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Correlation between microhardness and wear resistance of dental alloys against monolithic zirconia

Min-Sang Cha[1], Sang-Woon Lee[1], Yoon-Hyuk Huh[2], Lee-Ra Cho[2], Chan-Jin Park[2]*

[1]Department of Dentistry, Gangneung Asan Hospital, University of Ulsan College of Medicine, Gangneung, Republic of Korea
[2]Department of Prosthodontics and Research Institute of Oral Science, College of Dentistry, Gangneung-Wonju National University, Gangneung, Republic of Korea

ORCID
Min-Sang Cha
https://orcid.org/0000-0003-1695-0142
Sang-Woon Lee
https://orcid.org/0000-0002-0904-9391
Yoon-Hyuk Huh
https://orcid.org/0000-0003-4072-5199
Lee-Ra Cho
https://orcid.org/0000-0003-3989-2870
Chan-Jin Park
https://orcid.org/0000-0003-4734-214X

PURPOSE. The aim of this study is to compare the hardness according to the conditions of metal alloys. Moreover, the correlation between the cast crown hardness before and after wear testing and the degree of wear for each dental alloy was assessed. **MATERIALS AND METHODS.** Cast crowns of three metal alloys (Co-Cr, gold, and Ni-Cr alloys) opposing smooth-surface monolithic zirconia were used. The Vickers microhardness of the ingot (which did not undergo wear testing) and the cast crown before and after wear testing were measured for each alloy. Two-way ANOVA and Scheffé tests were used to compare the measured hardness values. Moreover, the Pearson correlation coefficient was used to evaluate the relationship between the surface hardness and the wear of the cast crown (α=.05). **RESULTS.** There was no significant difference in the hardness before and after wear testing for the gold alloy (P>.05); however, the hardness of the worn surface of the cast crown increased compared to that of the cast crown before the wear tests of Ni-Cr and Co-Cr alloys (P<.05). Furthermore, there was no correlation between the wear and hardness of the cast crown before and after wear testing for all three metal alloys (P>.05). **CONCLUSION.** There was a significant difference in hardness between dental alloys under the same conditions. No correlation existed between the surface hardness of the cast crown before and after wear testing and the wear of the cast crown. [J Adv Prosthodont 2021;13:127-35]

KEYWORDS
Dental alloys; Hardness; Wear; Zirconia

INTRODUCTION

The use of ceramic restorations continues to increase due to the increasing demands for esthetics.[1,2] However, due to the inherent good mechanical properties and reliability of dental alloys, various dental alloys are still used for the manufacturing of dental prostheses.[3] The main factors to consider

Corresponding author
Chan-Jin Park
Department of Prosthodontics and Research Institute of Oral Science College of Dentistry, Gangneung-Wonju National University
7 Jukheon-gil, Gangneung-si, Gangwon-do 25457, Republic of Korea
Tel +82336403153
E-mail doctorcj@gwnu.ac.kr

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when selecting an alloy include cost, biocompatibility, and physical properties.[4,5] Among dental alloys, cobalt-chromium (Co-Cr) and nickel-chromium (Ni-Cr) alloys have been traditionally used as materials for prosthetic restorations due to their relatively low manufacturing cost and excellent mechanical properties compared to those of gold alloys.[6-8] Gold alloys have been used for a long time because of their advantages, including biocompatibility, durability, and less wear of an opposing natural tooth.[9] It is believed that these dental alloys will be constantly used in the future due to their numerous advantages.

The use of monolithic zirconia restorations has increased in recent years. In particular, conventional dental zirconia, 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP), has been applied to the posterior zone due to its high fracture resistance, and successful results have been reported.[2,10] As a result, dental alloys and monolithic zirconia tend to oppose each other and to function in the oral cavity. Therefore, it is necessary to focus on the stability of these two different types of materials in prolonged mastication.

Normal tooth wear occurring in the oral cavity is recognized as a physiological change due to aging. It is affected by the type and properties of the material of the opposing restoration, surface roughness, and the nature and direction of the applied force.[11,12] Excessive wear can lead to occlusal disharmony and decreased masticatory function, a loss of the vertical dimension of occlusion, pathologic changes in the temporomandibular joint and masticatory muscles, and esthetic impairment.[13] Therefore, studying the wear of restorative materials that can affect long-term stability is required to select appropriate materials for fabricating dental prostheses. It is considered important to find and evaluate the factors that affect the wear of restorative materials.

