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Comparative Evaluation of Physical and Mechanical Properties of Different Brands of Primary Molar Stainless-Steel Crowns: An In Vitro Study

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Abstract

BACKGROUND: There is some cases of perforation and undesirable properties of some primary molars stainless steel crowns.

AIM: The aim of this study was to compare the physical and mechanical properties of different commercial brands of these crowns.

METHODS: In an in vitro study, 10 stainless steel tooth crowns of the second primary mandibular molars size 6 of 4 different commercial brands (a total of 280 crowns) were evaluated. These crowns were included KTR Pre-trimmed and Crimped Nichro Stainless Steel Primary Molar Crowns (KTR, China); 3M Stainless Steel Primary Molar Crowns (ESPE, St paul; USA); NuSmile SSC Pre-contoured (Inc, Houstone, TX; USA) and Kids crown (Shinghung, Seoul; Korea). Corrosion and galvanic corrosion, wear, microhardness, compressive strength, fatigue strength of crowns and weight percent of elements were investigated.

RESULTS: The highest rate of microhardness, compressive and Fatigue strength of the crowns were made by Nu Smile > 3M > Kids Crown > KTR respectively. The highest rate of corrosion potential in corrosion and Galvanic corrosion tests was in KTR > Kids crowns > 3M > Nu smile respectively. The order of crown wear was KTR > Kids Crown > 3M > Nu Smile respectively. The highest amount of nickel element was found in the Nu Smile crown and the highest amount of chrome in the 3M crown with a significant difference with others ($p < 0.001$). The KTR and Kids crowns lacked molybdenum.

CONCLUSION: The results showed that Nu Smile crown has better physical and mechanical properties than other evaluated crowns in this study.

Introduction

One of the most common problems in pediatric dentistry is the early childhood caries of deciduous teeth that affects infants and young children. These caries cause structural destruction of the teeth associated with nutritional problem and an unbearable appearance for child [1], [2]. The most common way to repair and maintain the remaining tissue of severely damaged teeth is using stainless steel crowns (SSC) and covering the damaged crowns of the teeth [3], [4], [5], [6]. The superiority of SSCs has been reported in various studies due to better retention and less recurrent caries compared to posterior composite and class 2 Amalgam restorations [6], [7]. Beside the advantages of the SSCs in restoring children teeth, such as easy technique, short duration procedure, the protection of the remaining tissue of the tooth, there are some limitations in the use of these crowns due to inadequate fitness of the edges of the crown with tooth and inadequate retention in severely damaged teeth, especially on the buccal and lingual surfaces [8], [9]. However, these crowns have no serious damage on adjacent gingiva and bones, and the reported rate of satisfaction of these crowns is high [10]. Due to the protective effect for future caries, caused by the full coverage of the teeth and the durability of these crowns, use of SSC should be strongly recommended in children who undergo general anesthesia [11], [12]. The term stainless steel is used for alloys of iron and carbon that contains chromium, nickel, manganese and possibly other metals to improve their properties and provide stainless quality to steel. Chrome is the main element that helps to prevent from the oxidation reaction [13]. The stainless steel is strong, resilient and malleable. The thickness of the metal is 0.2 mm in SSCs and does not require an excess thickness to obtain clinical acceptability [14].

In pediatric dentistry, metals and alloys are used to make space maintainers, SSCs and brackets. Despite of increasing daily use of SSCs, there is little information about their corrosion and release of metals, especially nickel and chromium. The electrochemical corrosion phenomenon occurs in the oral cavity, resulting in degradation of the alloy as a result of enzyme activity, microbes, heat and chewing. Additionally, in such environment, corrosion causes release of metals [15], [16]. Human saliva has a heterogeneous composition that contains proteins, electrolytes, hormones and other components that are sometimes present in the blood. The variable pH, the temperature of the oral cavity and the ingested foods provide an offensive environment for metal appliances in the mouth. Many studies have shown that stainless steel alloys in the vicinity of saliva exhibit corrosion and alteration of surface properties, and thus their biocompatibility is reduced and release metallic ions, which can be a causative factor of fatigue. Metal ions that are potentially released from the stainless steel alloy include Cr, Fe, and Ni [17]. The use of SSC for deciduous teeth has increased the concern about the release of heavy metals into the oral cavity due to corrosion. Among the released metals, nickel is more common, which can lead to sensitivity reaction and contact allergies [18]. There are reports that the stainless steel alloys can lead to DNA damage. Even non-toxic concentrations of nickel can induce changes in DNA [19], [20]. Additionally, sensitivity to nickel around the oral cavity is another common problem [21], [22].

