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Finite element analysis in defining the optimal shape and safety factor of retentive clasp arms of a removable partial denture

Definisanje optimalnog oblika i faktora sigurnosti retencionih ručica kukica parcijalnih skeletiranih proteza metodom konačnih elemenata

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Abstract

Bacground/Aim. Retentive force of removable partial denture (RPD) directly depends on elastic force of stretched retentive clasp arms (RCAs). During deflection RCA must have even stress distribution. Safety factor is the concept which can be applied in estimating durability and functionality of RCAs. This study was based on analyzing properties of clasps designed by conventional clasp wax profiles and defining the optimal shapes of RCAs for stress distribution and safety factor aspects. **Methods.** Computer-aided-design (CAD) models of RCAs with simulated properties of materials used for fabrication of RPD cobalt-chromium-molybdenum (CoCrMo) alloy, commercially pure titanium (CPTi) and polyacetale were analyzed. **Results.** The research showed that geometrics of Rapid-flex profiles from the BIOS concept are defined for designing and modeling RCAs from CoCrMo alloys. I-Bar and Bonihard clasps made from CPTi might have the same design as CoCrMo clasp only by safety factor aspect, but it is obvious that CPTi are much more flexible, so their shape must be more massive. Polyacetale clasps should not be fabricated by BIOS concept for CoCrMo alloy. A proof for that is the low value of safety factor. **Conclusion.** The BIOS concept should be used only for RCAs made of CoCrMo alloy and different wax profiles should be used for fabricating clasps of other investigated materials. The contribution of this study may be the improvement of present systems for defining the clasps shapes made from CoCrMo alloys. The more significant application is the possibility of creating new concepts in defining shapes of RCA made from CPTi and polyacetale.

Key words:
denture, partial, removable; dental prosthesis design; dental clasps; dental alloys; titanium; polyacetylenes; safety.

Apstrakt

Uvod/Cilj. Retenciona sila parcijalne skeletirane proteze (PSP) direktno zavisi od elastične sile rastegnute kukice. Da bi uspešno obavile svoju ulogu, retencione ručice kukice (RRK) prilikom defleksije moraju imati što ravnomerniju raspodelu napona. Stepen sigurnosti je pojam koji se može primeniti u proceni trajnosti i funkcionalnosti RRK. Ciljevi ove studije bili su analiziranje svojstava kukica koje su urađene pomoću konvencionalnih voštanih profila za izradu RRK, kao i definisanje optimalnih oblika RRK sa aspekta raspodele napona i stepena sigurnosti. **Metode.** Analizirani su CAD (*computer aided design*) modeli RRK kojima su simulirana svojstva gradivnih materijala koji se koriste za izradu legura: CoCrMo, komercijalno čist titan (CPTi) i poliacetal. **Rezultati.** Rezultati su pokazali da je geometrija *Rapid-flex* profila, korišćenih u okviru BIOS, definisana za projektovanje i modeliranje RRK koje se izrađuju od legure (CoCrMo). I Bar i Bonihard kukice od CPTi mogu se uraditi po istom konceptu kao i legure CoCrMo sa aspekta stepena sigurnosti, međutim, titanijumske kukice bile su znatno elastičnije i stoga su morale biti masivnije. Kukice od poliacetala ne smeju se modelovati po BIOS konceptu za leguru CoCrMo. Dokaz za to je vrlo mali stepen sigurnosti. **Zaključak.** BIOS koncept može da se koristiti samo za RRK koje se izrađuju od legure CoCrMo. Za izradu kukica od ostalih ispitivanih materijala neophodni su drugačiji voštani profili. Doprinos studije predstavlja i poboljšavanje postojećih sistema za definisanje oblika RRK izrađenih od legura CoCrMo. Značajnija primena rezultata je i mogućnost stvaranja novih sistema za definisanje oblika RRK od CPTi i poliacetala.

Ključne reči:
zubna proteza, parcijalna, mobilna; zubni protetski modeli; zubne kukice; legure, stomatološke; titan; poliacetileni; bezbednost.

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Introduction

Removable partial dentures, present for several decades, even in the era of dental implants can be incorporated into modern dental trends. Prophylaxis, noninvasive nature, aesthetics, durability and functionality of dental restoration are the most important principles that are applied in modern methods of removable partial denture (RPD) planning and creation.