Unlike conventional feldspathic porcelain and glass ceramics, dental zirconia has a polycrystalline structure that does not contain a glass matrix.[14] In addition, since zirconia has mechanical properties of high fracture toughness and surface hardness,[15] many studies on the wear of enamel and various restorative materials against zirconia have been conducted.[2,15-21] Among dental restorative materials, studies[16,17] on the wear of metal alloys against zirconia are sparse. In addition, the possibility of an excessive wear of dental alloys by zirconia was suggested.[22] For these reasons, we conducted an *in vitro* study[23] on the wear of three dental alloys against 3Y-TZP monolithic zirconia. It was shown that the wear of metal alloy differs according to the alloy type (the antagonist specimen) and the surface roughness of zirconia (the substrate specimen). Moreover, the wear of metal alloys tended to be lower as the hardness of the metal alloy at the ingot state, which is one of the different factors among alloy materials, was increased.

Although other previous studies[24,25] regarding the wear resistance of dental alloys reported that this parameter was not related to the hardness of metal alloys, these studies focused on materials other than zirconia. In addition, in a study[17] on the wear between titanium and zirconia, the difference in hardness was mentioned as the main cause of the difference in wear resistance between the two materials. Therefore, it is necessary to evaluate the relationship between the hardness and the wear resistance of dental alloys against zirconia.

Regarding the hardness of the metal alloy, we presume that the hardness of the cast crown may differ from that of the ingot due to the process used to fabricate dental prostheses.[23] In addition, considering studies that reported changes in the surface hardness of dental alloys after abrasion testing,[5,8] it is thought that the surface hardness of the cast crown will also change before and after wear testing.

Therefore, we assessed changes in surface hardness according to the alloy condition by measuring the surface hardness of the ingot (which did not undergo wear testing) and of the cast crown before and after wear testing. Furthermore, potential correlations between the surface hardness of the cast crown before and after wear testing measured in this study and the wear of the dental alloy measured in our previous study[23] was evaluated.

The first null hypothesis was that there would be no differences in hardness depending on the condition and type of the metal alloy. The second null hypothesis was that hardness of the cast crowns before and after wear testing would not be correlated to the wear of the cast crown.

MATERIALS AND METHODS

The Vickers surface microhardness of the three investigated dental alloys according to metal alloy conditions was measured. Metal alloys evaluated in this study are listed in Table 1. The evaluated dental alloys included a Co-Cr alloy, a low noble gold alloy, and a Ni-Cr alloy; they were termed C, G, and N, respectively. The conditions of the metal alloys included ingot, cast crown before wear testing, and cast crown after wear testing; these were termed I, B, and A, respectively. The ingot was the control group. The cast crown before and after wear testing were the experimental groups. A total of nine groups (CI, CB, CA, GI, GB, GA, NI, NB, and NA) were set using the combinations of material types and conditions. The number of specimens in each group was ten.

The process of fabricating cast crowns from each metal alloy, the condition of wear testing, and the method of measuring the volumetric wear of the cast crowns in our previous study[23] were as follows. A polymethyl methacrylate (PMMA) pattern that resembles the maxillary premolar was manufactured. Unlike the anatomical contours of natural teeth, the four axial walls of this PMMA pattern are flat surfaces. In addition, each of the four axial walls formed an angle of 90° to the adjacent axial walls and was parallel to the long axis direction of the crown. The reason for the difference in the shape and arrangement of the axial wall from the anatomical contour of the natural tooth was to make it possible to measure the hardness on the axial wall and the worn surface. According to the manufacturer's instructions for each metal alloy, the PMMA pattern was invested, cast, finished, and polished to produce Co-Cr, gold, and Ni-Cr alloy cast crowns (Fig. 1). 3Y-TZP powder (Zpex, Tosoh Corp., Tokyo, Japan) was pressure-molded, air-sintered, and polished to produce cylindrical monolithic zirconia specimens with Ra < 0.1 μm. Wear testing was performed by opposing the manufactured cast crown and smooth-surface monolithic zirconia specimen. Wear testing was performed in distilled water using a chewing simulator (CS-4.8, SD Mechatronik GmbH, Feldkirchen-Westerham, Germany). Specimens were subjected to heat circulation between 5°C and 55°C, horizontal movement in the range of 1 mm, and a force of 49 N. The frequency of a chewing cycle was 1.2 Hz. Wear testing was conducted with 240,000 chewing cycles, which is equivalent to approximately 1 year of clinical service. A 3D scanner consisting of a surveyor (DS-2030, Laser Design Inc., Minneapolis, MN, USA) and a laser probe (RPS-120, Laser Design Inc., Minneapolis, MN, USA) was used to 3D scan the cast crown specimens before and after wear testing. Each volume of the cast crown specimens before and after wear testing was measured by converting the scanned data using an inspection program (Geomagic Control 2015, 3D Systems Corp., Rock Hill, SC, USA). The wear volume loss (in mm^3) of the cast crown specimens was then obtained by calculating the dif-

