Acta of Bioengineering and Biomechanics
Vol. 19, No. 1, 2017

Original paper
DOI: 10.5277/ABB-00196-2014-05

A comparison of impact force reduction by polymer materials used for mouthguard fabrication

DOMINIKA GAWLAK[1], KATARZYNA MAŃKA-MALARA[1]*, ELŻBIETA MIERZWIŃSKA-NASTALSKA[1], ROMAN GIELETA[2], TOMASZ KAMIŃSKI[3], MAGDALENA ŁUNIEWSKA[4]

[1] Department of Prosthodontics, Faculty of Medicine and Dentistry, Medical University of Warsaw, Warsaw, Poland.
[2] Department of Mechanics and Applied Computer Science, Faculty of Mechanical Engineering, Military University of Technology in Warsaw, Warsaw, Poland.
[3] Department of Oral Surgery, Faculty of Medicine and Dentistry, Medical University of Warsaw, Warsaw, Poland.
[4] Psychology Department, Warsaw University, Warsaw, Poland.

Purpose: The essential function of mouthguards is protection against the effects of injuries sustained during sports activities. This purpose will be successfully achieved if appropriate materials ensuring sufficient reduction of the injury force are used for mouthguard fabrication. Objective: The objective of the study was to investigate the force reduction capability of selected materials as well as to identify which material reduces the impact force to the highest degree. *Methods*: The material for the study were samples of polymers (6 samples in total), obtained during the process of deep pressing (2 samples), flasking (3 samples) and thermal injection (1 sample), which were tested for impact force damping using an impact device – Charpy impact hammer. The control group comprised of the ceramic material samples subjected to the hammer impact. The statistical analysis applied in this study were one-way Welch ANOVA with post-hoc Games-Howell pairwise comparisons. *Results*: The test materials reduced the impact force of the impact hammer to varying degrees. The greatest damping capability was demonstrated for the following materials: Impak with 1:1 powder-to-liquid weight ratio polymerized with the conventional flasking technique, and Corflex Orthodontic used in the thermal injection technique of mouthguard fabrication. *Conclusions*: Impak with 1:1 weight ratio and Corflex Orthodontic should be recommended for the fabrication of mouthguards since they demonstrated the most advantageous damping properties.

Key words: *sport, teeth trauma, mouthguards, oro-facial injury*

1. Introduction

Mouthguards are elastic splints introduced into the oral cavity in order to protect oral tissues against injuries. Mouthguards prevent incisors from damage in case of being hit. They protect the upper teeth against being damaged by opposing teeth in case of a trauma to the mandible. They counteract bone fractures and damage to the temporomandibular joint by dispersing the force of the blow. By separating soft tissues from teeth, these appliances protect buccal, labial and tongue mucosa. Additionally, they reduce the risk of concussion and subarachnoid hemorrhage as a result of absorption, dispersion and limiting the impact force, which could be transmitted to higher levels of the central nervous system along bony trajectories. Many authors hold the opinion that sportsmen using mouthguards are less afraid of the possibility of being injured and are more concentrated on tasks connected with sport and on achieving better results [1]–[5]. An amortising function of mouthguards is achieved by fabricating them with materials that are able to disperse the impact force. This function is best performed by elastic and viscoelastic polymers in the structure of which, upon impact, part of the energy causing deformation is transformed into the phenomenon of molecular friction and heat as a result of internal changes. Damping of vibration occurs, which is favourable with respect to the prevention of oral inju-

* Corresponding author: Katarzyna Mańka-Malara, Department of Prosthodontics, Faculty of Medicine and Dentistry, Medical University of Warsaw, ul. Nowogrodzka 59, 02-006 Warsaw, Poland, e-mail: kmankamalara@gmail.com

Received: October 6th, 2014
Accepted for publication: May 5th, 2016

ries. Considering the basic application of mouthguards, the energy absorption capability of materials used in their fabrication is of great importance in studies focusing on these materials. One method to compare energy absorption is to carry out modified impact tests [5]–[9].