Prophylaxis is known as the first principle in planning RPD [1–5]. It refers to the reduction of the skeleton and avoiding the contact of solid parts of the prosthesis with free gingiva [6–12]. Methods of minimally invasive dentistry in the development of RPD, such as purposed fillings and selective grinding in the aim of defining proper guiding planes allows better therapeutic alternative to conventional dental procedures in order to week the same aesthetic and functional requirements with maximum preservation of healthy dental tissues [13, 14]. Aesthetic problems occur when the therapist is forced to plan retentive clasp arms (RCAs) in the visible sector. An attempt to improve the aesthetic effect by the reduction of RCA ends up with weakening of the retention force of RPD [15]. Retentive clasp arms of RPD are one of the factors that dictate the durability and function benefits of dentures [16]. It has been found that the durability of RCA depends on the material used as well as its design [17, 18]. Preference materials for RPD modeling include cobalt-chromium-molybdenum (CoCrMo) alloy, titanium and type IV gold alloys. Retentive clasp arms, made in the conventional way, out of CoCrMo alloy, from one-piece cast are not flexible enough to be able to respond the challenges in aesthetic areas. The aforementioned challenges imply that RCA can be placed in a position without being visually noticeable, or for the same reason, its length can be reduced. Elastic modulus for titanium alloy is approximately half the size of CoCrMo alloy, which enables the production of shorter retention elements and setting a clasp in deeper undercut area [19]. However, complicated titanium casting technology is one of the reasons for its poor commercial use.

Polyacetal copolymer can be an alternative to a cast metal alloy RCA [20, 21] and comparing with the metal alloy has a much better aesthetic due to the possibility of tooth and gingiva coloring and elastic properties. The results of previous studies suggest that more undercuts can be used with polyacetal clasps comparing to the already mentioned materials, but due to low elastic modulus the retention elements must be of much larger size [22].

RCAs can be applied in cases of all non-invasive methods for RDP modeling, but the question is whether this kind of denture, that meets the requirements for prophylaxis and non-invasive support, can meet the aestethic requirement, and still deliver durable and functional results.

RCAs are constantly exposed to elastic deformations resulting in the stress in the material. In order to perform its role successfully, the presence of uniform stress distribution in the cross section and along the clasp is essential [23–27].

Safety factor is the term that can be applied in assessing the durability and function of a RCA. Safety factor represents the relationship between working stress of clasp material originated by the action of a given load and stress within elastic limit, yield strength, respectively (data provided by the clasp material manufacturer). Safety factor is a term describing the structural capacity of a system beyond the expected loads or actual loads, and is represented by dimensionless number. The body or an object with safety factor, under force applied, of one or above, will not undergo plastic deformation under a given load [28–34]. In order to determine the safety factor successfully, it is necessary to clearly define which region of the arm is exposed to the highest stress during the application of retention force.

Whether plastic deformation will occur in RCA depends on the balance of strength and elasticity of the material it is made of. Stress distribution in RCA under forces applied, whether their application is balanced or there are regions particularly threatened and predisposed to plastic deformation, greatly influence the plastic deformation itself. This research should clarify the question regarding those particular regions within RCA made of CoCrMo alloys, commercially pure titanium or polyacetal.

Since the modeling process RCA implies wax models in many cases made of Rapid FlexTM wax profiles in accordance with the BIOS principles, the question is whether the BIOS can be used for RCA modelling out of various materials.

Based on the hypothesis that durability and functionality of retentive clasp arms in RPD made of various materials require clearly defined shapes, the aim of this research have was to determine and compare the safety factor of virtual RCAs on the models of premolars, modeled out of various materials by BIOS concept and to define optimal shape of RCAs on virtual models of premolars, made of various materials.

Methods

Designing a coronal part of a retentive tooth virtual model begins by scanning the enlarged plaster model of the upper first premolars. Scanning was conducted by the means of UHG 1500 device. Computera-aided design (CAD) program was used in defining the digital model of retention tooth. Scanned data were processed using the Auto Desc Inventor 7 software. Virtual premolars modeling in the aforementioned software was done in accordance with the average values of 0.25 mm for undercut depth and 30° for the angle of gingival convergence.

Defining virtual models of retentive clasp arms in the BIOS

In accordance with the BIOS system, virtual models of the I-Bar, Bonihard and circumferential clasps were defined within this experiment. Auto Desc Inventor 7 softwre was used in the modeling procedure. The hight and width ratio of the profiles was 10 to 8. Slope inclination of the profiles was 1.28, as measured on wax profiles (Rapidflex, Degusa) which are used in clasp modeling in the BIOS. The path of each clasps was defined by analyzing the undercut space of digital model on retentive tooth. Virtual models of clasps are planned in accordance with table values of BIOS profiles for CoCrMo alloy (Figure 1).