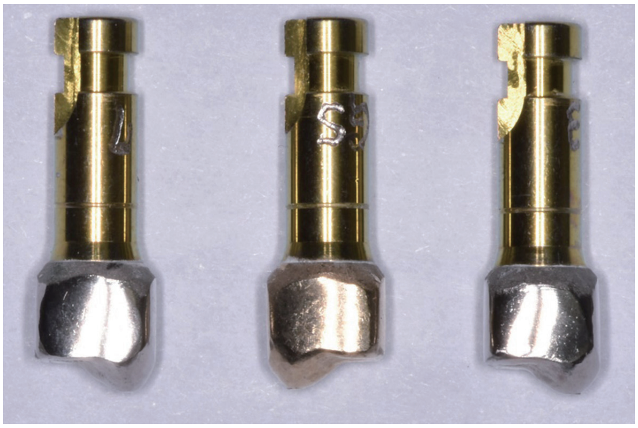

Fig. 1. Cast crown specimens (from left to right): Co-Cr, gold, and Ni-Cr alloys.

Table 1. Metals used in this study

Metal	Product	Composition (mass %)	Manufacturer
Co-Cr alloy	BC-Cast R	65 Co, 28 Cr, 5.5 Mo	Bukwang Inc., Busan, Korea
Gold alloy	DM 46	46 Au, 40 Ag, 4.9 Pd	Woori Dongmyung Co., Ltd., Seoul, Korea
Ni-Cr alloy	Argeloy N.P. star	61.2 Ni, 25.8 Cr, 11 Mo, 1.5 Si	Argen Corp., San Diego, CA, USA

ference in volume before and after wear testing.

The surface hardness of the ingot specimen was measured for each of the Co-Cr, gold, and Ni-Cr alloys used to fabricate the cast crown specimen. The surface hardness of each cast crown specimen was measured on an arbitrarily selected axial wall among the four axial walls of the cast crown, which did not undergo wear after wear testing; this approach was aimed at measuring the surface hardness of the cast crown before wear testing. Surface hardness was measured on the worn surface located at the cusp tip of the cast crown to measure the surface hardness of the cast crown after wear testing (Fig. 2). All hardness measurements were performed without changing the surface of the specimens. When measuring the hardness of the cast crown specimens before and after wear testing, the cast crown specimen was fixed using two axial walls adjacent to the axial wall where the hardness was measured. The hardness of the cast crown specimen before wear testing was measured to evaluate the effect of the cast crown manufacturing process using the casting method on the hardness of the metal alloy. The hardness of the cast crown specimen after wear testing was measured to evaluate the effect of wear testing on the hardness of the metal alloy. The Vickers hardness test was performed according to the ASTM E384-17 standard.[26] Vickers microhardness measurements were performed (measurement conditions: load, 500 g; load time, 4 s; dwell time, 15 s; no load time, 4 s; approach speed, 60 µm/s) using a hardness tester (HM-200, Mitutoyo Corp., Kawasaki, Japan). Hardness was measured on the flat surface of the specimen. After five measurements for each specimen, the average of the five Vickers hardness values was used as the result value (HV; Fig. 3).

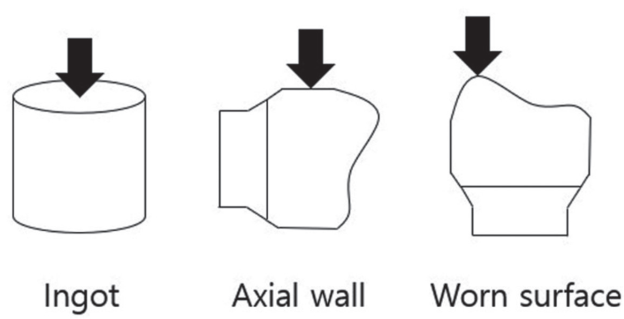

Fig. 2. Schematic representation of hardness measurements. The direction of each black arrow indicates the direction of the load when measuring the hardness. The tip of the arrow indicates the measurement position.