The objective of the study was to investigate the capability of selected materials to reduce the impact force, using a modified Charpy hammer and a self-designed phantom made of ceramic teeth, as well as to identify which material reduces the impact force to the highest degree.

2. Materials and methods

The material for tests were samples of polymer materials obtained in the following processes:

– thermoforming pressing, where single-layer samples were made of 5 mm Erkoflex plates (Erkoflex), two-ply samples were made of 3 mm and 2 mm Erkoflex plates (Erkoflex 2), (Erkodent, Germany),
– flasking, where a material (Impak, Vernon-Benshoff Comp., USA) was used in the following powder-to-liquid weight ratios: 1.5:1 (Impak 1.5); 1.25:1 (Impak 1.25); 1:1 (Impak 1),
– thermal injection using Corflex Orthodontic material (Pressing Dental, Italy).

Polymer materials were tested for force reduction capability on phantoms comprising of teeth made of pressed ceramics (IPS Empress 2, Ivoclar Vivadent, Liechtenstein), set at the central point of an acrylic cylinder-shaped base (Duracrol, Spofadental, Czech Republic). Ceramic teeth were obtained by taking a silicon mass impression of a natural upper central incisor tooth, preparing a wax model in the obtained form and placing it on the cone of a device (IPS Empress EP 500, Ivoclar), preparing a negative from investment material (Siladent Premium, Dr. Böhme & Schöps GmbH) in a casting ring and introducing the ceramic material in place of the burnt out wax (Figs. 1, 2). Such phantoms constituted the basis to obtain stone models, on which the samples of polymer materials were fabricated (Fig. 3). The deep pressing technique in Erkopress device was used to mould the polymer domes. These domes were then prepared, polished and duplicated in a traditional denture flask, in which the polymerization of the Impak material in 1:1, 1.25:1 and 1.5;1 powder-to-liquid weight ratios was carried out at a temperature of 165 °F (approximately 74 °C) for 5 hours, and also in a flask adjusted to the injection device, in which the domes made of Corflex Orthodontic material were obtained at a temperature of 165 °C and under a pressure of 4 bars. Prepared and polished samples, which were 4-mm-thick at the site of contact with the pendulum surface, were successively placed on prepared porcelain teeth set in the fixture of the impact device.

Fig. 1. Silicone form and wax models of ceramic phantom

Fig. 2. Ceramic phantom before being embedded in acrylic base

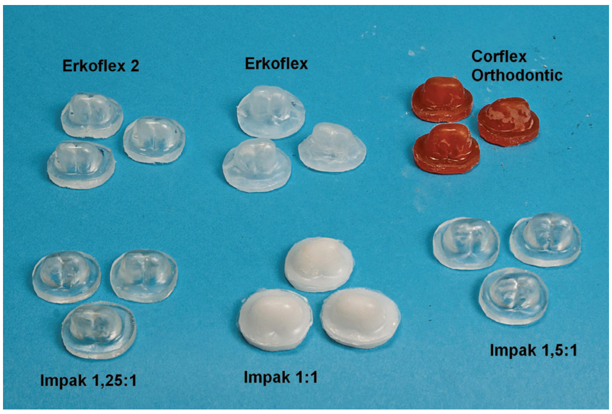

Fig. 3. Samples of polymer materials
utilized in the test of force reduction capability

The dome-shaped materials tested (3 samples of each material) were placed on ceramic teeth and then fixed in a specially designed support stand (Fig. 4) of the impact device – a Charpy impact hammer (model PSW-10/40, Louis Shopper, Lipsk, Germany) with a strain gage amplifier applied for force measurement [3], [10]–[16].

