

Polytetrafluoroethylene (PTFE): A resin material for possible use in dental prostheses and devices

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Polytetrafluoroethylene (PTFE) is chemically stable, non-toxic to humans, highly resistant to heat and chemicals, and has an extremely low coefficient of friction. Therefore, PTFE is used in medical applications. We focused on the physical properties of PTFE in relation to its application as a material for use in prostheses and dental devices/instruments. PTFE exhibited low wear (approximately 1/3 that of bovine tooth, and 1/2 that of type III gold alloy), low dynamic friction (approximately 1/5 that of the other specimens), low hardness (4.8HV1.0), low coloration, and low bacterial adhesion, compared to other specimens except porcelain in wear and coloration test ($p < 0.01$). These results suggest that PTFE could have applications in some prostheses for provisional and/or permanent use, and dental instruments/devices by providing excellent impact absorption, high wear resistance for maintenance of occlusal vertical dimension and original function, and ease of cleaning.

Keywords: Wear test, Surface roughness, Hardness, Coloration, Bacteria adhesion

INTRODUCTION

Polytetrafluoroethylene (PTFE), known as Teflon[®], is a fluorocarbon solid, and is a high-molecular-weight compound consisting wholly of carbon and fluorine. PTFE was accidentally discovered in 1938 and has numerous applications¹⁾.

PTFE is a hydrophobic molecule with excellent dielectric properties and one of the lowest coefficients of friction of any solid, which results in reduced friction, wear and energy consumption in machinery, industrial and medical devices, and cookware²⁾. In the medical and dental fields, it is commonly used as a permanent and temporary graft material in surgical interventions involving artificial blood vessels and membranes for guided bone/tissue regeneration (GBR/GTR)^{3,4)}. PTFE membrane is divided into two types by its structure, *i.e.* expanded-PTFE (e-PTFE) and high density-PTFE (d-PTFE) membrane. e-PTFE membrane with numerous small pores encourage cell attachment that stabilizes the host-tissue interface. e-PTFE membrane was the most common vascular prosthesis with limited graft patency and significant number of complications³⁾. It is also used extensively for digestive, cerebral and cardio-vascular surgeries, and bone /tissue regeneration in periodontal surgeries has indicated its effectiveness in tissue-guided repair⁵⁾. e-PTFE membrane is not available for dental use at present; however, d-PTFE membrane with a submicron pore size is one alternative to e-PTFE membrane. Its success in bone and tissue regeneration is well documented, and also reported to completely block

the penetration of food and bacteria, even if it is exposed to the oral cavity⁶⁻⁹⁾. It is also frequently employed as a coating on catheters to prevent bacteria and other infectious agents from adhering to catheters and causing hospital-acquired infections³⁾. PTFE tape can also be used for dental fillings, to isolate the contacts of anterior teeth so the filling material will not stick to the adjacent tooth^{10,11)}. These applications in medical and dental fields use its difficulty in adhesive property, which is also useful for maintenance of good oral hygiene, however prevent PTFE from application to prosthesis. Recently this adhesive problem is settled¹²⁻¹⁵⁾.

In this study, we investigated possible applications of PTFE for prostheses and dental instruments/devices by assessing its properties (wear, hardness, coloration by food and drinks, and bacterial adhesion) in comparison with conventional dental materials.

MATERIALS AND METHODS

Materials

To evaluate the physical properties of PTFE (composed of at least 20,000 C₂F₄ monomer units linked into very long unbranched chains (molecular weight; millions to ten million). melting point; 327°C, glass transition temperature; 130°C, density; 2.13–2.22g cm⁻³, contact angle of water; 110°, Fluoro Coat, Kawagoe, Japan) as a dental material, we prepared specimens (10×10×2 mm) of porcelain (VITA VM[®]13, VITA Zahnfabrik H. Rauter, Bad Säckingen, Germany) according to the manufacturer's instruction, gold alloy (YP GOLD type III, Yamakin, Osaka, Japan), bovine tooth (mandibular incisor, Yokohama Edible Meat Public, Yokohama,

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Japan), and composite resin (CR; Ceramage, Shofu, Kyoto, Japan) according to the manufacturer's instruction for comparison.

