Chapter 14

Systematic Study of Ethylene-Vinyl Acetate (EVA) in the Manufacturing of Protector Devices for the Orofacial System

Reinaldo Brito e Dias, Neide Pena Coto,
Gilmar Ferreira Batalha and Larissa Driemeier

Additional information is available at the end of the chapter

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Abstract

Fracture of facial bones and dental elements, and laceration of soft tissue, have increased in sports over recent years. Dentist is the only professional responsible for the mouth protection design, the knowledge about suitable materials is essential. EVA is a thermoplastic material, available in the market, easy of handling and processing, and low-cost. However, it is important to understand the mechanical properties and ability to absorb and to dissipate the impact energy, when this material is submitted to different environments, such as oral cavity with saliva and different temperatures. This chapter show provides a systematic evaluation of the EVA application in orofacial protectors while focusing on sports. The research comprises two aspects: experimental tests and numerical analyses. During experimental tests, EVA was analyzed in special buccal conditions, concerning temperature and presence of saliva. Regarding the presence of saliva, more specific studies about its influence on the mechanical behavior of EVA were performed. In the numerical analyses of the EVA orofacial protector, the studies focused on its effect on the nasal bone integrity, and in the zygomatic bone protection. However, life cycle should be analyzed, since its performance deteriorates over time. Mainly due to the saliva-originated changes to the EVA mechanical characteristics, it can behave as a rigid material. For facial protection, a better performance is obtained with a combination of rigid and soft EVA material. According to the experimental and numerical results from a systematic study of EVA, its application to orofacial protection can be considered satisfactory.

Keywords: material tests, orofacial protection, trauma in sports, protection in sports

1. Introduction

According to the World Health Organization (WHO) [1], "Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity."

Areas of study related to life, health and disease are called human health sciences. Medicine, Biology, Biomedicine, Nursing, Speech Therapy, Pharmacy and Biochemistry, Sports Science, Physical Education, Psychology, Occupational Therapy, Nutrition, Physiotherapy, Bioengineering and Dentistry are part of this program. All these research areas focus on improving or maintaining the patient quality of life, in accordance with the conditions dictated by WHO.

In dentistry, a particularly important area is related to the endless search for materials that can more efficiently help the maintenance and/or return of the individual's well-being. Researchers in dentistry seek and study materials that may replace dental organs, may be accepted in the alveolar and dentofacial complex, or may protect the orofacial complex from injuries.

Therefore, due to the technical-scientific excellence required in its attributions, dentistry is a science that requires constant updating of materials science and applications. It is worth highlighting that, to indicate a safe and efficient clinical application for a particular material, mechanical, physical, chemical and biological properties must be known.

According to Anusavice et al. [2], four groups of materials are used and studied in dentistry: metals, ceramics, composites and polymers. These materials are separated into modalities, according to their application: preventive, restorative or auxiliary materials.

Auxiliary are materials with recognized importance and application but which do not fit into the first two modalities. It is the best option for describing the function of polymers.

Polymers are an important category of materials for dentistry. They are versatile, since they can be combined in order to improve mechanical properties, and moreover, they are reproducible and homogeneous [3].

The term polymer derives from the Greek words: poly-many and mer-unit; or, more specifically, it is a macromolecule composed of repeating units linked by a covalent bond. Its physical properties depend on the length of the molecule and its molar mass. When the polymer is formed by a single type of *mer*, it is called **homopolymer**; otherwise, it is called a **copolymer**.

According to their malleability, polymers are classified into thermoplastic and thermosetting. When the temperature is raised above its melt point, the *thermoplastic polymer* becomes softer and more fluid, allowing it to be molded. When the heat source is removed, the thermoplastic hardens in the molded shape. Since it occurs without chemical curing, it is a reversible physical transformation. In turn, with the addition of a second material and/or heat, *thermosetting polymers* soften and cure, forming cross-links that prevent the material from returning to the primary form. This process cannot be repeated.

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Regarding mechanical behavior, polymers are classified as *elastomers*, *plastics* and *fibers* [4].