Fig. 4. Polymer sample placed on the ceramic phantom, which was set in the support stand of the Charpy hammer

The test consisted of hitting each sample centrally three times with a 0.225 m long pendulum at initial energy 1.6 J released from a height of 220 mm measured from the ground. The measurement system (ESAM CF strain gage amplifier, ESA GmbH, Germany) recorded the force, which was not absorbed by the mouthguard–teeth system (force F_{max} [N]). Data were recorded by a portable computer (TOSHIBA, Japan) with special software for strain gage measurements (ESA GmbH).

The recording of one impact was performed at 1/100000-second over a period of 1 second, hence one impact resulted in 100000 measurements. The maximum forces registered during 3 impacts of each sample of 6 materials were evaluated. In total, 54 tests were conducted.

Additionally, the force acting on a ceramic phantom without polymer shielding (force F_{ph} [N]) was determined. Data recorded during the first measurements for both the materials and the phantom significantly varied from the other ones, which is associated with the material's internal structure that needs to adapt to the acting load. They were ignored in the statistical analysis (statistics package SPSS 22). The model of one-factor analysis of variance was calculated, according to non-homogenity of variances (tested with Levene's test, $p < 0.05$) a Welch test was applied and then a Games-Howell test was run for post-hoc pairwise comparisons.

The absorption (damping) capability of a polymer material is equal to the quotient of the difference between the force acting on the phantom and the force unabsorbed by the system ($F_{abs} = F_{ph} - F_{av\ mat}$ [N]) and the force acting on the phantom. The higher the values, the better the amortization capability [17].

$$\text{Damping} = \frac{F_{ph} - F_{av\,mat}}{F_{ph}} \times 100\% .$$

3. Results

The test materials reduced the impact force of the impact hammer to various degrees. The results from measurements as well as arithmetic averages of the forces recorded during the fall of the hammer are compared in Table 1. Statistical analysis (Welch ANOVA) demonstrated that the test materials significantly differ from one another (Welch statistics = 625.5; $p < 0.001$; Table 2 and Fig. 5). According to a Games-Howell post-hoc test all materials differed significantly from the phantom ($p < 0.001$). The degree of the acting force reduced by Impak 1.5 was significantly lower than in all other materials. The most advantageous damping property was demonstrated by Impak 1 – it was significantly higher than in Erkoflex, Erkoflex 2, Impak 1.25 and Impak 1.5; the difference between Impak 1 and Corflex was insignificant.

4. Discussion

Based on the latest literature, it can be noticed that attempts are being taken to indicate which material has the most advantageous mechanical properties, i.e., demonstrates the greatest energy absorption with a small increase in layer thickness, which would not influence the comfort of use. Obtained results confirm the purpose of Impak and Corflex materials application, which

Table 1. Charpy hammer impact force depending on material

		F_{max}						F_{ph}
Sample	Measurement	Erkoflex	Erkoflex 2	Impak 1	Impak 1.25	Impak 1.5	Corflex	Phantom
1	1	431.7	447.8	437.4	474.9	477.7	426.3	548,3
	2	431.9	436.8	428.9	431.7	463.0	421.9	552,3
	3	432.3	437.2	413.9	434.7	451.5	420.1	548,2
2	1	433.2	439.3	447.6	426.8	434.2	440.4	552,1
	2	429.9	435.6	416.5	432.6	454.4	431.2	542,2
	3	424.0	436.3	414.7	435.3	449.0	430.4	552,4
3	1	427.8	422.8	453.4	482.0	491.2	407.4	557,0
	2	438.6	424.2	412.4	442.3	457.0	399.9	550,2
	3	437.8	424.5	409.1	445.2	459.5	401.7	549,6
Average force		431.9	433.8	426.0	445.1	459.7	419.9	550.3
Average force w/o first measurement		432.4	432.4	415.9	437.0	455.7	417.5	549.2
Force reduction $F_{ph}- F_{av}$		79.5	77.8	94.3	73.3	54.5	92.7	
Damping %		15.6	15.3	18.5	14.4	10.7	18.2	