Surface roughness

Before the experiments, the surface of each specimen prepared by cutting (PTFE and bovine tooth) and molding (porcelain, gold alloy, composite resin) was polished with

waterproof sandpaper #1200 (C34P, Riken Corundum, Saitama, Japan). The surface roughness, consisting of Ra (arithmetic average roughness) and Rz (maximum height roughness), was measured center of the surface of each specimen (1 mm length) with a surface texture and contour integrated measuring instrument (Surfcom 5000DX, Tokyo Seimitsu, Tokyo, Japan, Fig. 1).

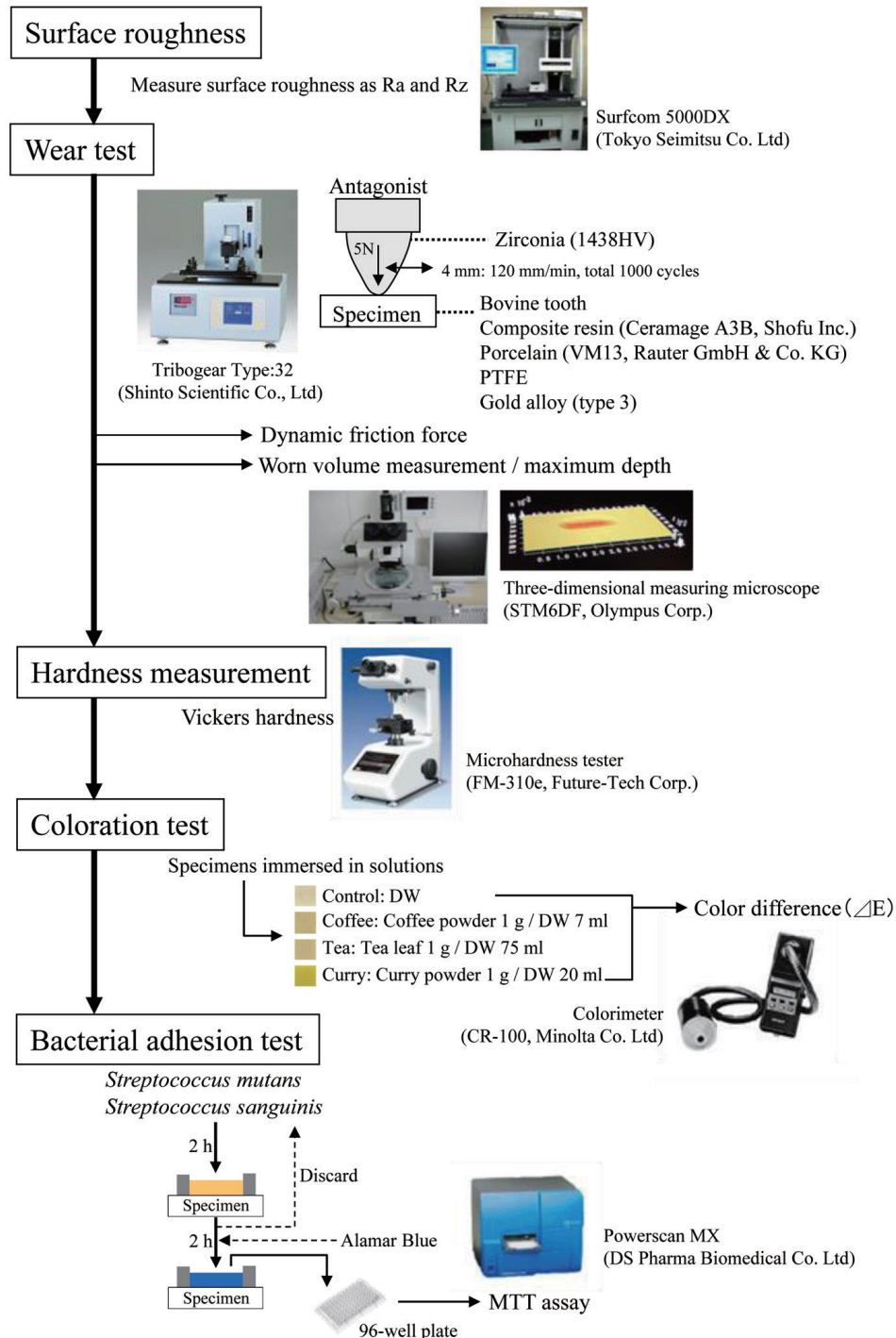


Fig. 1 Experimental flow of the study.

