement [PHZ], Kulzer). The lowest values were shown for temporary luting agents.

Table 3 Mean ± SD Bond Strength (MPa) and Retention Force (N) of the Different Luting Agents Depending on the Different Abutment Heights

Test series	Abutment height (mm)	n	Bond strength	P value	Retention force
HIS	4	10	0.76 ± 0.27	.051	40.48 ± 14.55
	5	10	1.07 ± 0.37		66.51 ± 23.16
DUR	4	9	2.51 ± 0.77	< .001	133.06 ± 41.10
	5	10	0.82 ± 0.23		51.18 ± 14.55
PHZ	4	10	3.19 ± 1.59	.468	168.77 ± 84.09
	5	10	2.77 ± 0.83		172.20 ± 51.86
BQM	4	10	1.80 ± 0.32	.067	95.40 ± 17.06
	5	10	1.54 ± 0.27		96.09 ± 16.77
P21	4	10	3.52 ± 0.49	.496	186.40 ± 25.80
	5	10	3.68 ± 0.54		229.10 ± 33.70
PV5	4	10	4.43 ± 1.06	.919	234.50 ± 56.31
	5	10	4.38 ± 0.93		272.90 ± 57.61
BSE	4	10	2.58 ± 0.66	.644	136.37 ± 34.85
	5	10	2.76 ± 1.02		171.60 ± 63.75
REX	4	10	3.78 ± 0.85	.759	199.90 ± 44.95
	5	10	3.65 ± 1.03		226.90 ± 63.77
SCP	4	10	4.14 ± 0.60	.310	219.10 ± 31.90
	5	10	4.47 ± 0.82		278.50 ± 50.90
PSA	4	10	5.70 ± 0.82	.122	301.70 ± 43.46
	5	10	5.10 ± 0.82		317.50 ± 50.97
AQM	4	10	3.63 ± 1.51	.856	192.00 ± 79.63
	5	10	3.73 ± 0.92		232.20 ± 57.31
KEC	4	10	5.86 ± 0.85	.006	310.20 ± 44.84
	5	10	4.56 ± 1.01		283.70 ± 63.10
FUJ	4	10	12.37 ± 1.49	.658	655.00 ± 78.93
	5	10	12.00 ± 2.16		746.90 ± 134.50

See Table 1 for abbreviations.

Influence of Different Abutment Heights

When comparing the bond strength values of all specimens with a reduced abutment height (n = 129) to abutments with a standard height (n = 130) regardless of the different luting agents, there were no significant differences in bond strength (4 mm: 4.19 ± 2.90 MPa; 5 mm: 3.89 ± 2.85 MPa) or maximum retention force at the time of debonding (4 mm: 221.67 ± 153.34 N; 5 mm: 241.94 ± 177.33 N).

The mean (± SD) bond strength in MPa for each test series and its subgroups are shown in Table 3. The use of a polycarboxylate cement (DUR; P < .001) and a glass-ionomer cement (Ketac Cem [KEC], 3M; P = .006) showed statistically significant differences, while all other materials showed no significant differences in bond strength when evaluating the influence of abutment height in relation to the different luting agents. However, the statistically significant difference was in favor of the lower abutment height.