Table 2. Significance of differences in force reduction test (Welch ANOVA with Games-Howell post-hoc comparisons)

	Erkoflex	Erkoflex 2	Impak 1	Impak 1.25	Impak 1.5	Corflex	Phantom
Erkoflex		n.s.	*	n.s.	***	n.s.	***
Erkoflex 2	n.s.		*	n.s.	***	n.s.	***
Impak 1	*	*		**	***	n.s.	***
Impak 1.25	n.s.	n.s.	**		***	n.s.	***
Impak 1.5	***	***	***	**		**	***
Corflex	n.s.	n.s.	n.s.	n.s.	**		***
Phantom	***	***	***	***	***	***	

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, n.s. not significant.

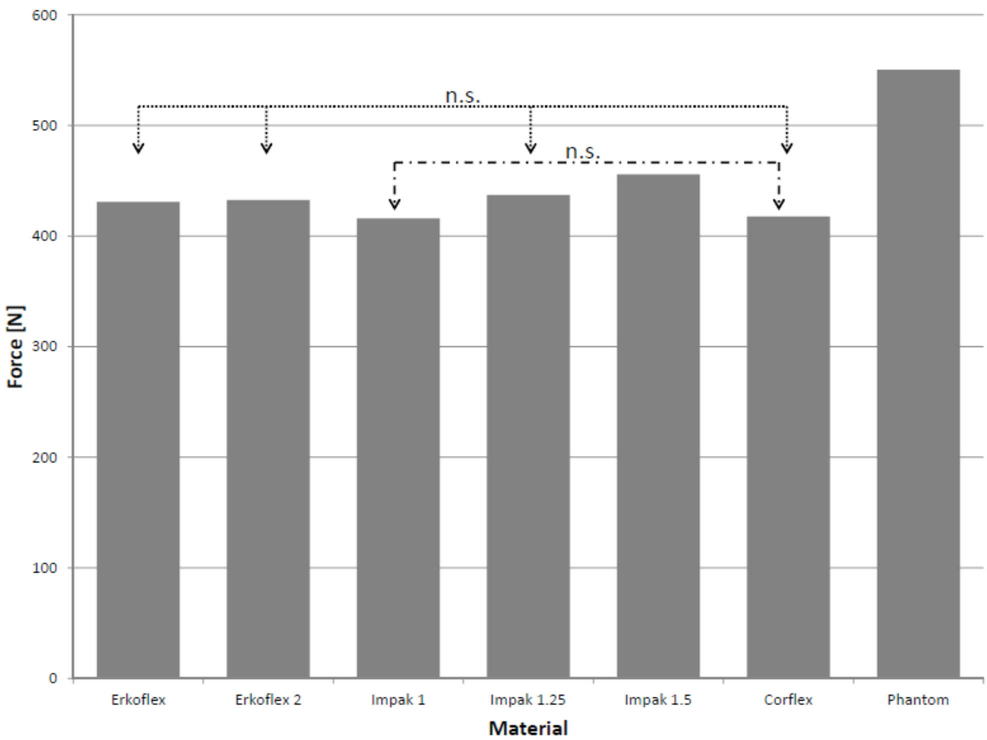

Fig. 5. Impact force reduction. All unmarked differences are significant ($p < 0.01$)

have advantageous properties of impact energy absorption, in mouthguards manufacturing. The application of currently investigated materials has not been previously described in literature.

Most studies focus only on comparing properties of pressure formed EVA mouthguards, which makes it impossible to compare the obtained results to literature data. Comparative assessment is difficult also due to the fact that results in the literature are presented in various units. Some of the similar studies are mentioned below.