Statistical software (v24.0, IBM SPSS Statistics, IBM Corp., Armonk, NY, USA) was used for data analyses ($\alpha = 0.05$). A two-way analysis of variance (ANOVA) was performed to analyze the main effects of the type and condition of the metal alloy on the surface hardness (HV). There was a statistically significant interaction between two factors (type and condition). Therefore, one-way ANOVA was conducted to compare all subgroups. The Scheffé test was performed for pairwise comparisons among the mean values. Correlations between the wear measured in our previous study[23] and the surface hardness of each experimental group (axial wall of the cast crown and worn surface of the cast crown) were evaluated using the Pearson's correlation coefficient.

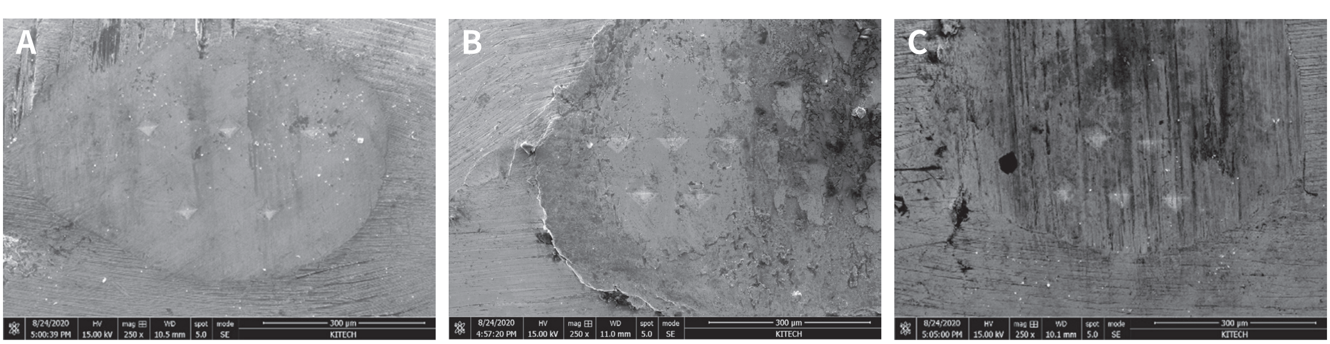

Fig. 3. Scanning electron micrographs of Vickers hardness test indentations on worn surfaces (original magnification ×250): (A) Co-Cr alloy, (B) gold alloy, and (C) Ni-Cr alloy.

RESULTS

The effects of alloy type and alloy condition on the Vickers microhardness were statistically significant (Table 2). A comparison of the hardness according to the type of metal alloy showed that the hardness of the Co-Cr alloy was the highest and decreased in the following order: Co-Cr, Ni-Cr, and gold alloys ($P < .01$). A comparison of hardness according to the condition of the metal alloy showed that the hardness of the ingot was the highest and decreased significantly in the following order: ingot, cast crown after wear testing, and cast crown before wear testing ($P < .01$). One-way ANOVA indicated statistically significant differences in the mean surface hardness of the tested groups (df = 8; F = 540.294; $P < .01$). The mean Vickers surface microhardness values of the tested groups are shown in Table 3. There were no significant differences between the hardness values of the GB and GA groups and those of the CB and NI groups ($P > .05$). The surface hardness of the cast crown before wear testing decreased when compared to that of the ingot ($P < .05$) for all Co-Cr, gold, and Ni-Cr alloys. There were no significant differences in hardness before and after wear testing for the gold alloy ($P > .05$); however, the hardness of the cast crown after wear testing was higher than that of the cast crown before wear testing for the Ni-Cr and Co-Cr alloys ($P < .05$).

The hardness and wear of individual cast crown specimens of the three metal alloys are shown in Fig. 4. There was no correlation between the Vickers hardness values of the CB, CA, GB, GA, NB, and NA groups and the wear of each metal alloy ($P > .05$). In other words, the hardness of the cast crown before and after wear testing was not correlated with the wear for all three metal alloys that opposed the smooth-surface zirconia.

DISCUSSION

According to the results of this study, the null hypothesis that the surface hardness of metal alloys would be unaffected by the type and condition of the metal alloys was rejected. Contrary to assumptions, the surface hardness of the metal alloys was significantly affected by the type and condition of the metal alloys.