Wear test

Wear tests were conducted for each specimen using a wear testing machine¹⁶⁾ (Tribogear Type: 32, Shinto Scientific, Tokyo, Japan) against an yttria-stabilized zirconia antagonist as the hardest dental material in common use (Fig. 1). Test conditions consisted of antagonist load: 5 N, amplitude distance: 4 mm, head speed: 120 mm/min, and total reciprocation movement: 1,000 times (0.5 Hz). In this test, dynamic friction (maximum value) between each specimen and the zirconia antagonist was also estimated. The worn volume (mm³) of each specimen was evaluated with a Windows workstation computer (MB-P5300X-WS, Mouse Computer, Tokyo, Japan) from the scanning data using a three-dimensional measuring microscope (STM6DF, Olympus, Tokyo, Japan). Wear of the zirconia antagonist was measured using a three-dimensional measuring microscope.

Hardness measurement

The Vickers hardness (HV) of each specimen was evaluated with a microhardness tester (FM-310e, Future-Tech, Kanagawa, Japan, Fig. 1) by measuring the diagonal length (d) of the cavity on the specimen resulting from loading with a diamond indenter at a 9.8 N (F) load for 15 s as follows:

$$\text{HV} = 0.102\text{F}/\text{S} = 0.102[2\text{F}\sin(\theta/2)]/d^2 = 0.1891\text{F}/d^2$$

S: surface area of the cavity

Coloration test

To measure color, each specimen (10×10×2 mm) was immersed in 10 mL of distilled water (DW; control), coffee solution (1 g of Nescafe Excella coffee powder, Nestle Japan, Hyogo, Japan in 7 mL of DW), tea solution (1 g of Lipton Yellow Label tea leaves, Unilever Japan, Tokyo, Japan in 75 mL of DW), and curry solution (1 g of S&B curry powder, S&B Foods, Tokyo, Japan in 20 mL of DW) for 48 h at 37°C¹⁷⁾. The specimens were then washed twice with DW and dried in a cold and dark place. The color of the intact and dried specimens was evaluated using a colorimeter (CR-100, Minolta, Tokyo, Japan, Fig. 1) following calibration against the standard white porcelain plate provided. We measured *L** (lightness of color; *L**=0 indicates black and *L**=100 indicates diffuse white), *a** (position between red/magenta and green; negative values indicate green and positive values indicate magenta), and *b** (position between yellow and blue; negative values indicate blue and positive values indicate yellow), and then calculated ΔE^*_{ab} (ΔE) using CIELAB^{18,19)}. Color differences between the control (immersed in DW) and specimens colored with drink/food solution were exhibited as ΔE , which was calculated using the following equation:

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

The color difference (ΔE) was defined by the NBS unit (National Bureau of Standards, National Institute of Standards and Technology, Gaithersburg, MD, USA) as follows: 0–0.5; trace, 0.5–1.5; slight, 1.5–3.0; noticeable, 3.0–6.0; appreciable, 6.0–12.0; high, 12.0–; very high. By comparing the ΔE value of specimens colored with drink/food solution we were able to establish the extent

of coloration of each specimen.

Bacterial adhesion test

Streptococcus (*S. mutans* and *S. sanguinis*) were cultured in 1% glucose added to brain heart infusion medium (BHI: Beckton, Dickinson, Franklin Lakes, NJ, USA) at 37°C. Solutions of *S. mutans* and *S. sanguinis* (200 µL of OD0.8 solution) were placed on each specimen and cultured for 2 h at 37°C¹⁵⁾. Specimens were washed twice with deionized distilled water after cultivation, and reacted with Alamar Blue® solution (Thermo Fisher Scientific, Kanagawa, Japan) for 2 h at 37°C²⁰⁾. These reacted solutions were placed in 96-well plates, and the absorbance was measured (excitation wavelength 540 nm; emission wavelength 590 nm) with a microplate reader (Powerscan MX, DS Pharma Biomedical, Osaka, Japan) to evaluate the mitochondrial activity of living bacteria adhering to each specimen (Fig. 1).