Fig. 1 – Virtual clasp models designed by the BIOS for CoCrMo alloy.

The dimensions of the cross section and inclination angle values of circumferential clasps are not found in the available literature, therefore those values were obtained by scanning a wax profile (Degussa-Rapid-Flex-System).

The finite elelment method in the process of stress and deflection analysis of refentive clasp arms

RCAs virtual models volume was divided into tetrahedral finite element shape. The finite element mesh consists of 2,994 nodes and 1,601 elements. The simulated force of 5 N was applied and directed towards the top of the clasp arm. The analysed clasp arm deflection, was 0.25 mm, due to the same undercut depth the clasp should overcome. Stress and displacement analysis of RCA models was done using the Autodesc Inventor 7 software. Stress values were expressed in MPa, while deflection in milimeters. Both values were represented by gradation – by differently coloured boxes. The analysis included factors that affect the intensity of the clasp retention force, such as the friction between the clasp and teeth where saliva is a lubricant. The average value of friction was 0.2 (Figure 2).

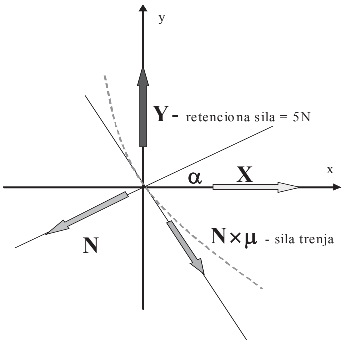

Fig. 2 – Illustration of the influence of forces on the retentive clasp arm.

The change of model parameters was related with the ability of changing elastic modulus and nominal yield strength, which enabled the analysis of virtual models that has the characteristics of different materials. Within the experiment, the analysis was conducted upon model properties of I-Bar, Bonihard and circumferential retentive clasps made of CoCrMo alloy, CP titanium and polyacetal (Table 1).

The constant values within this part of the experiment were: the undercut depth of 0.25mm, the angle of gingival convergence of 30° and friction between a retention tooth model and a RCA model 0.2. Variables were: the length, width and height of the clasp, elastic modulus of a material, nominal yield strength (0.2%) and clasp profile slope inclination.

Defining the optimal shape of a virtual RCA made of CoCrMo alloy

The clasp models were analyzed so that all the clasps were modelled by the BIOS. The length of the clasp path was measured on the digital tooth model. According to the BIOS table, rapid flex wax profile was reduced having the height and width ratio of 10 to 8.

As stated before, the wax profile was scanned by the means of optical scanner and its slope inclination was suggested to be 1.28°. All of these parameters were imported into the software obtaining RCA models that match real clasps planned by the BIOS. After the analysis the shape optimization of RCA was performed and the original models by the BIOS were called "initial BIOS models". Optimal models had the following characteristics: uniform stress distribution within the virtual clasp model, maxium utilization of material, deflection of 0.25 mm and the safety factor greater than 1. Optimization was carried out on the models with the aspect ratio of 10 to 8. Slope inclination angle of the profile was 1.28. "Optimal" RCA models were primely modeled by the parameters for Co,Cr,Mo alloy, having that "optimal" shape additionally examined for other tested materials. The premolar circumferential clasp model was used as the reference one.

On each successive model the dimensions of the profile cross section were changed at low stress intensity regions, towards the decrease in its dimensions. In cases of balanced stress distribution and stress intensity within the elastic limit, the model was accepted as "ideal" in relation to material utilization. The next stage in the optimization was deflection of 0.25 mm. An important term that optimal RCA had to meet was the safety factor value above 1.

The RCA in such way designed model was ideal in relation to stress distribution and material utilization, but missing the requirement of deflection at the clasp top of 0.25

Table 1

Elastic properties of the tested materials

Elastic properties	CoCrMo alloy	CP titan	Polyacetal
Ee	210 GPa	110 GPa	2.9 GPa
0.2% σ	610 MPa	450 MPa	87 MPa

Ee – elastic modulus; 0.2% σ – convential yield strength.

mm, under retention force of 5 N. To solve this problem, the requirement for maximal material utilization must be set aside as less important and to provide, by increasing the cross section dimensions, deflection of RCA tip model to be equal to the undercut value of 0.25 mm.