An interesting study determining the optimal thickness of a frequently used mouthguard material, ethylene-vinyl acetate (EVA), was conducted by Westerman et. al. [18]. Using a pendulum striking with 4.4 J energy and at a speed of 3 m/s, which could cause facial skeleton injuries, they proved that energy absorption increases linearly with the thickness of the material layer, however, only up to the value of 4 mm, which they consider as the most advantageous. The material thickness indicated by these authors was applied in the present study, which involved the evaluation of polymer materials in terms of the capability of impact force reduction. Usually, in order to do so a modified impact test is performed with the use of the Charpy hammer method or with devices operating in a similar manner. The present test cannot be considered as a typical impact test since fracture does not occur due to the materials [10]–[16]. Nevertheless, many authors apply this method in order to compare the absorbing properties of polymer materials utilized in mouthguard fabrication. The most frequent marker of absorbed impact energy, referred to also as amortisation capability [14] or damping effect [12], is how high the pendulum of the impact device or a falling ball bounces (smaller height – higher energy absorption). The leaders in this area of research are Craig and Goodwin [19], who, in 1967, using the Charpy method and comparing the height of the pendulum bounce after hitting the sample, announced that materials used to produce mouthguards should reduce the impact energy to at least 70% of the initial value. Results obtained in current research are comparable to recommendations. Corflex and Impak 1 material have reduced the initial force to about 80%. In 2002, during tests in which the Charpy hammer was also applied with an initial energy of 1.1 J, 8 standard mouthguards ("stock" and "boil and bite" type) and 7 materials used to produce individual mouthguards were tested. Taking into consideration various thickness, colour and quantities of layers, it was proved that the most advantageous properties in terms of energy absorption are demonstrated for individual mouthguards (on average 83–89%), in comparison with standard mouthguards [3]. The current study included only materials used to fabricate individual mouthguards.

The method of measuring the force on the side of the sample opposite to the impact with a falling ball of a determined mass, similar to the present study, was applied by Park et al. [20]. They came to the conclusion that mouthguards should be made of 4 mm EVA material reinforced inside with a much harder polymer.

The method of a striking pendulum with a steel ball on its end, which was replaced with a baseball ball, was also applied by Takeda et al. [21] to compare the properties of energy absorption. They constructed a very complex measurement system to evaluate mouthguards. The system was composed of two 3 mm layers of EVA material, two 3 mm layers with hard resin reinforcement and two 3 mm layers with hard reinforcement and space between the test mouthguard and the jaw model. The sensors located between the mouthguards and the labial surface of the phantom as well as its palatal surface recorded the lowest accelerations for mouthguard with a hard reinforcement non-adherent to tooth surfaces on the model, which indicated that it had the most advantageous absorbing properties. Sensor in the method proposed in the present study was located in the stand of the Charpy hammer, making it impossible to quantitatively compare the results.

A very similar method to the one presented was described by Auroy et al. [22], who compared the capability of energy absorption of 27 polymer materials by measuring the force recorded by a transducer placed under the material struck by the pendulum of the modified Charpy hammer. First, they measured the impact force without the material, then they read the maximum forces for each sample tested. The lowest percentage value indicated the greatest absorption of impact energy. They proved that harder materials are less likely to absorb impact energy.

An interesting method of comparing mouthguard properties was proposed by de Wett et al. [12]. They constructed a device composed of: an artificial skull fixed to a mobile cone simulating the natural movement of the neck, 3 strain gauges, 2 accelerometers and a hammer with an integrated sensor for force measurement. They pointed out significant differences between 25 mouthguards (5 samples of each type) made of: one 2-mm layer of Bioplast material, 2 mm of Bioplast material and 3 mm of Proform, 2 and 3 mm of Bioplast reinforced with a metal arch, 2 and 3 mm of Bioplast with an integrated sponge fragment, 2 mm of Bioplast with 3 mm of Proform and a fragment of a sponge. The control value was a force of 1.5 V recorded after a hammer struck the skull without any mouthguard (0% damping effect). The most advantageous damping effect was demonstrated for the mouthguard made of 2 mm of Bioplast material, 3 mm of Proform and a sponge fragment (55% of damping). The method proposed in the present study is considerably less complex and material-consuming, and provides comparison of study materials at an adequate level.