Experimental conditions, data and statistical analysis

All experiments were performed in a laboratory environment maintained at 22±1°C. Each experiment was repeated eight times independently, with the maximum and minimum values in each data set being removed before calculation of mean values. Data are given as the mean±standard deviation. The statistical significance of the differences within and between groups was determined with the Tukey-Kramer test, comparing all columns. Statistical significance was accepted at *p*<0.01.

RESULTS

Before measurement of each physical property, the surface roughness (*Ra* and *Rz*) of each specimen was evaluated (Fig. 1). The surface roughness values for porcelain, gold alloy, bovine tooth, and CR were almost the same, and were much lower than that of the PTFE specimens (*p*<0.01). The *Ra* and *Rz* values of the zirconia antagonist were also high, falling between the values for PTFE and the other specimens (*p*<0.01, Table 1).

The worn volume of PTFE and porcelain was almost the same, and was smaller than gold alloy, bovine tooth, and CR (*p*<0.01, Table 2A). However, the maximum depth of the worn cavity of PTFE was exhibited lower value of porcelain and gold alloy, bovine tooth, and CR (*p*<0.01, Table 2A). Wear of the zirconia antagonist, porcelain, and gold alloy was almost the same, and smaller than bovine tooth, and CR (*p*<0.01, Table 2B). Dynamic friction during the wear test was much lower in PTFE than in the other specimens (*p*<0.01), which were approximately 1/5–1/6 of the value exhibited by PTFE (Table 2A).

The Vickers hardness test revealed that PTFE was an extremely soft material compared to other materials (*p*<0.01, Table 3). The order of Vickers hardness was porcelain (540 HV)>bovine tooth (283 HV)=gold alloy (270 HV)>CR (65 HV)>PTFE (4.8 HV). Vickers hardness of zirconia antagonist was 1,437.9±39.70. The results of the wear and hardness tests indicated that PTFE

Table 1 Surface roughness of specimens and zirconia antagonist

	Surface roughness (μm)	
	Ra	Rz
PTFE	0.98 ^d (0.107)	7.47 ^d (0.699)
Porcelain	0.12 ^a (0.044)	1.83 ^{a,b} (0.727)
Gold alloy	0.19 ^b (0.031)	2.30 ^b (0.349)
Bovine tooth	0.18 ^b (0.031)	1.55 ^a (0.304)
Composite resin	0.18 ^b (0.066)	2.11 ^{a,b} (1.202)
Zirconia antagonist	0.45 ^c (0.097)	3.64 ^c (1.133)

$n=6$ for each experiment. Values are mean and (S.D.).

Different superscript small letters denote statistically significant differences ($p<0.01$) within each measurement item.

Table 2 Wear of specimens and zirconia antagonist

A. Specimens

	Wear test		
	volume (mm^3)	depth (mm)	friction (N)
PTFE	0.006 ^a (0.0011)	0.013 ^a (0.0024)	0.37 ^a (0.030)
Porcelain	0.005 ^a (0.0013)	0.027 ^b (0.0036)	2.12 ^{c,d} (0.089)
Gold alloy	0.012 ^b (0.0014)	0.027 ^b (0.0011)	1.90 ^b (0.047)
Bovine tooth	0.017 ^c (0.0021)	0.047 ^c (0.0039)	2.07 ^{b,c} (0.350)
Composite resin	0.056 ^d (0.0128)	0.077 ^d (0.0036)	2.15 ^d (0.158)

$n=6$ for each experiment. Values are mean and (S.D.).

Different superscript small letters denote statistically significant differences ($p<0.01$) within each measurement item.

B. Zirconia antagonist

Wear of antagonist against each specimen (mm^2)				
PTFE	Porcelain	Gold alloy	Bovine tooth	Composite resin
0.069 ^a (0.0604)	0.056 ^a (0.0337)	0.059 ^a (0.0273)	0.179 ^b (0.0434)	0.365 ^c (0.0460)

$n=6$ for each experiment. Values are mean and (S.D.).

Different superscript small letters denote statistically significant differences ($p<0.01$).

Table 3 Vickers hardness of specimens

Vickers hardness (HV1.0)				
PTFE	Porcelain	Gold alloy	Bovine tooth	Composite resin
4.8 ^a (0.45)	539.7 ^d (20.24)	270.1 ^c (1.92)	282.7 ^c (12.01)	64.6 ^b (1.88)

$n=6$ for each experiment. Values are mean and (S.D.).