During dentists' day-to-day operations, *resin* is the most commonly used polymer. Most of these resins are based on methacrylate, with methyl methacrylate as the main ingredient. Resins are easy to manipulate, without demanding elaborate techniques; the final resin products are esthetically acceptable and offer excellent balance when used in the oral environment, in the presence of saliva and chewing conditions, besides being low cost [5].

Ethylene-vinyl acetate (EVA), object of this study, is a thermoplastic copolymer derived from petroleum. For dental use, it is in the form of rigid or flexible flat plates, in thicknesses of 1–5 mm, without the presence of blowing agents, differently from EVA plates available in the common market. It is indicated as a shock absorber material, for producing mouth and facial protectors for sports practice, as pointed out by Coto et al. [6], as well as dental bleaching trays, orthodontic restraints and as the base for facial prostheses.

2. Ethylene-vinyl acetate

The copolymer of ethylene and vinyl acetate is a thermoplastic polymer, formed by different monomers: ethylene and vinyl acetate (**Figure 1**). Monomers merge through a polymerization process—a set of reactions among simple molecules to form a macromolecule of high molar mass.

The EVA presents semi-crystalline structure; its geometry is composed of an amorphous and a crystalline part. The damping capacity of EVA increases as the percentage of vinyl acetate decreases. As already mentioned, EVA is a macromolecule composed of repeated units linked by covalent bonds and its primary units of constitution are two monomers whose physical properties depend on their size and molecular weight. Polymeric materials generally exhibit density ranging from 0.926 to 0.950 g/cm^3, temperature resistance (glass transition temperatures

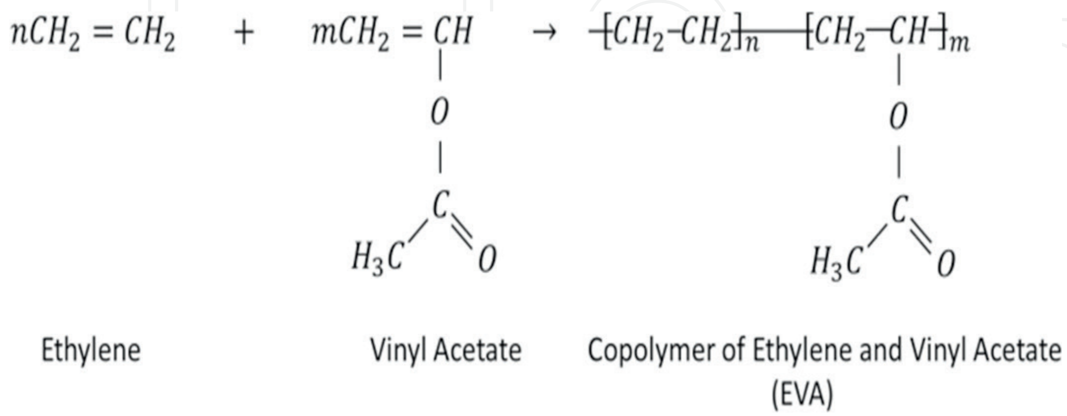

Figure 1. Polymerization reaction between ethylene and vinyl acetate, resulting in EVA.

close to 0 to −7°C). Among the main characteristics of EVA, its elastic behavior characterized by the Young Modulus ranging from 15 to 80 MPa can be highlighted. Flexible EVA, for example, behaves similarly to elastomers, and its elasticity is considerable.

In most practical situations in which EVA is applied or mechanically tested, it is possible to observe that the material's mechanical response is time dependent, that is, it is a viscoelastic material. This characteristic of viscosity is important for energy dissipation.

In the chemical industry, EVA is presented in grain form as shown in **Figure 2**.

Some mechanical properties of EVA are discussed as follows.

2.1. Stiffness

The initial stiffness of the EVA can be measured by its modulus of elasticity, that is, angle of inclination of the approximated straight line that relates stresses as a function of the strains, in elastic regime. In the elastic regime, the energy absorbed by the deformed material is totally restored by removing the stress. The higher the vinyl acetate concentration, the more flexible the EVA material is, due to the reduction in the degree of crystallization.

