Translucency and flexural strength of monolithic translucent zirconia and porcelain-layered zirconia

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This study aims to investigate the effectiveness of monolithic translucent TZP with different colors and porcelain-layered TZP by evaluating their colors and strengths. Different mixing ratios of Zpex to Zpex-Yellow as translucent TZP, conventional opaque TZP (TZ-3YB-E) (Tosoh, Tokyo) as a control, and veneering porcelain (CERABIEN ZR, body porcelain, Noritake, Tokyo) with shade A3 as a typical shade. Disk-shaped specimens of 13 mm diameter and 1.5 mm thickness were prepared. These specimens were observed under reflected and transmitted light, and the translucency parameter (TP) values were measured. Strength was also evaluated with flexural strength in a biaxial bending test. The TP values of the monolithic TZP, Zpex100>Zpex70>Zpex50>TZ3YB, were larger in this order. The flexural strength of all the monolithic TZP showed approximately 1,000 MPa. It is suggested that colored translucent TZP is clinically useful when used as monolithic restorations.

Keywords: Translucent zirconia, Monolithic, Translucency, Strength

INTRODUCTION

All-ceramic restorations have been widely used for their superior aesthetic results and biocompatibility¹⁻⁴. Various ceramic materials have been developed, and in some studies, their mechanical and physical characteristics have been evaluated and reported on⁵⁻⁷. While all-ceramic crowns are aesthetically superior, there have been concerns about their clinical application due to their relatively lower mechanical strength than metal-ceramic crowns⁸.

With recent developments in CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) technology, the possibility of milling full-contour ceramic restorations with high-strength zirconia, tetragonal zirconia polycrystals (TZPs) in particular, have gained increasing importance and popularity⁹⁻¹³. These TZPs are often layered with porcelain when used clinically because they are opaque, however, fracture and chipping of the veneering porcelain have also been reported^{4,14-16}. To avoid such chipping of the veneering porcelain, monolithic TZP restorations have been investigated, and colored TZPs have been made commercially available. The monolithic TZP restorations are limited in clinical application because these TZPs are opaque. To overcome this problem, translucent TZP has been researched and developed extensively¹⁷⁻²². In addition, recently, highly translucent TZP that enable color expression is commercially available with the trade name Zpex²³, and there are high expectations for its clinical application.

However, since there have been no reported studies

examining the translucency and strength of monolithic translucent TZP with various colors and porcelain-layered TZP, a clinical assessment of colored translucent TZP has yet to be established.

This study aimed to investigate the effectiveness of monolithic translucent TZP with different colors and porcelain-layered TZP by evaluating their translucency and flexural strength comparing with those of conventional opaque TZP.

MATERIALS AND METHODS

Preparation of zirconia specimens

Translucent TZP including Zpex and Zpex-Yellow, conventional opaque TZP (Tosoh, Tokyo, Japan), and veneering porcelain (Shade A3, Body porcelain, CERABIEN ZR, Noritake, Tokyo, Japan) were used in this study (Table 1). Both TZPs contained 3 mol% of Y₂O₃, and translucent TZP was decreased to 0.05 mass% of Al₂O₃ compared to opaque TZP of 0.25 mass%. Fe₂O₃ content was increased to 0.15 mass% for Zpex-Yellow.

Zpex (translucent white) and Zpex-Yellow (translucent yellow), either alone or mixed, were used. The mixing ratio of Zpex to Zpex-Yellow was 100:0 (Zpex 100), 70:30 (Zpex 70), and 50:50 (Zpex 50) was shown in Table 2. The TZP powders were cold isostatic pressed at 176 MPa, then sintered at 1,450°C for translucent TZP and 1,350°C for opaque TZP in air atmosphere with the heating rate of 600°C/h, holding time at maximum temperature of 2 h. Subsequently, disk-shaped specimens of 13 mm diameter and 0.5, 1.0 and 1.5 mm thickness were prepared. Finally, both sides of the disks were polished with a diamond wheel (#DIA140,

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Table 1 Materials used in this study
TZP

	Translucent		Opaque (conventional)
	Zpex	Zpex-Yellow	TZ-3YB-E
Y ₂ O ₃ (mol%)		3	3
Al ₂ O ₃ (mass%)		0.05	0.25
SiO ₂ (mass%)		≤0.02	≤0.02
Fe ₂ O ₃ (mass%)	≤0.01	0.15	≤0.01
Feldspar porcelain			
	Product name		Shade
	Noritake CERABIEN ZR		A3B TZP