Different superscript small letters denote statistically significant differences ($p<0.01$).

exhibited low hardness and low wear with low friction (Table 2A), while the physical properties of gold alloy and bovine tooth were almost identical to each other (Table 3).

The scatter diagram showing the relationship between dynamic friction and worn volume reveals that PTFE exhibited both low wear and low friction (Fig. 2). CR exhibited both high wear and high friction. The

relationship between dynamic friction and worn volume was almost the same for porcelain, gold alloy, and bovine tooth (Fig. 2).

The coloration test revealed that PTFE and porcelain exhibited extremely low coloration compared with bovine tooth and CR immersed in all food and drinks ($p<0.01$, Table 4, Fig. 3). Especially in coffee immersion, PTFE coloration was lower than that of porcelain ($p<0.01$).

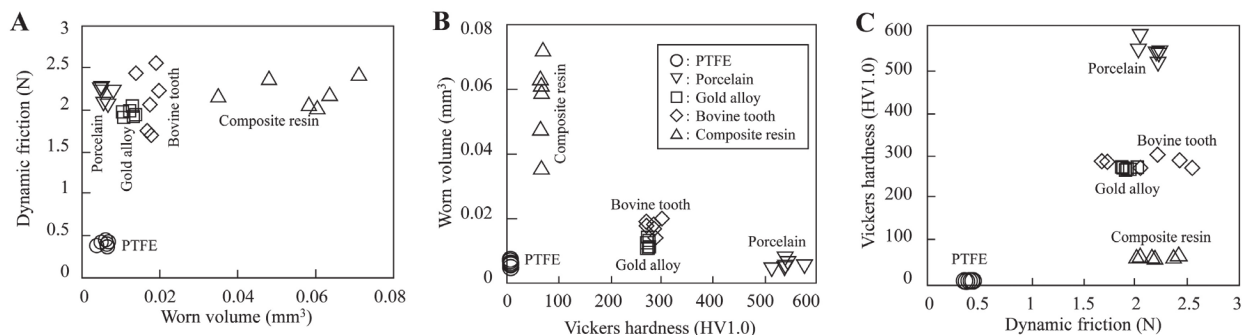


Fig. 2 Relationship between worn volume, dynamic friction, and Vickers hardness.

A: Relationship between worn volume and dynamic friction, B: Relationship between Vickers hardness and worn volume, C: Relationship between dynamic friction and Vickers hardness.

Table 4 Color difference of specimens immersed with food and drinks

	Color difference (ΔE^*ab)		
	coffee	tea	curry
PTFE	0.71 ^a (0.073)	0.43 ^a (0.064)	2.01 ^a (0.108)
Porcelain	1.93 ^b (0.487)	0.53 ^a (0.148)	2.14 ^a (0.313)
Bovine tooth	14.87 ^d (0.355)	23.31 ^c (0.397)	7.05 ^b (0.272)
Composite resin	5.12 ^c (0.183)	1.07 ^b (0.117)	34.62 ^c (0.396)

$n=6$ for each experimental condition. Values are mean and (S.D.).

Different superscript small letters denote statistically significant differences ($p<0.01$) within each drink/food.

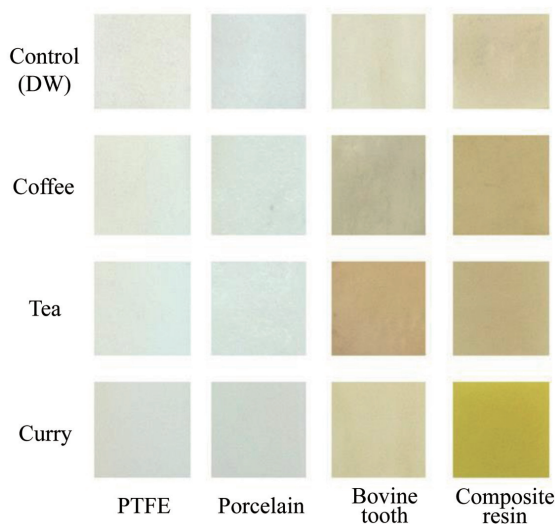


Fig. 3 Coloration of each specimen with food and drinks.