The degree of EVA crystallization is proportional to the latent heat of fusion (ΔH_f), and its value increases as the concentration of crystals present in EVA increases. However, EVA is not a totally crystalline polymer because, in the solid state, it contains two phases: amorphous and crystalline. In fact, the presence of a glass transition temperature (T_g) means that it contains an amorphous phase, since T_g is a thermal transition exclusive of the amorphous phase, that is, it is the temperature at which the macromolecules of the amorphous phase acquire rotational mobility. The amorphous phase of EVA is represented by a macromolecule entanglement which lacks an ordered and periodic three-dimensional structure. The crystalline phase, on the other hand, is characterized by a three-dimensional ordered and periodic structure of macromolecules folded one on the other, assuming the lamellar format. The melting temperature (T_f) is also a thermal transition, in which the crystalline phase disintegrates and the polymer becomes a viscous liquid.

Figure 2. EVA in granules.

2.2. Hardness

The hardness of a polymer is determined by the penetration of the Durometer indenter foot into a small sample (Shore Hardness). The increase in vinyl acetate content reduces the hardness of EVA, mainly due to the decrease in its degree of crystallization. Although hardness and stiffness are different properties, in some cases, it is possible to establish an empirical correlation between them for a given family of polymers. In some cases, as the degree of crystallization of EVA increases, the stiffness and hardness increase proportionally.

2.3. Transparency

The polymer crystals of EVA act as physical obstacles to the passage of light. Accordingly, as the polymer crystals concentration decreases, increasing the content of vinyl acetate, the material becomes more transparent.

2.4. Damping

It is the ability of the material to absorb the mechanical energy to mainly overcome internal friction. The damping capacity of EVA increases as the vinyl acetate content reduces. Damping capacity is sometimes unduly related to hardness. However, a hard polymer can be designed to have the same damping capacity of a soft polymer.

2.5. Viscoelasticity

In many of the practical conditions in which polymers are requested or tested, their mechanical response is found to be time-dependent, which characterizes these materials as viscoelastic, as already mentioned. This absorption may occur due to the internal friction between the macromolecules, by shape changes (rotation of the carbon–carbon bonds around its own axis) or by flow. Furthermore, in case of impact, the viscous portion is responsible, for the delay in the elastic response, which will depend on the stimulus and on the time necessary to coil and to uncoil the polymer macromolecule [4, 7–9].

3. Experimental study of EVA applied to oral protection

The study of the mechanical properties of EVA focused on mouth guards and facial protectors. Particularly for the facial protector designed in this study, a patent was applied (number BR 20 023048 9).

Several experimental tests made with the material, available in the literature [10–12], confirm this percentage, which is proportionally inverse to the EVA damping capacity. Moreover, the EVA was carefully characterized in POLITENO—Brazil (now BRASKEN) for analysis. The analyses of vinyl acetate percentage were performed by means of pyrolysis.