The term of hardness is referred to resistant to penetration or permanent indentation of the surface. Hardness is effective on ease of cutting, finishing and polishing of material, as well as scratch resistance during servicing [23]. The term of wear can easily be defined as the process of removing of material from the surface when two surfaces are rubbed together. The occlusal surface of the SSCs can show a lot of wear, and even can be pierced due to prolonged use in the mouth or the high chewing forces in children with bruxism. Occlusal wear is the main cause of occlusal surface perforation and SSC failure [24]. The Fatigue process in metals occurs when the metal undergoes repeated or swinging stress that results in breaking or deformity of it. The compressive strength in metals is the highest pressure that a metal tolerates before deformation. According to various studies, the average chewing force in children aged 5 to 10 is 375 N. Although the SSCs are very durable restorative materials for children's deciduous teeth, they can be damaged and deformed in long-term clinical use, if they undergo forces higher than average chewing force [25]. One of the problems that may occur for the SSCs is galvanic corrosion following contact with dental amalgam, which is due to presence of metal in both of them. The presence of two different metals in the electrolyte solution creates a galvanic connection. The electrolyte solution helps ion migration and corrosion occurs immediately. The contact surface of metals in this type of corrosion is very important. The weaker metal (anode) is corroded in this process [26].

Since SSCs are placed in the oral environment for several years and affected by physical and chemical factors such as saliva secretion, chewing, brushing, acidic beverages, abrasion and composition of biofilms, their surface changes. The changing of surface area, increases bacterial adhesion and surface roughness [27]. As a few cases of perforation have been seen in crowns, it was attempted to test the physical and mechanical properties of some brands of SSCs in the market. Given that in some time periods some of the known brands of these crowns are not available on the market and because of the price difference of these crowns, the aim of this study was to compare the physical and mechanical properties of different commercial brands of these crowns.

Methods

This in vitro study was carried out at the Dental Materials Research Center of the Babol University of Medical Sciences, Faculty of Chemistry of the Mazandaran University and the Razi Metallurgy Research Center of Karaj in 2018. Ten (10) stainless steel crowns of the second primary mandibular molar size 6 of 4 different commercial brands (a total of 280 crowns) were evaluated in this study. These crowns included KTR Pre-trimmed and Crimped Nichro Stainless Steel Primary Molar Crowns (KTR؛ China); 3M Stainless Steel Primary Molar Crowns (ESPE, St paul; USA); NuSmile SSC Pre-contoured (Inc, Houstone, TX; USA) and Kids crown (Shinghung؛ Seoul; Korea).

Method of preparing the specimens

To prepare specimens for each of the tests, all the crowns were filled with glass ionomer cement type 1 (GC, Japan) and mounted on a base of epoxy resin dye. To perform wear and hardness tests, the specimens were horizontally mounted with the mesial surface upward to provide the best possible smooth level for testing. For other studies the specimens were mounted vertically. To test the Fatigue strength of the specimens, the specimens were mounted into the chewing simulating device by Acryl. To investigate galvanic corrosion, dental crowns were placed adjacent to the Amalgam alloy (GS-80; SDI USA).

Assessment of corrosion and galvanic corrosion

These two experiments were carried out in a 3-electrode glass cell, which included the working electrode (desired crown), a counter electrode with a platinum rod and an Ag/AgCl/KCl reference electrode. The dental crowns are preserved in a Ringer's solution [28], [29] for one month. The corrosion rate of the specimens was investigated by Tafel plot analysis. The anode, or the dental electrode, was connected to a potentiostat/galvanostat (Origalys Company, France) by a copper wire. The software of the device recorded the flow. Linear sweep voltammetry (LSV) was used to record the current-potential flow curve. The two parameters of corrosion including potential (Ecorr) and current (icorr) can be obtained from the Tafel curve, which is performed by extending the cathodic and anodic branches (Extrapolation).

Wear assessment

A total of 10 stainless steel crowns of each brand were studied by an abrasive machine PEDEBE1 made by Alaghemand et al., [30]. The specimens were first weighed by an electronic scale and after placement on the abrasion machine, they were abrased at 5000, 10000, 20000, 40000, 80000 and 120000 under a load of 20 N, respectively. At the end of each abrasing period, the specimens were carefully evacuated from water and the wear rate at the mesial surface of the crowns was examined. Finally, the specimens were weighted again and their weight difference was calculated.