In PTFE and the prosthesis material specimens, the order of coloration was curry>coffee>tea, in contrast with bovine tooth, in which the order of coloration was tea>coffee>curry.

The bacterial adhesion test using *S. mutans* and *S. sanguinis* revealed similar tendencies in PTFE and

the prosthesis material specimens, all of which recorded lower bacterial adhesion than bovine tooth ($p<0.01$). Especially, bacterial adhesion of PTFE was extremely lower than other specimens ($p<0.01$). Bacterial adhesion of gold alloy was higher than PTFE, however: lower than that of porcelain and composite resin ($p<0.01$). The order of adhesion tendency was bovine tooth>CR=porcelain>gold alloy>PTFE (Table 5).

DISCUSSION

PTFE has inconsistent physical properties; it is a soft material, exhibiting low values for wear, friction, coloration, and bacterial adhesion^{1,2}). PTFE is often used in medical and dental fields as well as industrial and aeronautic fields¹⁻¹¹). In the medical and dental fields, it is used as a permanent and temporary graft material in surgical interventions involving artificial blood vessels and membranes for GBR/GTR³⁻⁹).

The Ra and Rz values of PTFE (Ra; $<1.0\ \mu\text{m}$, and Rz; $<8\ \mu\text{m}$), were higher than the other specimens, which all recorded similar lower values for surface roughness. Specimens with a rough surface generally exhibit wear more readily²¹). However, despite the high surface roughness of PTFE compared to other specimens, it exhibited low wear, signifying extremely high wear resistance compared to other specimens (Tables 1, 2). In the wear test in this study, we selected yttria-stabilized zirconia as the antagonist, because it is the

Table 5 Bacteria adhesion of specimens

	Mitochondrial activity of bacteria (% of bovine tooth)	
	<i>S.mutans</i>	<i>S.sanguinis</i>
PTFE	3.4 ^a (0.61)	0.8 ^a (1.03)
Porcelain	35.1 ^c (6.17)	17.1 ^c (8.82)
Gold alloy	18.0 ^b (2.87)	4.9 ^b (2.88)
Bovine tooth	100.0 ^d (4.13)	100.0 ^d (12.52)
Composite resin	38.6 ^c (3.56)	13.3 ^c (3.53)

$n=6$ for each experiment. Values are mean and (S.D.).

Different superscript small letters denote statistically significant differences ($p<0.01$) within each bacteria.

hardest material widely used in dental prostheses. We also selected bovine teeth, because of the close similarity of its mechanical properties to human teeth, and in consideration of research ethics¹⁹. The worn volume of PTFE and porcelain was smaller than gold alloy (1/2 volume), bovine tooth (1/3 volume), and CR (1/9 volume, $p<0.01$, Table 2A). These results suggested the possibility that high wear resistance of PTFE and porcelain should help maintain the occlusal vertical dimension. The worn volume of the PTFE and porcelain specimens were almost the same, but the maximum depth of porcelain was almost the same as that of gold alloy, and twice that of PTFE, suggesting that the worn cavity of the porcelain specimens was narrow and deep. The maximum depth of the worn cavity of PTFE was exhibited lower value of porcelain and gold alloy (1/2 depth), bovine tooth (1/3 depth), and CR (1/6 depth) ($p<0.01$, Table 2A). The wide and shallow worn cavity of the PTFE specimens could be a result of its extremely low friction, which caused the antagonist to slip on the PTFE surface. From the results of worn depth, PTFE could be a suitable material for maintenance of the occlusal vertical dimension compared to porcelain. The wear of the zirconia antagonist against PTFE, porcelain, and gold alloy was almost the same, and smaller than bovine tooth (1/3 volume), and CR (1/6 volume). The similar wear of the zirconia antagonist against PTFE, porcelain, and gold alloy indicate that low wear was exhibited both against specimens with high wear resistance, and against gold alloy, which had mild wear resistance (Table 2B). The Vickers hardness test revealed that PTFE was an extremely soft material compared to other materials, and that of bovine tooth and gold alloy was almost same (Table 3). The scatter diagram showing the relationship between dynamic friction and worn volume reveals the special mechanical properties of PTFE, and similar mechanical properties of bovine tooth and gold alloy (Fig. 2). In clinical situations, gold alloy is often said to be the best dental restorative material²², probably because its mechanical properties are similar to those of human teeth resembling bovine teeth²³. However, gold alloy prostheses are aesthetically displeasing because of the stark contrast with tooth color. From the results of mechanical property of materials in this study, PTFE was soft materials with low wear