Table 2. Results of the two-way ANOVA for Vickers microhardness of the tested groups

Source	Type III Sum of Squares	df	Mean Square	F	*P*
Type	1489309.019	2	744654.509	1925.776	< .001
Condition	175493.859	2	87746.929	226.925	< .001
Type × Condition	6555.800	4	1638.950	4.239	.004
Error	31320.895	81	386.678		
Total	14743025.340	90			
Corrected Total	1702679.572	89			

Table 3. Mean Vickers surface microhardness ± standard deviation in tested groups (HV)

Type	Condition		
	I	B	A
C	596.3 ± 14.0^{a}	473.3 ± 14.1^{b}	533.5 ± 38.1^{c}
G	266.5 ± 3.1^{d}	178.8 ± 15.9^{e}	213.2 ± 18.4^{e}
N	437.9 ± 7.2^{b}	324.4 ± 19.7^{f}	401.8 ± 24.4^{g}

One-way ANOVA with Scheffé test for multiple comparisons used. Values with the same superscript letter are not statistically different ($P > .05$).
C, Co-Cr alloy; G, gold alloy; N, Ni-Cr alloy; I, ingot; B, before wear testing; A, after wear testing.

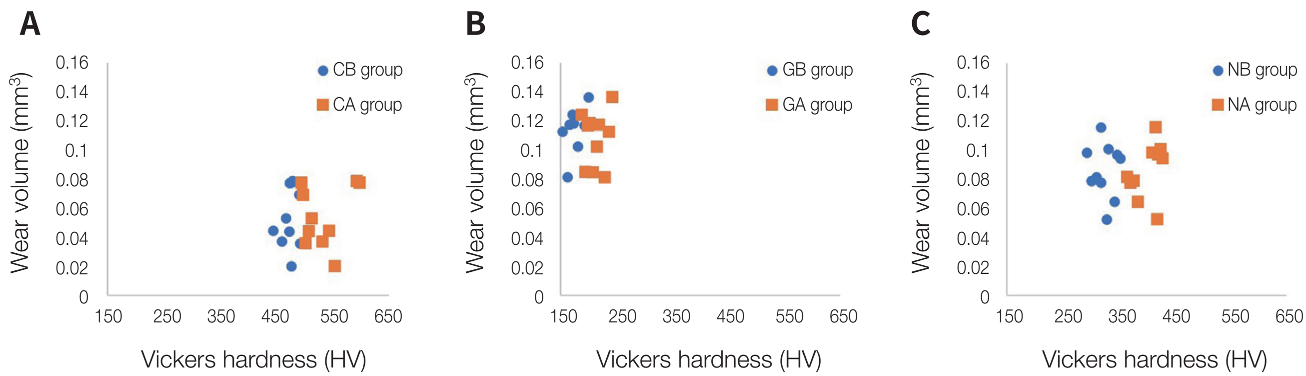

Fig. 4. Scatter plots relating the hardness (x-axis) and wear (y-axis) of individual cast crown specimens of three metal alloys: (A) Co-Cr alloy, (B) gold alloy, and (C) Ni-Cr alloy.

However, we failed to reject the other null hypothesis that the surface hardness of the cast crowns before and after wear testing were not correlated with wear; i.e., the surface hardness of the cast crown before and after wear testing was not correlated with the wear of the cast crown.

It is known that the hardness of manufactured prostheses is affected by various factors, regardless of the metal alloy used for manufacturing. It has been reported that the hardness of a prosthesis varies according to the fabrication method, such as casting, milling, additive manufacturing (depending on the mold used, even if the same casting method is used), and the cooling rate after casting.[7,27] Although changes in grain size are not related to changes in yield strength and hardness in the case of gold alloys, it has been reported that mechanical strength and surface hardness decrease when the grain size increases during the metal casting process.[7,28,29] According to the results of this study, the hardness of the cast crown before wear testing was significantly lower than that of the ingot for all three metal alloys ($P < .01$); decreases in hardness of the cast crown before wear testing compared to that of the ingot were 20.6%, 32.9%, and 25.9% for the Co-Cr, gold, and Ni-Cr alloys, respectively. The cast crown employed in this study was manufactured using a casting method commonly used by dental laboratories. Therefore, when fabricating cast crowns for patients, a decrease in hardness of each metal alloy may occur at a level similar to that mentioned previously, when compared to ingots. Though hardness is not an intrinsic property of a metal alloy, it can be a factor that predicts yield strength.[4] Therefore, it is believed that clinicians need to be aware of this decrease in hardness to predict appropriate mechanical properties.