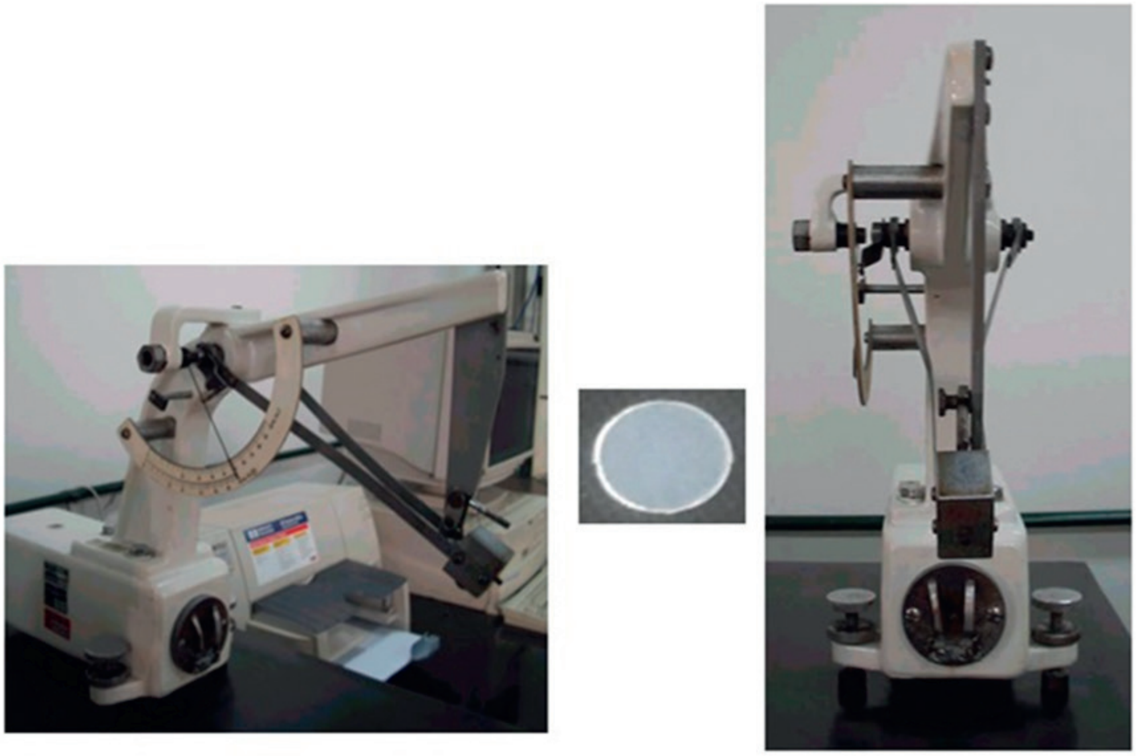

Figure 3. Compression test of the EVA specimens—ABNT NBR 8690—with Schob Pendulum.

In **Figure 3**, the Schob pendulum was used to measure the resilience of the EVA. Six experiments were performed, three used to calibrate the system and three to measure the property. The EVA was observed to have a great damping potential, since it absorbed 50% of the applied energy.

Experimental compression tests were performed to the mechanical characterization of the EVA.

Figure 4 shows the Instron® machine and the recording of the compression tests, performed by a Photron Ultima APX-RS high-speed camera (3000 frames per second). The record helped the study of the nonlinear material behavior of the EVA.

Particularly, **Figure 5** shows that EVA undergoes considerable plastic deformation before failure.

3.1. Mechanical study of the operation of a mouth guard

To reproduce conditions as close as possible to a real situation, models in epoxy resin were manufactured from a patient model (**Figure 6**).

As illustrated in **Figure 7**, the models of the upper and lower arches were fixed in a compression device that allows the lower arch to move while maintaining the upper arch fixed. The compression device was coupled to a Universal Kratos Test Machine, data acquisition system, 20 kN load cell. The aperture, initially in occlusion, was controlled by the extensometer, with a maximum opening of 18 mm. Compression tests were performed, at a velocity of 42.86 mm/min.

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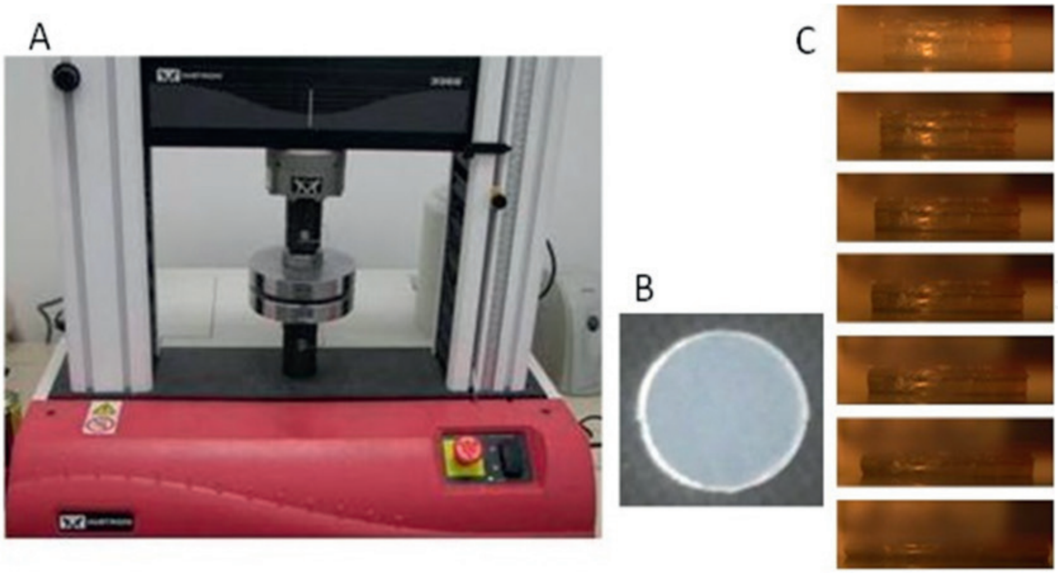