Assessment of Microhardness

The total of 10 stainless steel crowns from each brand was placed on a Vickers microhardness Tester (Koopa pazhoohesh model MH3, IRAN) under a vertical load of 200 g for 15 seconds. The crowns were placed horizontally to provide the best possible smooth level for the indentor. After placing the specimen under the microscope, the effect of indentor on the specimen was measured. After applying the force, the created effect was measured with a magnification of × 20. Given the diameter and depth of the effect, the hardness number of the specimen was calculated by the machine. For each specimen, the hardness was measured at 3 points at the mesial area and the average was reported.

Assessment of the Compressive Strength

For assessment of compressive strength, the Epoxy resin dye was used. For reparing 40 epoxy specimens, the SSCs were placed into a silicon mold. After filling the inside of the crowns with a glass ionomer cement type 1, an epoxy stand in dimensions of 30 × 20 × 10 × 10mm was made. Then, the epoxy dye was inserted into the metal stand with the sample size and the specimens were installed in the universal testing machine for force application. Compressive force with the speed of 1 mm/min was applied by a ball with diameter of 4 mm to the central fossa of the specimens to record the deformity and power drop by the machine.

Assessment of Fatigue Strength

For this test, 10 stainless steel crowns in each brand were placed within the chewing simulating machine (FD Mechatronic Company, UK). At first, the specimens were mounted by acrylic inside the mold of the device and were subjected to a vertical force of 250 N, with a cycle equal to 500,000 rounds (equivalent to 6 months of chewing). After completing the required cycles, the specimens were prepared for the fracture test. The vertical acceleratory force increasing from to 0 to 1000 N at a speed of 1 mm/min was applied on the specimens. The force was increased to the level that the shape of specimens deformed and the maximum force for creating deformity was obtained.

EDAX Assessment

EDAX is an analytical method used for analysis of structural or chemical characteristic of a specimen. Ten (10) stainless steel crowns from each brand were used to determine the weight percent of Ni, Cr and Fe metals and other elements in the crowns. The investigation was performed by analysis of Energy Dispersive X-ray Spectroscopy and scanning electron microscope (SEM) and the images were taken. All analyses were made at the central area of the occlusal surface of the crowns.

Statistical analysis

Data were analyzed using SPSS version 23 software, T-test, ANOVA, Mann-Whitney and Kruskal-Wallis tests. $P < 0.05$ was considered significant.

Results

The Mean ± SD of compressive strength, fatigue strength and hardness related to the four types of crowns have shown in Table 1. There were significant differences in Mean ± SD among the four groups ($p < 0.05$). In terms of microhardness, the highest degree of hardness was related to the Nu Smile crown and there was a significant difference between Nu Smile and the other crowns. About compressive strength, the least amount was belonged to the KTR and there was a significant difference between KTR and the other crowns. In terms of fatigue strength there was no significant difference between Nu Smile and 3M, but Nu Smile and 3M had a significant difference with KTR and Kids crowns.

Table 1: Compressive Strength, Fatigue strength and Microhardness of the studied crowns

	KTR (n = 10) Mean ± SD	Kids crown (n = 10) Mean ± SD	3M (n = 10) Mean ± SD	Nu Smile (n = 10) Mean ± SD	P-value
Micro-hardness (VHN)	284.48 ± 26.22[a]	284.96 ± 52.09[a]	278.05 ± 23.87[a]	321.34 ± 36.52[b]	0.047
Compressive Strength (MPa)	10.82 ± 1.80[b]	13.31 ± 2.65[a]	14.68 ± 2.62[a]	15.20 ± 2.32[a]	0.001
Fatigue Strength (MPa)	30.53 ± 7.17[a]	31.20 ± 6.98[a]	71.20 ± 22.16[b]	81.96 ± 7.54[b]	0.001

Similar letters mean no significant difference between groups in each level.

The Mean ± SD of the weight percent of the constituent elements of the crowns have shown in Table 2. There was a significant difference in weight percent among the groups ($p < 0.05$). In Nu Smile crown, aluminum was significantly less than other crowns. For iron element, there was a significant difference between KTR with Nu Smile and 3M. The highest weight percentage of chromium and manganese was seen in 3M crown. There was a significant difference in chromium element between all the crowns and the highest amount was observed in 3M crown. The weight percentage of nickel and silicon in Nu Smile was the highest. In the nickel element, Nu Smile had a significant difference with the other crowns. There was no molybdenum element in the Kids Crown and KTR crowns, but this element was observed in the 3M and Nu Smile crowns. There was a significant difference between 3M and Nu Smile crowns for molybdenum element.