friction compared with other materials, *i.e.* porcelain was hard materials with low wear and low friction, gold alloy was very close to bovine enamel, and CR was soft materials with high wear and high friction (Table 2A). These mechanical properties of PTFE, which should be due to its low friction rather than low hardness, suggest that it could be some kind of good dental restorative material with provisional use as treatment/training prosthesis or permanent use as facing crown/bridge backing with hard materials: its low hardness and friction should protect the teeth, periodontal tissue, muscle, and temporomandibular joint, and its high wear resistance should help maintain the occlusal vertical dimension.

The coloration test included coffee, tea, and curry because of their high rate of coloration¹². In contrast with CR, PTFE and porcelain exhibited extremely low coloration from food and drinks. Moreover, PTFE coloration was lower than that of porcelain in coffee immersion. PTFE comprises numerous small pores, which should be disadvantage for coloration, however: super-water-repellent property of PTFE should result in low coloration²⁴. Despite the high rate of coloration in CR, bacterial adhesion to CR specimens was comparable with the other dental restorative materials. Bacterial adhesion on the surface of prosthesis materials is an important factor in the maintenance of oral hygiene, and a high level of bacterial adhesion could cause dental caries, periodontal disease and systemic diseases²⁰. PTFE possessed excellent property with extremely low coloration and bacterial adhesion compared with other materials, *i.e.* porcelain was exhibited low coloration with moderate bacterial adhesion as well as CR, gold alloy was low bacterial adhesion but far from tooth color, and CR was exhibited high coloration and moderate bacterial adhesion. In spite of presence of numerous small pores, PTFE exhibited low bacteria adhesion. This property of PTFE could be due to its super-water-repellent property as well as its low coloration²⁴. These results suggest that porcelain, with its translucent tooth color, and PTFE, which is visually different from the natural tooth color and opaquer than porcelain, are both long-lasting materials; however, PTFE is more conducive to the maintenance of good oral hygiene.

The application of PTFE products for clinical use as a restorative material and in instruments/devices in the dental field could provide advantages of protecting opposing teeth, and maintaining oral aesthetics, occlusal vertical dimension and good oral hygiene. PTFE has been considered for applications in some kind of dental restoration (treatment/training/temporary prosthesis for provisional use or facing crown/bridge backing with hard materials for permanent use), and artificial teeth for treatment/training dentures, wire slots of brackets, surface coating of orthodontic wires, occlusal pressure buffers for dental implants, and components of dental instruments/devices. To realize these applications, two problems must be solved: the forming and bonding methods. PTFE products are usually formed by injection molding. However, prostheses are generally custom-made products, so injection molding is not a suitable method for fabricating a prosthesis. There is a need for development of a simpler high-performance method of custom-making counter-dies, or alternatively using computer-aided manufacturing technology. Another problem is bonding of PTFE products to the tooth surface, because of its lack of adherent properties^{5,6}. Plasma irradiation and chemical application have been reported to enhance the bonding of PTFE⁷⁻¹⁰. Further study should be undertaken to investigate possible applications of PTFE for dental clinical use, to take advantage of its desirable properties of low hardness, low friction, low coloration, and low bacterial adhesion.

CONCLUSION

The results of the current study showed that PTFE possesses properties of low hardness, low friction, low coloration, and low bacterial adhesion, highlighting its potential as an excellent material for clinical use in prostheses, *i.e.* treatment/training/temporary prosthesis for provisional use or facing crown/bridge backing with hard materials for permanent use, and dental instrument/device components to provide excellent impact absorption, high wear resistance for the maintenance of occlusal vertical dimension and original function, and ease of cleaning.

We conclude that PTFE has the potential to be an excellent material for clinical use as a material/component of prosthesis and dental instruments/devices.