Influence of Surface Pretreatment

When using primers with adhesive resin-based luting agents (Bifix QM [BQM], Voco; without primer: 4 mm vs 5 mm: P = .917; with primer: 4 mm vs 5 mm: P = .169; and Panavia V5 [PV5], Kuraray Noritake; 4 mm [no primer] vs 4 mm [primer used]: P < .001; 5 mm [no primer] vs 5 mm [primer used]: P < .001), there was a significant difference in bond strength for both abutment heights (Fig 5). The influence of pure sandblasting when no ceramic primer was used showed no significant difference when using the adhesive resin-based luting agents PV5 (4 mm [no sandblasting or use of primer] vs 4 mm [sandblasting and no primer used]: P = .922; 5 mm
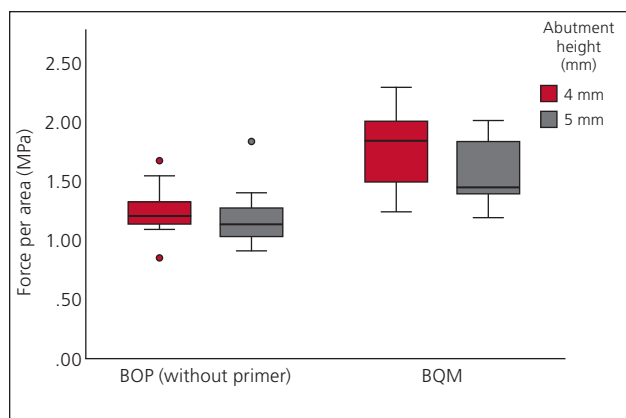
Fig 4 Bond strength values (MPa) of the adhesive cement Bifix QM (BQM) using different conditioning methods for pretreatment of the inner surface of the ceramic crown.
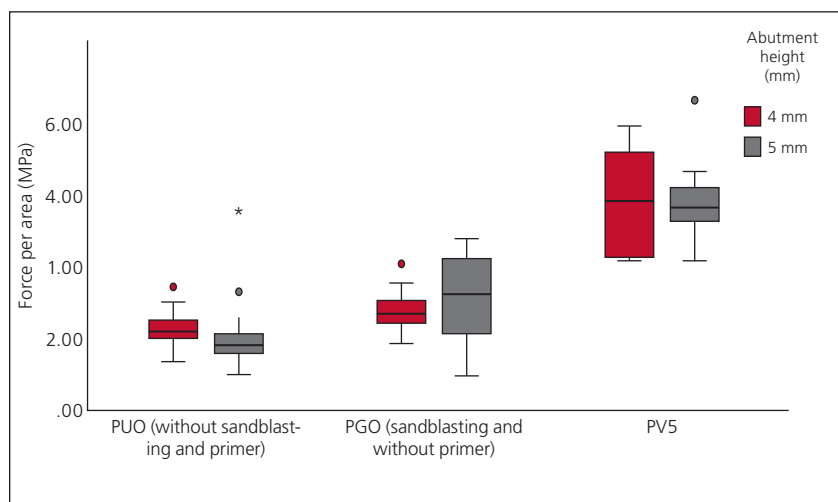

Fig 5 Bond strength values (MPa) of the adhesive cement Panavia V5 (PV5) using different conditioning methods for pretreatment of the inner surface of the ceramic crown. See Table 1 for abbreviations.

[no sandblasting or use of primer] vs 5 mm [sandblasting and no primer used]: *P* = .539) (Fig 5).

Fracture Behavior Analysis

The resin-based glass-ionomer cement (FujiCem 2 [FUJ], GC Europe) specimens mainly showed cohesive fracture behavior within the luting material and small amounts of adhesive fractures. In the test series with a polycar-boxylate cement (DUR), a phosphate cement (PHZ), two adhesive resin-based luting agents (BQM and Panavia 21 [P21], Kuraray Noritake), and a self-adhesive resin-based luting agent (Bifix SE [BSE], Voco), most of the luting material was found on the inner surface of the ceramic crowns, with small parts also detected on the lower half of the abutments. Examining the use of a temporary cement (Harvard Implant Semi-Permanent [HIS], Harvard Dental International), an adhesive resin-based luting agent (PV5), three adhesive resin-based luting agents (RelyX Unicem [REX], 3M; SpeedCEM Plus [SCP], Ivoclar Vivadent; and Panavia SA Cement Plus [PSA], Kuraray Noritake), and two glass-ionomer cements (Aqua Meron [AQM], Voco; and KEC), most of the luting material was found on the inner surface

of the crowns and only a small portion on the lower half of the abutments. Cohesive fractures could only be observed sporadically.