Table 2 Mixing ratio of Zpex to Zpex-Yellow

TZP category	Ratio	Code
Translucent	Zpex:Zpex-Yellow=100:0	Zpex100
	Zpex:Zpex-Yellow=70:30	Zpex70
	Zpex:Zpex-Yellow=50:50	Zpex50
Opaque	TZ-3YB-E	TZ3YB

Table 3 Ratio of thickness of TZP to porcelain

TZP : Porcelain (mm)	Code
1.5:0.0	P0.0
1.0:0.5	P0.5
0.5:1.0	P1.0
0.0:1.5	P1.5

Sankyo Diamond, Kanagawa, Japan) using a profile grinder (PGX2000S, Waida, Gifu, Japan). The method of surface preparation was determined according to the previous report that was resembled to final polishing in the clinical situation²⁴⁾. Finally, the surface roughness (Ra) was 0.35±0.06 μm.

Sintering of veneering porcelain

One side of the 0.5 and 1.0 mm-thick TZP was blasted with alumina particle of 50 μm. The surface roughness (Ra) of the alumina-blasted surface was 0.65±0.10 μm. Subsequently, veneering porcelain was layered and sintered on the TZP specimens using a porcelain furnace (CeraFusion BX, Morita, Tokyo, Japan).

Disk-shaped specimens of a 13 mm diameter and 1.5 mm thickness were prepared as shown in Table 3. Specifically, monolithic TZP (P0.0) and porcelain alone (P1.5), and two kinds of laminate specimens with different ratios of thicknesses of TZP to porcelain were

Table 4 Sintering conditions of porcelain

Porcelain furnace	: CeraFusion BX (Morita)
Sintering start temperature (°C)	: 600
Drying time (min)	: 7
Heat rate (°C/min)	: 45
Vacuum (kPa)	: -6
Sintering temperature (°C)	: 930
Holding time (min)	: 1
Cooling time (min)	: 4
Vacuum start temperature (°C)	: 600
Vacuum end temperature (°C)	: 930
Vacuum end time (min)	: 0

prepared. The thickness after sintering was adjusted with VITRIFIED DIA (Shofu, Kyoto, Japan). The surface roughness (Ra) after the adjustment was 0.42±0.09 μm. The sintering conditions of porcelain are shown in Table 4.

Color observation using reflected and transmitted light

Prepared specimens were placed the on frosted glass, and were evaluated them visually with reflected and

transmitted light, and took photographs.

Evaluation of color characteristics

Using a colorimeter (MCR-A<06769, Lack Office, Tokyo, Japan), color evaluation was performed with the CIE Lab ($L^*a^*b^*$ color system). Before measuring, calibration was carried out both black and white backgrounds. The L^* , a^* , b^* values for the black and white backgrounds were 17.8, -0.5, -0.4, and 98.0, 0.3, 1.7, respectively. Then, as a measure of translucency, the translucency parameter (TP) value was calculated. After measuring the L^* , a^* , b^* value against the black and white backgrounds, the TP value was obtained from the following formula²⁵⁾.

$$\text{TP value} = (L_w^* - L_b^*)^2 + (a_w^* - a_b^*)^2 + (b_w^* - b_b^*)^2)^{1/2}$$

(W=white background, B=black background).

Flexural strength test

The strength was evaluated with the flexural strength based on the biaxial bending test using a universal testing machine (AUTOGRAPH AG-1 20 kN, Shimadzu, Kyoto, Japan) with a cross-head speed of 0.5 mm/min. On the testing, veneering porcelain and TZP were set on the compression side and the tension side, respectively, in consideration of the clinical situation. For the monolayer specimens, biaxial flexural strength was calculated according to ISO6872. For the double layered specimens, biaxial flexural strength was calculated using the following equations with the porcelain on the compression side (top layer; porcelain) and TZP on the tension side (bottom layer; TZP), and following conditions: Young's modulus 210 GPa for TZP and 70 GPa for porcelain, and Poisson's ratio 0.25 (Fig. 1)^{7,26)}.

$$\sigma_f = \left[\frac{t_b}{t_a + t_b} \right] \sigma_{top} + \frac{E_a}{E_b} \left[\frac{t_a}{t_a + t_b} \right] \sigma_{bottom} \quad (1)$$

$$\sigma_{top} = \frac{-6M}{t_a^2 k_{2p}} \left[1 + \frac{E_b t_b (1 + t_b/t_a)}{(E_a t_a + E_b t_b)} \right] \quad (2)$$

$$\sigma_{bottom} = \frac{6M}{t_a^2 k_{2p}} \left[\frac{E_b t_b}{E_a t_a} + \frac{E_b (t_a + t_b)}{(E_a t_a + E_b t_b)} \right] \quad (3)$$