Table 2: The Mean ± SD of the elements present in the studied crowns based on the weight percent of the elements

	KTR (n = 10) Mean ± SD	Kids crown (n = 10) Mean ± SD	3M (n = 10) Mean ± SD	Nu Smile (n = 10) Mean ± SD	P-value
Aluminium	2.002 ± 0.35[b]	1.74 ± 0.67[b]	1.7 ± 0.62[b]	0.49 ± 0.12[a]	< 0.001
Chromium	16.47 ± 0.23[a]	17.22 ± 0.09[c]	17.69 ± 0.19[b]	15.85 ± 0.2[d]	< 0.001
Manganese	1.62 ± 0.06[a]	1.9 ± 0.28[b]	2.03 ± 0.26[b]	1.57 ± 0.12[a]	< 0.001
Iron	70.12 ± 1.03[c]	69.94 ± 0.85[bc]	68.80 ± 0.81[a]	69.15 ± 0.37[ab]	0.002
Nickel	8.66 ± 0.42[a]	8.71 ± 0.7[a]	8.59 ± 0.28[a]	9.76 ± 0.79[b]	< 0.001
Silicon	0.49 ± 0.12[a]	0.53 ± 0.1[ab]	0.62 ± 0.16[ab]	0.64 ± 0.58[b]	0.013
Molybdenum	-	-	0.78 ± 0.11[b]	2.37 ± 0.1[a]	< 0.001

Similar letters mean no significant difference between groups in each level.

The amount of corrosion potential (Ecorr) and logarithmic current density (icorr) of the four types of crowns included Nu Smile, kids crown, KTR and 3M has shown in the Figure 1 and Figure 2. After crossing each of the curves with the axes, the rate of corrosion potential of each crown was measured. The larger the Ecorr value (the more positive), was indicated the more resistance to corrosion and the less corrosion potential.

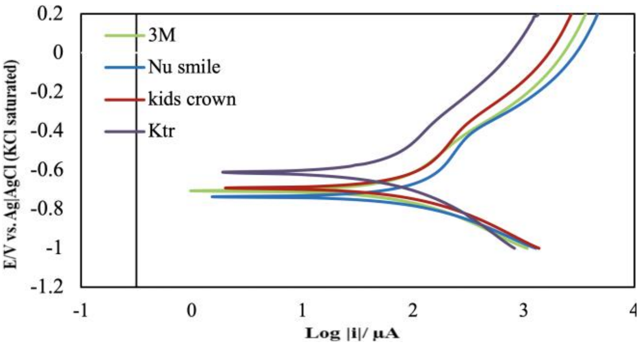

Figure 1: The corrosion of investigated crowns according to the logarithmic current density and the potential difference with the reference electrode Ag/AgCl/KCl

The Ecorr value of Nu Smile, 3M, Kids crown, and KTR related to corrosion test is -0.59, -0.65, -0.68, and -0.72, respectively. Regarding the numerical value reported by the curve, it can be concluded that the value of the corrosion is KTR > Kids crown > 3M > Nu Smile.

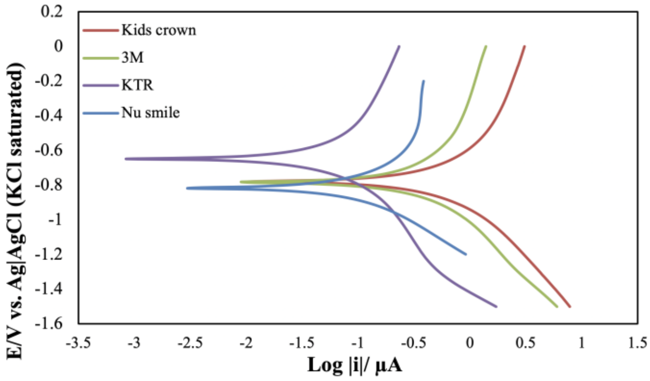

Figure 2: Galvanic corrosion of the studied crowns based on the logarithmic current density and the potential difference with the reference electrode Ag/AgCl/KCl

Ecorr value of Nu Smile, 3M, Kids crown, KTR for galvanic corrosion test was -0.67, -0.73, -0.78, and -0.82, volt respectively. Regarding to the numerical value reported by the curve, it can be concluded that in the galvanic corrosion test, the rate of corrosion potential was KTR > Kids crown > 3M > Nu Smile respectively.