Like most of the above-mentioned publications, the present study also involved comparison of absorption properties of polymer materials utilized in mouthguard fabrication with the use of the modified hammer and the system of strain gauge amplifiers. The most advantageous impact absorption was demonstrated by the following materials: Impak in 1:1 weight ratio and Corflex [12], [17].

The presented data taken from literature prove that due to the considerable number of methods comparing energy absorption of materials (different testing devices, sensors and their spatial distribution, measured parameters, units), the evaluation of test results for this parameter is very difficult and standardization of tests conducted on polymer materials is required. Specific conclusions are drawn from the presented tests regardless of the methods applied, on the basis of which the following parameters were determined: the minimum required reduction of impact force [3], the force causing tooth damage [23], the force transmitted to tissues located under the mouthguard [12], [14], the number of damaged teeth [13], [24], accelerations received by teeth and head during the impact [17] or quantity of the energy absorbed [25], [18]. Mouthguards reduce the number of damaged teeth, intracranial pressure, risk of mandible deformation, accelerations and impact force transmitted to the tissues and are also capable of damping the injury force [2], [26]–[28], which empowers their promotion due to the significant limitation of the effects of injuries taking place during various sports activities.

As opposed to research presented before, in current investigation samples were prepared not only using thermoforming pressing technique but also thermal injection and flasking in order to assess the possibility of application in mouthguards manufacturing. The vicoelasticy of polymeric materials with complicated chain structure, provide cushioning and absorbing of the impact energy by transformation in different type of energy. As an effect of deformation, elements of polymeric material are relocated and part of the mechanical energy is transformed in molecular friction and heat. Such absorption of vibrations is advantageous in oral cavity trauma prevention. As presented in previously published studies, energy absorption depends to a great extent on material hardness. Materials of 50–80 Shore A hardness exhibit the most advantageous energy absorption [29] and with respect to this, in this paper, samples were included of required hardness parameter [29].

5. Conclusion

Impak material polymerized in 1:1 weight ratio with the use of traditional flasking technique and Corflex Orthodontic material utilized in the thermal injection technique should be highly recommended for mouthguard fabrication since they demonstrate the most advantageous damping properties.

References

[1] PATRICK D.G., VAN NOORT R., FOUND M.S., *Scale of protection and the various types of sports mouthguards*, Br. J. Sports Med., 2005, 39, 278–281.

[2] KNAPIK J.J., MARSHALL S.W., LEE R.B., DARAKJY S.S., JONES S.B., MITCHENER T.A., DELA CRUZ G.G,. JONES B.H., *Mouthguards in Sport Activities. History, Physical Properties and Injury Prevention Effectiveness*, Sports Med., 2007, 37, 117–144.

[3] CRAIG R.G., GODWIN W.C., *Properties of athletic mouth protectors and materials*, J. Oral. Rehab., 2002, 29, 146–150.

[4] GOING R.E., LOEHMAN R.E., CHAN M.S., *Mouthguard materials: their physical and mechanical properties*, J. Am. Dent. Assoc., 1974, 89, 132–138.

[5] GAWLAK D., ŁOJSZCZYK R., *Materials and techniques used in manufacturing mouthguards*, Stomatologia Współczesna, 2010, 1, 8–15.

[6] CRAIG R.G., POWERS J.M., *Dental Materials*, Urban & Partner, Elsevier, Wrocław 2008.

[7] MARCINIAK J., KACZMAREK M., ZIĘBOWICZ A., *Biomaterials in dentistry*, Silesian University of Technology Press, Gliwice 2009.

[8] PIELICHOWSKI K., *Dynamic mechanical analysis (DMA)*, Laboratorium, 2009.

[9] DUHAIME C.F., WHITMYER C., BUTLER R., KUBAN B., *Comparison of forces transmitted through different EVA mouthguards*, Dent. Traumatol., 2006, 22, 186–192.