Comparative analysis of the safety factor of retentive clasp arms made of various materials by the BIOS

In order to illustrate the diversity of material properties used for fabricitaion of RPD retention elements, we conducted a comparative analysis of safety factors upon identical profiles of I-Bar, Bonihard and circumferential RCAs designed by the principles of the BIOS. The modulus of elasticity and conventional yield strength (0.2% σ) were variable parameters (Table 1).

Results

The results of the conducted comparative analysis of the safety factor in virtual RCAs models designed from different materials by the BIOS, showed that the same RCA modeling manner with various materials used was absolutely unacceptable (Table 2). Due to identical design of I-Bar and Bonihard clasp, except for the difference in the crescent-shaped end of the Bonihard clasp, which did not affect the level of security factor, only the results for the I-Bar clasp were presented (Figure 3).

Table 2

Safety factor comparative values

Clasp type	Simulated materials used for clasp model	
	CPTi	Polyacetal
I-Bar	1.34	0.24
Circumferential premolar	0.69	0.12

CPTi – commercially pure titanium.

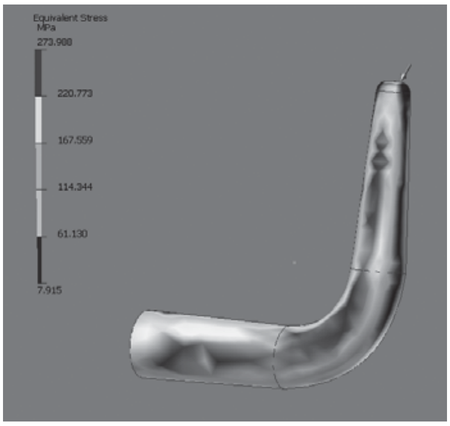

Fig. 3 – Stress distribution in the I-bar retentive clasp arms virtual model.

Optimization of the shape of RCAs made of CoCrMo alloy allowed the creation of clasp shape, by the change in cross section aspect ratio and the slope inclination of profiled, that provides displacement of 0.25 mm, a uniform stress distribution under the force of 5 N and safety factor greater than 1.

Optimization was achieved on the model with the profile aspect ratio of 5 to 10, horizontal gradient of 0.859°, curved area of 0.91° and 3° of vertical area. The required deflection of 0.25 mm defines geometry, thus I-Bar clasp safety factor reaches 1.00662, which indicates the possibility of providing an optimal clasp shape by changing the profile slope inclination and dimension.

The dimensions of optimal Bonihard clasp model made of CoCrMo alloy were compatible with I-Bar clasp. The retention force was deliberately moved to the crescent-shaped tip for the worst case of load to be simulated. Deflection of 0.3 mm was observed at the top of Bonihard clasp arm. Clasp arm-vertical area connection was deflected about 0.25 mm.

Optimization of the circumferential premolar clasp made of CoCrMo alloy was achieved by increasing dimension of the initial BIOS profile by 8% and changing the slope inclination by cubic parabolas. By such geometry modification a safety factor greater than 1 was obtained (Figure 4).

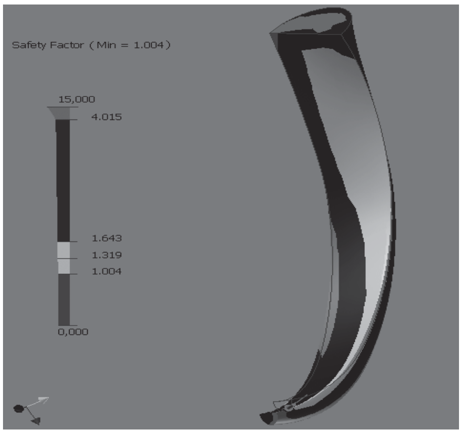

Fig. 4 – Illustration of the safety factor in the optimal premolar circumferential clasp made of CoCrMo alloy.

RCA optimal shapes made of CoCrMo alloy were modified because of the lower values for CPTi modulus of elasticity. By increasing the cross section dimensions of the premolar I-Bar clasp by 19%, the shape was obtained leading to the optimal I-Bar RCA model made of CPTi. There was a slope inclination of 0.98° on the horizontal region, of 0.91° on the curved, and of 3° on vertical. Stress distribution indicates its uniformity along the clasp. The highest values of measured stress were 169 MPa, and safety factor was 2.66.

Evenly distributed stress was observed in the illustration of safety factor distribution. In order to provide a sufficient clasp stiffness the optimal shape of premolar circumferential clasp model made of CPTi was increased by 19%, compared to the optimal clasp made of CoCrMo alloy. Safety factor was 1.67.