REFERENCES

- Buerkle M, Asai Y. Thermal conductance of Teflon and Polyethylene: Insight from an atomistic, single-molecule level. *Sci Rep* 2017; 7: 41898.
- Biswas S, Vijayan K. Friction and wear of ptfе —a review. *Wear* 1992; 158: 193-211.
- Naoum JJ, Arbid EJ. Bypass surgery in limb salvage: polytetrafluoroethylene prosthetic bypass. *Methodist Debaque Cardiovasc J* 2012; 8: 43-46.
- Carbonell JM, Martín IS, Santos A, Pujol A, Sanz-Moliner JD, Nart J. High-density polytetrafluoroethylene membranes in guided bone and tissue regeneration procedures: a literature review. *Int J Oral Maxillofac Surg* 2014; 43: 75-84.
- Lee JY, Kim YK, Yun PY, Oh JS, Kim SG. Guided bone regeneration using two types of non-resorbable barrier membranes. *J Korean Assoc Oral Maxillofac Surg* 2010; 36: 275-279.
- Bartee BK. Evaluation of new polytetrafluoroethylene-guided tissue regeneration membrane in healing extraction sites. *Compendium* 1998; 19: 1256-1264.
- Bartee BK. The use of high-density polytetrafluoroethylene membrane to treat osseous defects: clinical reports. *Implant Dent* 1995; 4: 21-26.
- Rominger JW, Triplett RG. The use of guided tissue regeneration to improve implant osseointegration. *J Oral Maxillofac Surg* 1994; 52: 106-112.
- Barber HD, Lignelli J, Smith BM, Bartee BK. Using dense PTFE membrane without primary closure to achieve bone and tissue regeneration. *J Oral Maxillofac Surg* 2007; 65: 748-752.
- Sattar MM, Patel M, Alani A. Clinical applications of polytetrafluoroethylene (PTFE) tape in restorative dentistry. *Br Dent J* 2017; 222: 151-158.
- Dunn WJ, Davis JT, Casey JA. Polytetrafluoroethylene (PTFE) tape as a matrix in operative dentistry. *Oper Dent* 2014; 29: 470-472.
- Fujii M, Kamibayashi H, Shimoura H, Miyashita Y. Development of adhesive technology for PTFE on metal substances —Surface modification of PTFE by plasma etching treatment—. *Mitsubishi Densen Kogyo Jiho* 2002; 99: 78-84.
- Yanagishita E. Surface preparation for polymer materials. *J Adhes Soc Jpn* 2001; 37: 75-83.
- Momose Y. Plasma surface treatment of materials. *J Jpn Soc Colour Mater* 1998; 71: 186-193.
- Hai W, Hi T, Shimizu K, Yajima T. Preparation of a super hydrophilic polytetrafluoroethylene surface using a gaseous ammonia-water low-temperature plasma. *J Photopolym Sci Technol* 2015; 28: 479-483.
- Wonglamsam A, Kakuta K, Ogura H. Effects of occlusal and brushing cycles on wear of composite resins in combined wear test. *Dent Mater J* 2008; 27: 243-250.
- Kameda T, Kameda A. Development of a new elastomeric module with low coloration by foods and drinks —Part 1. Coloration by various kinds of foods and drinks. *J Begg Orthod* 2010; 32, 13-17.
- Official recommendations on uniform colour spaces, colour-difference equations, and metric colour terms, supplement No.2 to CIE publication No.15, colorimetry (E-1.3.1) 1971, 1976.
- Guidelines for coordinated research on colour difference evaluation, prepared by the colour difference subcommittee of CIE TC-1.3 (colorimetry), 1978.
- Sakuma Y, Washio J, Sasaki K, Takahashi N. A high-sensitive and non-radioisotopic fluorescence dye method for evaluating bacterial adhesion to denture materials. *Dent Mater J* 2013; 32: 585-591.
- Ono M, Inoue Y. Effects of surface roughness and manganese phosphate coating on friction and wear characteristics. *Hyoumen Gijutsu* 2005; 56: 52-56.
- Okuno O, Yoneyama T, Hamanaka H. Titanium alloys in dental and medical field. *Tetsu to Hagane* 1990; 10: 1633-1641.
- Yassen GH, Platt JA, Hara AT. Bovine teeth as substitute for human teeth in dental research: a literature. *J Oral Sci* 2011; 53: 273-282.
- Latthe SS, Terashima C, Nakata K, Fujishima A. Superhydrophobic surfaces developed by mimicking hierarchical surface morphology of lotus leaf. *Molecules* 2014; 19: 4256-4283.