In Eqs. 2 and 3 the constant:

$$k_{2p} = 1 + \frac{E_b t_b^3}{E_a t_a^3} + \frac{3E_b t_b (1 + t_b/t_a)^2}{E_a t_a + E_b t_b} \quad (4)$$

and the bending moment:

$$M = \frac{P}{8\pi} \left[(1+v) + 2(1+v) \ln \frac{a}{b} + (1-v) \left(1 - \frac{b^2}{2a^2} \right) \frac{a^2}{R^2} \right] \quad (5)$$

where: P=load, t=disc thickness (t_a =top layer; t_b =bottom layer), a =radius of support circle, b =radius of uniform loading at center, R =radius of disc, v =Poisson's ratio, E =Young's modulus (E_a =top layer; E_b =bottom layer).

The number of specimens for each condition included three for color evaluation and five for strength evaluation.

Fig. 1 Schematics of biaxial flexural test.

Left: Device for biaxial flexural test with specimen. Center: The specimens are placed on the three balls on the right side, and have pressure applied by the tip of the device. Right: Testing jig with three balls.

For statistical analysis, an analysis of variance followed by Bonferroni multiple comparison was performed. The significance level was set at $\alpha=0.05$ for all statistical analysis.

Scanning electron microscopy (SEM)

After the strength evaluation, SEM observation was performed on the fracture surface. The fractured specimen underwent ultrasonic cleaning with alcohol and distilled water for each 10 min, and was coated with an Au-Pd. Then, the fracture surface was observed using a scanning electron microscope (SU6600, Hitachi, Tokyo, Japan).

RESULTS

Color observation using reflected and transmitted light

Figure 2 shows the specimens observed under the reflected light. Among the monolithic specimens (P0.0), 5. For Zpex, Zpex100 was white, and Zpex70 and Zpex50 were increasingly yellow. As for the porcelain-layered specimens, the P0.5 specimens had colors that were affected by the color of the TZP base material, presumably because the veneering porcelain was thin.

Figure 3 shows the specimens observed under the transmitted light. Among the monolithic specimens (P0.0), TZ3YB, which appeared white with the reflected light, was observed as dark, showing its obviously decreased translucency. On the other hand, Zpex100, Zpex70 and Zpex50 were all observed as light, indicating a high level of translucency. As for the porcelain-layered specimens, the P0.5 specimens were observed as brighter than TZ3YB for all of Zpex100, Zpex70 and Zpex50. The colors of the P1.0 specimens were closer to the porcelain color, but TZ3YB was observed dark, indicating a decreased translucency.

Color characteristics (L^* values) against white and black backgrounds (Fig.4)

Monolithic specimens (P0.0); TZ3YB showed the highest L^* values. Among Zpex, the L^* values were significantly greater in the order of Zpex100>Zpex70>Zpex50 ($p<0.05$), and higher against the white background than the black

Fig. 2 Specimens observed under the reflected light. Monolithic TZPs have different colors (Zpex100, Zpex70, Zpex50 and TZ3YB). Porcelain-layered TZPs were veneered with same porcelain (A3shade).

Fig. 3 Specimens observed under the transmitted light. Monolithic TZPs have different colors (Zpex100, Zpex70, Zpex50 and TZ3YB). Porcelain-layered TZPs were veneered with same porcelain (A3shade).

background ($p < 0.05$).

Porcelain-layered specimens (P0.5, P1.0); The L^* values decreased with increasing the thickness of porcelain against both the white and black backgrounds ($p < 0.05$).

Color characteristics (a^ values) against white and black backgrounds* (Fig.5)

Monolithic specimens (P0.0); The a^* values for all the TZP specimens were significantly smaller than that

of P1.5 (porcelain alone) ($p < 0.05$). Zpex50 showed the highest value among the TZP specimens. All the specimens except for TZ3YB showed significantly higher a^* values against the white background than the black background ($p < 0.05$).

Porcelain-layered specimens (P0.5, P1.0); The a^* values increased as the thickness of porcelain increased for the Zpex specimens ($p < 0.05$), but there was no significant difference between P0.5 and P1.0 for TZ3YB ($p > 0.05$).