DISCUSSION

For the one-piece ceramic implants and the existing abutment geometry evaluated herein, no negative influence on bond strength was found when examining a reduced abutment height compared to the standard height, irrespective of the luting material or pretreatment methods.

Comparison of the study results to those of similar studies is very difficult due to the multitude of different experimental setups and parameters, and only a few studies are comparable. Even the many research reports with a similar experimental setup and similarly selected parameters examine a wide range of different materials for single-tooth crowns and abutments. Only studies with zirconia ceramic abutments and monolithic zirconia ceramic crowns evaluated with a crown pull-off test can be considered comparable to the study at hand. As long as there are no standardized test procedures

for determining retention and resistance behavior using standardized test setups, even small changes in the parameters during implementation can have a major impact on the results obtained.[24–27] Likely the biggest difference when compared to other test set-ups is the fixation of the test specimen in the universal testing machine. The specimen is often attached to the upper jig of the machine by wires or special crowns with built-in loops, while the implant or abutment is polymerized in resin or similar materials and is in contact with the lower part of the machine via an indirect connection.[24,28–37] The abutments or implants in turn are fixed with resins or clamps to the lower part.

In the experimental setup presented here, a specially developed test fixture was used. It is a further advancement of an established fixture for shear and tensile bond strength testing.[38,39] The type of upper and lower fixation was chosen such that the tensile load is applied purely axially without any influence of a load moment or torque. This also ensures that only the contact areas between the materials of interest (ie, the implant-crown complexes themselves) are tested while avoiding confounders due to additional fixation materials and the kind of fixation, often indirect. The upper fixation consists of a mounting box, which has a bottom opening analogous to the width of the implant and which can be fixed by an internal thread to the external thread of the upper part of the machine. The holding box is then put over the external thread of the implant but stops in the area of the crown margin because the crown walls have been thickened. In the lower area of the testing machine, the implant is fixed directly over the thread in the testing machine.

In the present study, the bond strength values of the individual luting agents showed a wide range, but a trend between the individual material classes could be observed. Comparing the achieved bond strengths of the different classes of luting materials achieves the following ranking: glass-ionomer cements > self-adhesive resin-based luting agents > resin-based adhesive luting agents > phosphate cement > polycarboxylate cement > temporary cements.

This can be attributed to the different mechanisms of attachment of the luting agents. Conventional materials are held in place by mechanical mechanisms such as friction, which is why the design of the preparation and the surface quality play an important role here.[21] These materials therefore necessitate a very close fit between the restoration and the natural tooth/implant abutment in order to achieve sufficient retention.

In adhesive materials, a chemical component is used in addition to the macromechanical retention, which is clearly noticeable in the interaction of luting material and tooth or abutment surface and the resulting retention strength. Several studies particularly recommend the use of dual or self-adhesive resin-based luting agents when zirconia ceramics are used.[40–43] Since removability is an inherent property of (semi)permanent luting materials, it is not surprising that the lowest adhesion values are achieved with these.

Some studies showed similar values of bond strength for the same materials tested in the present study.[33–37] In particular, differences were found for phosphate cements when compared to other studies. These cements showed much higher bond strength values compared to the present study.[35] The retention force of phosphate cement is the result of friction only. As no surface treatment was applied to the implant abutments used in this study, resulting in a smooth surface and a lower retention, this smoothness could be a reason why luting agents with adhesive molecules showed to some degree higher bond strength values than conventional materials. The resin-based glass-ionomer cement showed the highest values for bond strength. Due to the strength of the adhesive bond, a direct chemical bond between the luting material and the zirconia surfaces cannot be ruled out. In the authors' opinion, this bond cannot be explained by friction alone.

The reduction of the abutment height showed significant differences in the test series when using a polycarboxylate cement (DUR) and a glass-ionomer cement (KEC).

The fact that 4-mm abutments (ie, those with reduced height) also showed significantly higher values depending on the respective luting material allows the conclusion that, although statistically significant, there is no clinical relevance of the abutment height of the one-piece implants investigated here. Otherwise, the 5-mm abutments should have consistently shown the higher bond strength values. This conclusion is based solely on the comparison of the abutment geometries tested here.