Figure 4. (A) EVA compression test in an Instron machine. (B) Detail of the geometry of the specimen: flat discs with 30 mm in diameter. (C) Compression test recording.

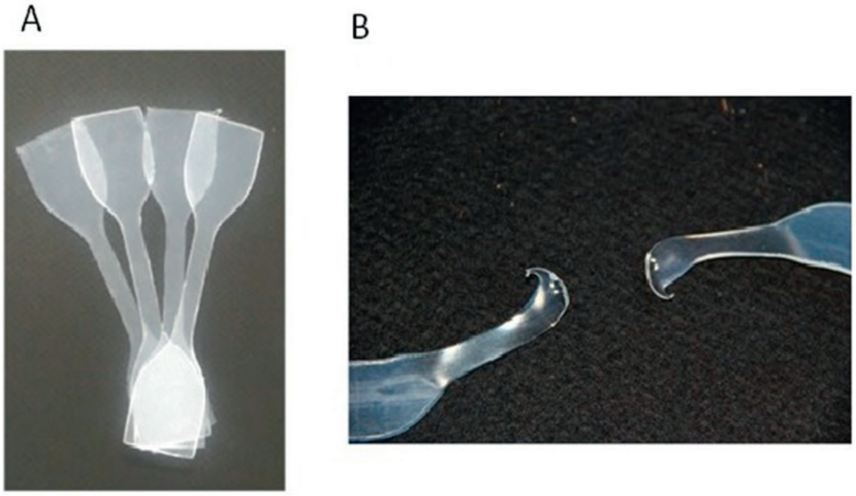

Figure 5. (A) EVA specimens for tensile test. (B) Detail of the specimen after failure.

The test was controlled by optical pyrometer, maintaining the temperature around 37–39°C, close to the mouth temperature (**Figure 8**).

Five EVA mouth guards of each thickness (3 and 4 mm) were made for each test group, using models of a superior dental arch in stone gypsum and metalvander® vacuum-form machine. The geometry respected the recommendation of American Academy for Sports Dentistry [13], that is, 2 mm below the bottom of the vestibular groove, 10 mm beyond the palatine gingival and extension up to the second upper molars.

The heating time for both thicknesses was 4 min, approximately; aspiration time was 45 s (**Figure 9**). All the protectors were immersed in cold water for 10 min.

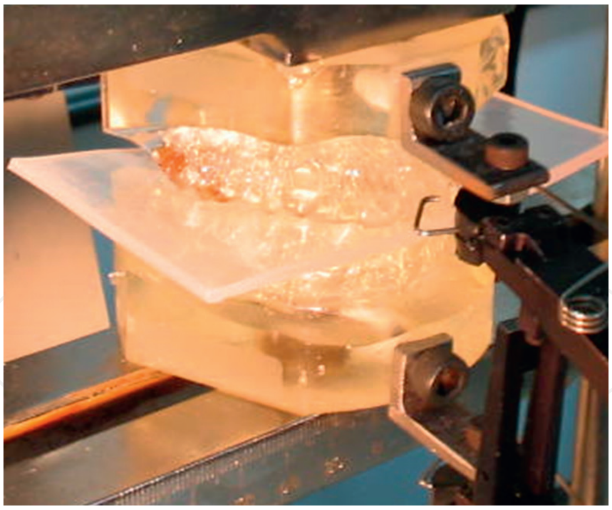

Figure 6. Model of dental arches made of epoxy resin.