In this study, surface hardness of the cast crown after wear testing was significantly greater than that of the cast crown before wear testing in the case of Co-Cr and Ni-Cr alloys ($P < .05$). The changes in the worn surface hardness of a metal alloy after wear testing using a chewing simulator have not been assessed in previous studies. However, the cause of the increase in hardness was mentioned in studies that reported an increase in hardness of the worn surface of metal alloys after abrasion testing, which is considered to be somewhat similar to wear testing. Nogués *et al.*[5] reported that plastic deformation occurred on the surface of the material during metal abrasion, which led to a high density of dislocation on the surface of the metal, thereby increasing surface microhardness. Bezzon *et al.*[8] stated that the surface of the metal underwent strain hardening as a cause of an increase in the hardness of the metal after the abrasion test. We believe that an additional study evaluating the microstructure of the worn metal surface is required to determine the cause of the increased hardness of cast crowns after wear testing (compared to cast crowns before wear testing observed in this study). In a previous study,[23] the wear mechanism of Co-Cr and Ni-Cr alloys against smooth-surface zirconia was assumed to be abrasive wear, while the wear mechanism of the gold alloy against smooth-surface zirconia was assumed to be delamination wear. In this study, unlike for other metal alloys (Ni-Cr and Co-Cr), there were no significant differences in the gold alloy surface hardness before and after wear testing ($P > .05$). We presume that the difference in the wear mechanism between gold alloys and other metal alloys is one of the possible causes of this result. However, additional studies assessing wear mechanisms (including wear particle analysis) are required to confirm this hypothesis.

The hardness of the cast crown before and after wear testing was measured in this study based on the study by Bezzon *et al*.,[8] which evaluated the assumption that there might be a relationship between the changed surface hardness and abrasion resistance of the metal alloy after abrasion testing. We assessed the correlation between the wear measured in our previous study[23] and the hardness of the cast crown before and after wear testing in this study. Unexpectedly, there was no correlation between the hardness of the cast crown before and after wear testing and wear ($P > .05$). Chan *et al*.[24] and Faria *et al*.[25] reported that the wear resistances of dental alloys exhibited higher correlations with their microstructure and alloy phases than microhardness. In a previous study,[23] the wear of three metal alloys opposing smooth-surface monolithic zirconia after wear testing was observed to increase in the following order: Co-Cr, Ni-Cr, and gold alloys, and the mean wear volume of these alloys was 0.054 ± 0.021 mm^3, 0.086 ± 0.019 mm^3, 0.108 ± 0.019 mm^3, respectively. The wear of the Ni-Cr alloy did not differ significantly from that of the Co-Cr and gold alloys, while that of the gold alloy differed significantly from that of the Co-Cr alloy. Comparing the results of our previous study[23] to those obtained in this study, the following can be concluded: although there was a significant difference in hardness among metal alloys, the wear of the relatively softer gold alloy did not differ from that of the Ni-Cr alloy with better mechanical properties. The clinical interpretation of this result is that a gold alloy (which, as a material for metal alloy restoration opposing meticulously polished monolithic zirconia restorations, is expected to undergo greater wear due to its weaker properties) can be as stable as a Ni-Cr alloy in terms of wear.

We demonstrated in this study that there was no correlation between the hardness and wear resistance of dental alloys against 3Y-TZP monolithic zirconia. Therefore, additional studies that evaluate other factors such as the coefficient of friction (which is thought to be related to the wear resistance of dental alloys) are required. Since the results of this study were obtained through the 2-body wear test, it is thought that different results could have been obtained if the 3-body wear test with an abrasive medium was performed.[2] In addition, this study is considered to be limited in that it did not completely reproduce the actual intraoral environment, in which 2-body wear and 3-body wear occur in combination.[30] Therefore, it is considered necessary to evaluate wear and the change of physical properties of dental alloy against monolithic zirconia restorations through clinical studies.

CONCLUSION

Although there was a significant difference in the surface hardness values among the three dental alloys (Co-Cr, gold, and Ni-Cr alloys) under the same conditions, there was no correlation between the surface hardness of cast crowns before and after wear testing and the wear of cast crowns against smooth-surface monolithic zirconia. Within the limitations of this study, it is suggested that the surface hardness of metal alloys, which is one of the factors that can be considered when selecting a metal alloy for the fabrication of dental prostheses opposing monolithic zirconia restorations, cannot predict the wear resistance of metal alloys.

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