Fig. 4 The L^* values.

Fig. 7 Translucency parameter (TP) values.

Fig. 5 The a^* values.

Fig. 8 Biaxial flexural strength.

Fig. 6 The b^* values.

Color characteristics (b^ values) against white and black backgrounds (Fig.6)*

The b^* values were greater than the a^* values, and showed a similar tendency to the a^* values for all except Zpex50. The b^* values for Zpex50 did not change as the

thickness of porcelain increased ($p>0.05$).

Translucency parameter (TP) values (Fig.7)

Monolithic specimens (P0.0); Among the monolithic specimens (P0.0), the TP values were significantly greater in the order of Zpex100>Zpex70>Zpex50>TZ3YB ($p<0.05$).

Porcelain-layered specimens (P0.5, P1.0); The TP values did not change as the thickness of porcelain increased ($p>0.05$) except for TZ3YB. For TZ3YB, the value for P1.0 was significantly greater than those of the other specimens ($p<0.05$).

Biaxial flexural strength (Fig.8)

Monolithic specimens (P0.0); All the TZP specimens showed a flexural strength of about 1000MPa, which is more than ten times greater than that of porcelain, 70 MPa.

Porcelain-layered specimens (P0.5, P1.0); The flexural strength decreased as the thickness of porcelain increased ($p<0.05$): approximately 500 MPa for P0.5, and approximately 150 MPa for P1.0. There was no significant difference among the TZP specimens ($p>0.05$).

Fig. 9 Representative SEM images of fractured specimens after being biaxial flexural test.

Scanning electron microscopy (SEM)

Figure 9 shows the representative SEM images of fractured specimens after being biaxial flexural test. In the monolithic TZP specimens (Figs. a and c), fractures occurred directly between compression and tension sides (arrow). On the other hand, for the porcelain-layered specimens (Figs. b and d), a fracture line ran from the TZP-porcelain interface upwards (to the porcelain side) (arrow). In addition, delamination of the TZP-porcelain interface was observed (arrow head) on some specimens.

DISCUSSION

This study aimed to investigate the effectiveness of monolithic translucent TZP with different colors and porcelain-layered TZP by evaluating their translucency and flexural strength comparing with those of conventional opaque TZP.

Monolithic TZPs

In this study, under the reflected light, TZ3YB and Zpex100 were observed as white though TZ3YB was whiter than Zpex100. Zpex70 and Zpex50 were observed as increasingly yellow. On the other hand, under the transmitted light, while TZ3YB showed an obvious decrease in translucency, all of the Zpex specimens were observed as light, confirming a high level of translucency. This tendency was also supported by the color characteristics evaluation. The TP value was greater in the order of Zpex100>Zpex70>Zpex50>TZ3YB.

Therefore, it confirms that the monolithic Zpex specimens except monolithic Zpex50 are highly translucent like porcelain compared with TZ3YB. For the Zpex specimens, the reason why translucency decreased with increasing the mixing ratio of Zpex-Yellow considered to be the influence of added Fe_2O_3 ; in other words, the translucency decreased because of those dark colors.

However, with the reflected light, no Zpex specimen showed similar colors to porcelain. One of the possible reasons for this is that the porcelain used in this study was shade A3. The shade of porcelain used in this study was A3 that is widely used in clinic. Accordingly, different results might be obtained by using other shades. Another reason may be that the color of Zpex-Yellow is adjusted by Fe_2O_3 alone; further examinations involving the addition of trace amounts of other metal oxides will be necessary to fit all of shades in clinical application.

With regard to strength of monolithic (all-ceramic) restorations, the Zpex specimens and TZ3YB showed the almost same flexural strength in this study. Johansson *et al.* reported that translucent TZP shows high strength, supporting the results of this study²⁷. The fact that the Zpex specimens showed the same level of strength as conventional TZ3YB suggests that Zpex can be used clinically. In addition, Seydler *et al.* reported that the fracture load of a 1.0–1.5 mm-thick all-ceramic crown made of lithium disilicate glass-ceramic (IPS-Empress) was 600 N or greater, whose flexural strength was about 350 MPa²⁸. Yoshinari *et al.* reported that the fracture load of an all-ceramic crown made of InCeram-Alumina,