RCA optimal shapes made of polyacetals were significantly different from the other materials. Due to the high values of deflection, in addition to increase cross-section dimensions it was necessary to shorten the horizontal dimension of the clasp made of polyacetal. The cross section dimensions were 3–4 mm. The clasp had three times higher deflection than required, and low safety factor of 0.8.

Stresses on the optimal premolar circumferential clasps made of polyacetals were generally evenly distributed and the intensity was low. Deflection was 0.28 mm. Safety factors, although favorably distributed, exceed the values of 4 to 8. Optimization of premolar circumferential clasp models made of polyacetals resulted in the clasp models of 3.64 in width and 2.9 mm in height in the clasp-skeleton RPD connection area.

The results of the research show that there are significant differences in the height of optimal profiles used for premolar circumferential RCAs made od different materials (Figure 5). The difference in slope inclination of rapid-flex profiles was lower than the optimal shape of profiles for CoCrMo alloy and CPTi. Clasp arm made of polyacetals must be 2.5 times bigger than previously mentioned one in order to achieve the retention force of 2.5 N. The research shows that the aspect ratio for clasp modeling should be 10 to 8, while the slope inclination of the profiles for polyacetal clasp arms should be 10°, and 3° for CoCrMo alloy and CPTi (Table 3).

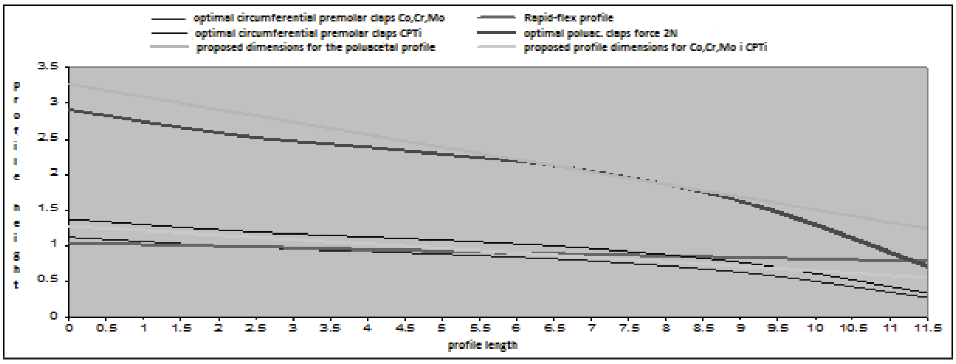

Fig. 5 – The change in height of profiles used for fabricating circumferential premolar clasps.

Table 3

The inclination, height and width (h/w) ratio for the initial, optimized and proposed wax profiles used for RCA fabrication

Wax profiles	I bar and Bonihard		Circumferential premolar	
	inclin. °	h / w ratio	inclin. °	h / w ratio
Rapid-flex wax profiles	1.28	10 / 8	1.28	10 / 8
Optimal profile for CoCrMo	0.8 0.9 3	10 / 5	modifiable	10 / 8
Optimal profile for CPTi	0.9 0.9 3	10 / 5	modifiable	10 / 8
Optimal profile for polyacetal		10 / 5	modifiable	10 / 8
Propos. for CoCrMo and CPTi	0.9 0.9 3	10 / 5	3	10 / 8
Propos. for plyacetal/-can not be done-			10	10 / 8

RCA – retentive clasp ars; CoCrMo – cobalt-chrome-molybdenum; CPTi – commercially pure titan.

Discussion

The finite element method is the most commonly used method for the analysis of retention elements of RPD [28, 29]. The largest contribution to the analysis of RCA using this method was given by Sato et al. [30, 31]. The basis of their research was I-Bar clasp analysis, circumferential retentive clasps and rests of RPD-s [32, 33]. They studied the optimal shape of RCAs with the aspect of stress uniformity and stress distribution. They also simulated the modeling of retentive claps made of CoCrMo alloys, which had the undercut depth of 0.25 mm and 0.50 mm. The results of the research are the proposed dimensions and gradient of RCA claps profile which were very similar to our study.

Mahmoud et al. [35] presented a study with finite element analysis of cast clasps made from Ti–6Al–7Nb, Co–Cr and type IV gold alloys. All objects were loaded in three different directions (outside, inside and outside inclined 30°), and the resulting permanent deformation values were recorded. Nonlinear finite element analysis simulations based on the maximum distortion energy criterion for yielding, were conducted for the clasp models that were reproduced according to the dimensions of each experimental specimen. In their results Ti–6Al–7Nb showed a significantly less permanent deformation followed by type IV gold, while Co–Cr alloy had the greatest permanent deformation. Thes results suggest that the method we used is suitable for predicting different material clasp behavior.