[10] BRONIEWSKI T., KAPKO J., PŁACZEK W., THOMALLA J., *Testing and evaluation of the properties of plastics*, WNT, Warszawa 2000.

[11] BULSARA Y.R., MATTHEW I.R., *Forces transmitted through a laminated mouthguard material with Sorbothane insert*, Endod. Dent. Traumatol., 1998, 14, 45–47.

[12] DeWet F., Heyns M., Pretorius J., *Shock absorption potential of different mouth guard materials*, J. Prosthet. Dent., 1999, 82, 301–306.

[13] Greasley A., Imlach G., Karet B., *Application of a standard test to the in vitro performance of mouthguards*, Br. J. Sports Med., 1998, 32, 17–19.

[14] Hoffmann J., Alfter G., Rudolph N.K., Goz G., *Experimental comparative study of various mouthguards*, Endod. Dent. Traumatol., 1999, 15, 157–163.

[15] Westerman B., Stringfellow P.M., *Forces transmitted through EVA mouthguard materials of different types and thickness*, Aust. Dent. J., 1995, 40, 389–391.

[16] Gawlak D., Mańka K., *Mouthguards strength evaluation – a review of the literature*, Protet. Stomatol., 2011, 6, 490–495.

[17] Takeda T., Ishigami K., Handa J. et al., *Does hard insertion and space improve shock absorption ability of mouthguard?*, Dent. Traumatol., 2006, 22, 77–82.

[18] Westerman B., Stringfellow P., Eccleston J., *EVA mouthguards: how thick should they be?*, Dent. Traumatol., 2002, 18, 24–27.

[19] Craig R.G., Godwin W.C., *Physical properties of materials for custom – made mouth protectors*, J. Mich. Dent. Assoc., 1967, 49, 34–38.

[20] Park J.B., Shaull K.L., Overton B., Donly K.J., *Improving mouth guards*, J. Prosthet. Dent., 1994, 72, 373–380.

[21] Takeda T., Ishigami K., Kawamura S., Nakajima K., Shimada A., Sumii T., Swain M., *Adhesive strength and its improvement referring to the laminated-type mouthguard*, Dent. Traumatol., 2006, 22, 205–214.

[22] Auroy P., Duchaterlard P., Zmantar N., Hennequin M., *Hardness and shock absorption of silicone rubber for mouth guards*, J. Prosthet. Dent., 1996, 75, 463–471.

[23] Oikarinen K.S., Salonen M.A., Korhonen J., *Comparison of the guarding capacities of mouth protectors*, Endod. Dent. Traumatol., 1993, 9, 115–119.

[24] Greasley A., Karet B., *Towards the development of a standard test procedure for mouthguard assessment*, Br. J. Sports Med., 1997, 31, 31–35.

[25] Morikawa M., Taniguchi H., Ohyama T., *Evaluation of athletic mouthguards through vibration test on maxillary teeth of human dry skull*, J. Med. Dent. Sci., 1998, 45, 9–18.

[26] Takeda T., Ishigami K., Ogawa T. et al., *Are all mouthguards the same and safe to use. The influence of occlusal supporting mouthguards in decreasing bone dis tortion and fractures*, Dent. Traumatol., 2004, 20, 150–156.

[27] Takeda T., Ishigami K., *The influence of the sensor type on the measured impact absorption of mouthguard material*, Dent. Traumatol., 2004, 20, 29–35.

[28] Spinas E., Savasta A., *Prevention of traumatic dental lesions: cognitive research on the role of mouthguards during sport activities in paediatric age*, Eur. J. Paediatr. Dent., 2007, 8, 193–198.

[29] Gawlak D., Mańka-Malara K., Mierzwińska-Nastalska E., Waśniewski B., Ryszkowska J., *Comparison of hardness, energy absorption and water absorbability of polymeric materials used in manufacture of mouthguards*, Dent. Med. Probl., 2015, 52, 78–85.