The Mean ± SD of the wear test for each of the four types of crowns in different abrasion cycles of 5000, 10000, 20000, 40000, 80000 and 120000 were given in Table 3. There was a significant difference between the groups related to the wear test. The KTR crown had a significant statistical difference in the abrasive cycles of 5000, 10,000, and 120,000 with the other crowns and in the abrasion cycle of 20,000 with 3M and Nu Smile crowns. In abrasion cycles of 40000 and 80000, KTR had no significant difference with the other crowns. There was no significant difference between the Kids crown in the abrasive cycles of 5000, 10,000, and 120,000 with 3M and Nu Smile crowns, but a significant difference was found with

KTR. The Kids crown had no significant difference in abrasive cycles of 20,000 and 80,000 with the other crowns but a significant difference was seen in abrasive cycle of 40000 with 3M and Nu Smile, and no significant difference observed with KTR.

The 3M and Nu Smile crowns had no significant difference at any of the abrasion cycles. In KTR crown, of the total of 10 crowns, 4 were perforated in abrasive cycles of 120,000 and 80,000. In the 3M crown, from total of 10 crowns, 1 was perforated in abrasion cycle of 40,000. In the Nu Smile crown, of a total of 10 crowns, 1 crown was perforated in abrasion cycle of 120,000. In the Kids Crown, 3 of the total 10 crowns were perforated at 80,000 and 120,000 abrasive cycles.

Table3: Wear in the studied crowns based on the weigh difference in different abrasing cycles

Wear cycle	KTR Mean ± SD	Kids crown Mean ± SD	3M Mean ± SD	Nu Smile Mean ± SD	P Value
5000	0.00095 ± 0.00052[a]	0.0005 ± 0.00047[b]	0.00035 ± 0.00032[b]	0.00017 ± 0.00014[b]	0.001
10000	0.00091 ± 0.00065[a]	0.00036 ± 0.00029[b]	0.00018 ± 0.00006[b]	0.00014 ± 0.00019[b]	< 0.001
20000	0.00097 ± 0.00066[a]	0.0006 ± 0.0007[ab]	0.00031 ± 0.00043[b]	0.00014 ± 0.00017[b]	0.009
40000	0.00057 ± 0.00031[ab]	0.00097 ± 0.0007[a]	0.0004 ± 0.00067[b]	0.00013 ± 0.00011[b]	0.009
80000	0.0005 ± 0.00033[a]	0.00027 ± 0.00032[a]	0.00035 ± 0.00048[a]	0.00018 ± 0.00012[a]	0.324
120000	0.0007 ± 0.00032[a]	0.00016 ± 0.00015[b]	0.0003 ± 0.00022[b]	0.00015 ± 0.00011[b]	< 0.001

Similar letters mean no significant difference between groups in each level.

Discussion

According to the reports on perforation of stainless steel crowns and undesirable physical and mechanical properties in some of the commercial types of crowns, this study was designed to offer a durable crown. In this study, seven physical and mechanical properties included: microhardness, compressive strength, fatigue strength, wear, corrosion, Galvanic corrosion and EDAX were compared in four types of primary molars stainless steel crowns composed of Nu Smile, 3M, Kids Crown and KTR. The studied crowns had significant different physical and mechanical properties. In this study the highest corrosion potential was observed in KTR > Kids Crown > 3M > Nu Smile crowns respectively. In a study by Eliades et al., [31] resistance to corrosion is highly dependent on the chromium oxide layer as a passive layer. But in our study, Nu Smile crown, which had the lowest chromium content, had the lowest level of corrosion. According to Eliades et al., study [31], the passive layer can be formed by other metals such as iron, nickel, and molybdenum, in addition to chromium. This could justify less corrosion of Nu Smile crown in our study. Corrosion leads to surface roughness and the release of elements from metal or alloy. Releasing of elements can cause color changes of the adjacent soft tissue and development of allergic reactions in sensitive individuals [28]. If the alloy has a high corrosion resistance, the effects of corrosion and release of the elements from the alloy will be reduced.