Virtual clasp arms modeled after real clasps made of rapid flex wax profiles by the BIOS concept do not fully meet the reqirements placed upon them. An I-Bar clasp, modeled by the BIOS concept in virtual form, realises excessive deflection, poor stress distribution and excessive safety factor. The horizontal part of the clasp remains inactive, under-utilized respectively, thus the solution to this problem should be sought in the change of slope inclination of the wax profile.

By observing and comparing the illustrations of stress distribution, deflection and safety factors in virtual I-Bar and Bonihard clasp models, it was found that a Bonihard clasp under load acted analogically to the respective I-Bar clasp. The exception being the tip of the Bonihard clasp arm itself, which actually has only a prophylactic effect on retention tooth in terms of stress distribution over a larger tooth area and has no significant role in RPD retention. Stress distribution on a virtual premolar circumferential RCA BIOS model, is uniform, except for the tip area of the clasp arm which remains inactive. The safety factor is much higher than desired despite the excessive value for deflection, which means that the increase in slope inclination on profiles used for clasp fabrication can provide greater flexibility of RCA and more eaven stress distribution.

BIOS and rapid-flex profiles are provided solely for designing and modeling the retentive clasp arms made of CoCrMo alloy.

I-Bar and Bonihard clasps made of CPTi can be designed by the same concept as the corresponding clasps made of CoCrMo alloy in terms of safety, but it is obvious that clasps made of titanium alloy would be much more flexible. The safety factor with circumferential retentive clasp arms is below plastic deformation limit of the material.

Clasps made of polyacetals must not be modeled by the BIOS concept for CoCrMo alloy, and the proof of it is the safety factor.

By changing the geometry of virtual I-Bar and Bonihard clasp models made of CoCrMo alloy we concluded that those clasps can have an optimal shape in terms of uniform stress distribution and safety factor. The difference between the optimal and other models analyzed is presented in the change of slope inclination on the vertical region of the slope arm. The aspect ratio of the optimal virtual I-Bar and Bonihard clasp models does not match the aspect ratio of rapid flex profiles for the BIOS. Optimal premolar circumferential clasp model made of CoCrMo alloy has the identical aspect ratio to rapid flex profile, but with increased dimensions and changeable inclination slopes.

The optimal shape of all RCAs made of CPTi is geometrically similar to a corresponding shape of enlarged clasp arms made of CoCrMo alloy. I-Bar and Bonihard clasp arms are the simplest RCAs by shape and shape optimization. The optimum ratio of wax profiles used for this clasp fabrication is 5 to 10. Profiles of such dimensions are generally present in the market. The obtained results coincide with the researches by Sato et al. [32, 33]. It should be, however, noted that the results of their study refer to the CoCrMo alloy.

The results of this study suggest that wax profiles fabrication of clearly determined dimensions and slope inclination can be used for RCA modeling out of CoCrMo alloy, as well as of CPTi. It is also established that an optimal I-Bar and Bonihard clasp arm is not possible to be made of polyacetals. Premolar circumferential clasp arms made of polyacetals cannot meet the desired deflection and retention force. Even with unacceptably large-scale cross section dimensions of polycetal clasp arms, stresses exceed the limit of plasticity in clasp arm materials. The clasp arm that would meet the requirements would be over-dimensioned and of poor aesthetic performances. The only way for the tested clasp arms to be presented in practice is to distribute the retention force over more teeth or to plan two retentive clasp arms on the same tooth (vestibular and oral), if it is possible. Another solution is to use polyacetal clasp arms in cases of inserted saddles in visible sector, and to use retentive clasp arms made of metal alloys in the sidewide sector. By conducting an accurate analysis on the optimal shapes of polyacetal RCAs, it is possible to make a wax profile which can be further used for modeling of polyacetal RCAs.

Conclusion

The BIOS concept should be used only for RCA made of CoCrMo alloy. The results showed that the finite element method is a good analysis of virtual retentive clasp arms on the models of premolars, modeled out of various materials by the BIOS concept. This method confirms that the safety factor of virtual retentive clasp arms made by CPTi has a higher value than those made of polyacetale RCA. The finite elements method application offers the possibility of defining the optimal shape and design of virtual retentive clasps on a virtual model of premolars. Polyacetale RCAs have different optimal shape design comparing to RCAs made of CPTi. The case of defining polyacetals RCA shows that it is not possible to design an optimal form in terms of flexibility and security factor level.

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