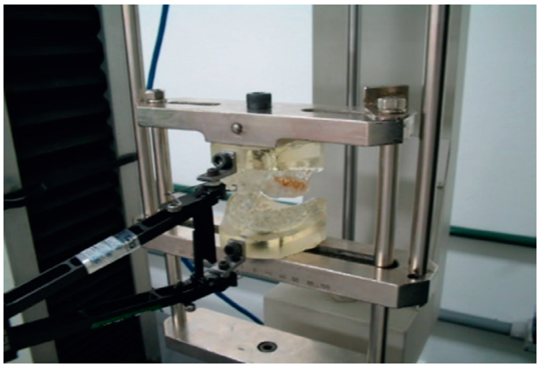

Figure 7. Test set: the Kratos® Universal Testing Machine, dental arch models and extensometer.

Figure 8. Maintenance of the system temperature with an optical pyrometer.

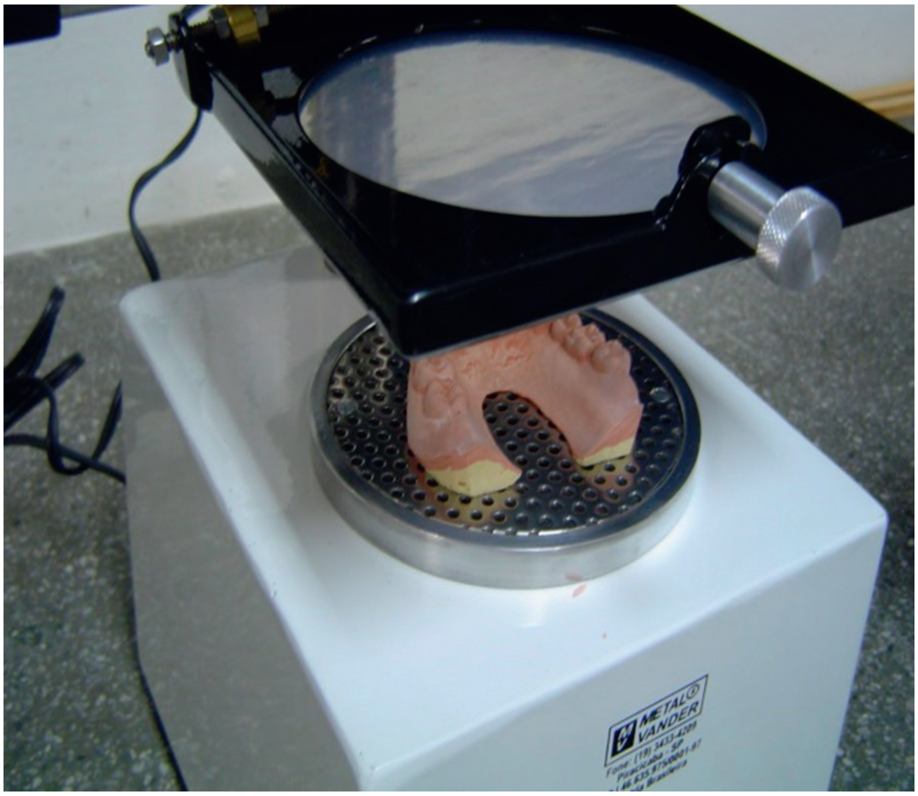

Figure 9. Manufacture of mouth guards in vacuum form Metalvander® machine.

The groups are divided as follows:

A. Mouth guard—3-mm-thick blade

- Room temperature/without saliva
- Room temperature/saturated in saliva
- Oral temperature/without saliva
- Oral temperature/saturated in saliva

B. Mouth guard—4-mm-thick blade

- Room temperature/without saliva
- Room temperature/saturated in saliva
- Oral temperature/without saliva
- Oral temperature/saturated in saliva

Table 1 shows a variation in the compression maximum load in Newtons (N) when evaluating the 3-mm-thick mouth guard (here named $\mathbf{prot_A}$) and the 4-mm-thick mouth guard (here named $\mathbf{prot_B}$).