A similar in vitro study examined the influence of 4-mm and 5.5-mm zirconia abutments and found significant differences in the use of temporary cements, self-adhesive materials, and glass-ionomer cements. The possible use of an additional ceramic primer and the pretreatment of the zirconia abutments was not described.[35] Other studies using different materials for abutments and crowns showed that the influence of several abutments with a height of 5 mm or less did not significantly differ, while abutments with a height of 5 mm or more showed an increase in retention.

Different pretreatment methods for zirconia crowns are controversially discussed in the literature. The results of this study showed that the use of sandblasting with aluminum oxide particles and the use of ceramic primers led to an increase in bond strength. These observations are also confirmed by other studies.[30,44–46] Roughening of the surface results in expansion and improved wettability of the contact area. When using resin-based luting

agents, an additional treatment of the surface with a silane coupling agent or ceramic primer with 10-methacryloyloxydecyl dihydrogen phosphate (MDP) molecules showed significantly increased bond strength values.[44,46]

The fracture analysis showed mainly adhesive fracture behavior and thus revealed a weak point in the bond between the respective luting agents and the smooth abutment surface. Only the luting agents with the highest bonding strength values showed areas of cohesive fracture. According to the manufacturers' instructions, additional surface pretreatment was not required. In this study, a clear improvement in bond strength could be achieved after pretreating the abutment surface with appropriate means, such as alumina particle sandblasting. Several studies showed that a significant improvement in bond strength could be reached on both natural teeth and titanium abutments when using sandblasting products for surface pretreatment of the inner surfaces of restorations.[29,36,47]

Currently, there is no laboratory test procedure with which the clinical parameters of the oral cavity can be exactly reproduced. This should be considered when looking at in vitro results.[24,29,48] However, laboratory tests have the advantages of being cost effective, clearly reproducible, and a rapid alternative to clinical studies, which is important for estimating the technical properties of new materials.[24,26,29] As temperature may influence the setting or curing of luting materials, the implants were stored at 37°C until immediately before luting and removed from the warming cabinet only for the actual luting process. In addition, the setting time at body temperature specified by the manufacturer was doubled, and the connected specimens were immediately returned to the warming cabinet to take this aspect into account.

In order to be able to reuse the single-tooth crowns, cement residues were removed and the surfaces cleaned as described above. The cementation gap was not measured before the bonding of the individual test series nor after each cleaning, as other in vitro investigations of the research group using densely sintered ZrO_2 specimens showed an eventual loss of surface material in the single-digit micrometer range (less than 6 μm) after sandblasting with aluminum oxide particles of 25 μm in size and below 10-bar pressure and repeated noncontact optical measurements.[49] While a more precise measurement was not possible due to the lack of a suitable measuring method at the research site, the potential loss was assessed as negligible.

The negative influence of long-term water storage or thermocycling, the existence of which is known,[50,51] was not the subject of this in vitro study and should be the subject of future investigations.

The present results apply only to abutments with the same outer shape and taper. In addition to abutment height, even minimal changes in parameters such as abutment shape or taper can lead to major differences in study results. Therefore, only results of studies with similar testing procedures and parameters are comparable.[17,24–27]

CONCLUSIONS

The proper selection of a luting agent when fixing zirconia single crowns onto one-piece zirconia implants is important. Materials classified in the group of glass-ionomer–based cements or self-adhesive resins showed the highest bond strength values, followed by adhesive resins, conventional luting agents, and temporary materials.

Depending on the use of different luting agents, only a minority of the selected materials showed significant differences in bond strength in favor of the lower abutment height, thus being inconsequential for clinical application. For this kind of one-piece zirconia implant, comparable bond strength values can be achieved with both abutment heights under in vitro conditions.

Surface pretreatment with ceramic primers showed significantly higher bond strength values.

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