Because corrosion resistance plays an important role in determining the possibility of using metal alloys as biological materials, in vitro evaluation of such parameters is useful. Although the results obtained from in vitro experiments cannot directly be used for predicting the behavior of the alloy in real oral conditions, it will be useful for comparison of the different alloys. A study by Ha et al., [32] was conducted to evaluate the effect of molybdenum on pitting corrosion resistance in stainless steel austenitic alloys. Their results showed that molybdenum was effective in improving the corrosion properties of stainless steel. Therefore, the low corrosion in Nu Smile and 3M crowns in this study may be related to present of molybdenum element. In the mouth, the crowns are immersed in the saliva, which acts as an electrolyte and cause corrosion. According to Eliades et al., [31] the acidic and chloride conditions may lead to the destruction of the chromium oxide layer. Acids can include plaque acids and acids in foods. In the present study, the highest nickel content was found in Nu Smile crown with an average of 9.76 ± 0.79 weight percent and the lowest found in 3M crown with an average of 8.59 ± 0.28 weight percent. Kids Crown and KTR were placed in the second and third rank. It has been shown that the release of metal ions is not related to the percentage of nickel in the alloy composition, but is largely dependent on the resistance to corrosion of the alloy during abrasion in the mouth. Nowadays, crowns containing 72% of nickel are replaced with SSCs containing 8-10% nickel, because of the several reports about the role of nickel ions in allergic, toxic or carcinogenic effects [15]. Children under general anesthesia for dental restorations may have up to 8 stainless steel crowns at a time in their mouth so the release of these ions becomes more important. Stainless steel alloy based on iron-chromium-nickel has favorite mechanical properties and suitable corrosion resistance. Although there is always a passive layer on the surface of the alloy, various ions can be released from the metal surface in the acidic environment of the mouth and causes a corrosion phenomenon. It has shown, the chromium element in the stainless steel alloys can form a thin, sticky layer of Cr_2O_3, which protects the underlying alloy against corrosion. Of course, the minimum chromium content should be 11% to form this protective layer [33], [34]. In the present study the weight percent of chromium in each of four crowns was higher than the minimum required for formation of protective layer.

Surface hardness is used to estimate the wear of restorative dental materials. It seems that excessive hardness typically results in more wear of the opposite tooth enamel and the hardness of the metal is associated with the wear of the opposite tooth enamel [35]. Although in the present study, the highest degree of hardness is observed in the Nu Smile crown, and the higher hardness can be a well characteristic of a crown, it can also cause the wear of the opposite tooth enamel especially in children with severe bruxism. Also, the highest compressive strength and fatigue strength of the crowns were obtained by Nu Smile > 3M > Kids Crown > KTR crowns, respectively. This difference can be due to the different composition of the alloy in these four crowns. In the present study, the resistance of four types of stainless steel crowns to abrasive forces was evaluated by measurement of the weight loss, and it was determined which crown undergoes faster abrasion against chewing forces and probably will be punctured. The wear rate of the crowns was observed from low to high in Nu Smile < 3M < Kids Crown < KTR crowns respectively. In this study, KTR crown had the highest wear and the least compressive and fatigue strengths.

Perforation of stainless steel crowns over the time is one of the problems that is seen in the clinic, and limited studies have been conducted to identify the causes of this phenomenon. Occlusion instability, premature contact and bruxism in children may be the causative factors in the perforation of stainless steel crowns [36]. Additionally, dental material wear is affected by the properties of the opposite restoration materials [24]. In this study, there was 4 perforated KTR crowns from a total of 10, which was more than Kids Crown perforations (3 crowns), Nu Smile (1crown), and 3M (1crown) in different abrasive cycles. The amounts of aluminum, silicon, chromium, manganese, iron, nickel and molybdenum were different in the four types of crowns mentioned here, which can cause different behaviors by the crowns. Among the seven studied properties of these crowns, KTR showed weaker physical and mechanical properties than the others. According to the EDAX analysis, the weight percent of aluminum and iron in the KTR was higher than the others and it lacked molybdenum. Maybe one of the reasons for the higher rates of corrosion, wear and perforation; and lower compressive strength, fatigue strength and microhardness of this crown is due to the different composition of the elements in the alloy. It seems that we cannot declare about the role of each element alone and the general characteristics are achieved due to the combination and ratio of the elements in each alloy. However we recommend the assessment of different ions release of stainless steel crowns in children saliva as a marker for their biological safety.

In conclusion, stainless steel crown with the highest amount of chrome (Nu Smile) has promising mechanical and physical properties to be used in pediatric dentistry.

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