with an occlusal surface thickness of 2.0–2.9 mm and a margin thickness of 1.0 mm, was about 1,000 N, whose flexural strength was about 600 MPa^{29,30}). Ting *et al.* reported that a TZP of 1.0 mm thickness showed the same level of fracture load as metal-ceramic crowns³¹). Johansson *et al.* reported that the fracture load of a TZP crown with an occlusal surface thickness of 1.8 mm was 2,700 N or more²⁷). Furthermore, under the biaxial flexural test in this study, the fracture load of 1.0 mm-thick translucent TZP can estimate the 600 N that is equivalent value of the average biaxial flexural strength of the same TZP with 1,060 MPa. Considering the aforementioned results of flexural strength, the fracture load of clinical crowns for various all-ceramic materials, and the maximum occlusal load of 600 N in the clinical situation, it appears to be possible to reduce the thickness of TZP, even though the strength of crown depends on not only thickness, but also on shape, size, test method, load direction, adhesive cements, *etc.*

Porcelain-layered TZPs

Through visual observation of the layered specimens under reflected light, it was observed that the P1.0 specimen, which had a thicker porcelain layer than P0.5, showed more similar colors to P1.5 (porcelain alone) than the P0.5 specimen did. On the other hand, under the transmitted light, similarly to the monolithic specimens, TZ3YB showed an obvious decrease in translucency, and all the Zpex specimens were observed as bright. On the color characteristics evaluation, the TP value did not depend greatly on the thickness of the veneering porcelain. These results showed that the translucency of TZ3YB was lower than that of the Zpex specimens, even when the thickness of the veneering porcelain changed. Baldissara *et al.* reported on the low translucency of opaque TZP²¹). Wang *et al.* reported that the translucency of ceramic materials is affected by the thickness of the material, but the effect of thickness on opaque TZP is small³²). These reports were in consistency with results in this study. For the Zpex specimens, it appears that both Zpex and the veneering porcelain are highly translucent, suggesting that, in terms of the TP value, the Zpex specimens can be used without layering any porcelain.

The b^* value of Zpex50, unlike the other specimens, did not change with increasing the porcelain thickness as unique result. This is because the b^* value (yellow) of Zpex50 was similar to that of porcelain. Thus, satisfactory color shade can be obtained in clinical application, if the translucent color Zpexs are developed, which have closely-matched color with porcelain shade.

However, the strength of both Zpex and TZ3YB decreased as the thickness of TZP decreased, showing that the strength was depended on the thickness of the core material. The SEM observation also showed that porcelain, which had a lower strength, fractured first. This result supports the report of Aboushelib *et al.* that delamination between TZP and a fracture of a fragile veneering material leads to a fracture of TZP, the core material³³). Therefore, it appears that layering porcelain

increases the risk of fracture.

In the preset study, veneering porcelain and TZP were set on the compression side and the tension side, respectively, for biaxial flexural test. In general, when the loading is applied on the TZP crown veneered with porcelain, the TZP is tension side, because the TZP side of the veneered crown is placed on tooth. Therefore, in this study, TZP was set on the tension side in consideration of the clinical situation, although the veneering porcelain is generally weak against the tension. The delamination of the TZP-porcelain interface was also observed on some specimens in this study. However, even if the fractured origin was the interface between TZP and porcelain, the specimens including TZP and porcelain were totally fractured in final stage. Accordingly, it is considered that the flexural strength of double layered specimens was able to be calculated by above-mentioned equation.

Clinical implications

The results in the present study indicate that, considering the color, translucency and strength, monolithic translucent TZP is assessable for clinical application that is capable of selection of shade and has a translucency similar to natural tooth. In particular, in cases involving crown prosthesis for a lower and upper tooth, for aesthetic reasons, since the veneering material will cover the incisal edge and occlusal surface. Though this will probably increase the chipping risk of the veneering porcelain, the use of monolithic TZP will solve the chipping problem, and the use of monolithic translucent TZP will also improve the appearance. In addition, smooth-polished TZP has been reported to cause less wear on the antagonist enamel, making it more clinically useful^{24,34}). Furthermore, the fact that the flexural strength of all the monolithic TZP showed approximately 1,000 MPa indicate no requires for drastic increase in thickness compared with conventional crown restorations, and it may become a clinical benchmark for decreasing the amount of tooth to be removed.

CONCLUSION

The results of this study showed that translucent zirconia with different colors can improve translucency over conventional opaque zirconia and achieve similar colors to those of porcelain without layering porcelain. Moreover, translucent TZP has the same level of strength as opaque TZP, and the strength decreases as the thickness of veneering porcelain increases.

Therefore, it is suggested that colored translucent TZP is clinically useful when used as monolithic restorations.

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