Coefficient	Max. load (N)	Standard deviation	Significance p
$prot_A$	2046	20	0.00
$prot_B$	2219	20	0.00

Table 1. Maximum load variation (N) as a function of the thickness variable, with their respective standard deviations (SD) and significance levels ($p \leq 0.05$), for protectors A and B.

When comparing **$prot_A$** and **$prot_B$** protectors in **Table 1**, **$prot_B$** was observed to require an additional force of 173 N. It agrees with Craig and Godwin [14]: "The energy absorbed in the cyclic moment of compressive deformation should reduce the locally transmitted energy" and thus avoid the rupture of the polymer layer between the teeth. The EVA material acts as a shock absorber, guaranteeing a low energy transmission to the teeth of the dental arch [15].

These data become more relevant when the final measurements of the guard thicknesses are observed. At the end, they presented mean differences in thickness of approximately 0.55 mm, instead of the nominal 1 mm difference. This is already expected, since during the manufacture of the individualized buccal protector there is a loss of thickness between 25 and 50%, also observed in the literature [14, 16]. Analyzing **Table 1** again, one can conclude that a small difference, 0.55 mm, increased the force around 173 N.

4. Numerical analysis of EVA applied to facial protection

Studies in the biological area involving impact have become impossible to perform *in vivo* due to ethical awareness. On the other hand, engineering presented rapid technological development of tools that allow for more detailed analyses, using complex geometries and offering refined results of behavior of virtually modeled bodies [17]. Particularly, the finite element method (FEM) is a powerful tool, able to virtually mimic different complex phenomena, including the impact of an object on a human face.

However, to analyze the performance of different EVA geometries and properties (flexible and rigid forms) via FEM, it is necessary to determine the parameters and constitutive laws for the materials (tissue, bone, EVA), geometry of the studied problem (face and projectile) and boundary conditions (initial velocity of the projectile, displacement restrictions in the system).

4.1. Material parameters and constitutive laws

4.1.1. Face bones

Most of the bony framework of the face has high-level resistance, since it protects vital elements, such as the brain, the eyes and the neuromuscular structures. Yet, it is also composed of very fragile bones, such as the maxilla, nasal bones and the malar portion of the zygomatic bone [18–22].

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When a facial bone is fractured, undergoing or not surgery reduction, it should not be exposed to any trauma during the bone healing process, which lasts about 30 days [23–27]. If surgical reduction is required, it should occur within the first 2–3 h after the injury occurs [28, 29].

Cases of surgical reduction may disrupt the performance of athletes. In these cases, the use of the facial protector can allow an early and safe return of the athlete to training and competitions [22, 27, 28, 30]. In general, 4–7 days are required for the face molding and for manufacturing/producing the protector.

For the present FEM analysis, the cortical bone is represented as a linear elastic, homogeneous and isotropic material. The mechanical properties—density, Young's modulus, Poisson coefficient and maximum strength—of each bone depend on its composition, as reported by Lotti et al., Handbook in 2006 [31].

Table 2 presents the maximum compressive load of each bone portion of interest for dentistry. Particularly for the cortical bone, the elastic material parameters are listed in **Table 3**.

4.1.2. Human soft tissue

The soft tissue named here is composed of the skin and the muscular portion of the studied region.

The soft tissue is a hyperelastic nonlinear material [33–37] here represented by the well-known Ogden model [35, 37].

Table 4 lists the parameters used for soft tissue in the FEA. The elastic parameters are the same as those adopted by several car manufacturers to simulate pedestrian—car impact—and Ogden parameters were obtained by Coto et al. [6], according to the definition in the finite-element software LS-Dyna.

Bone	Max. load (N)	Max compressive stress (N/mm²)
Frontal	1000–6494	≥7.58
Zygomatic	489–2401	1.38–4.17
Mandible	668–1801	1.03–2.07
Nasal	342–450	0.13–0.34

Table 2. Face bone resistance [32].

Structure	Young Modulus (MPa)	Poisson coefficient	Density (t/mm³)
Cortical bone	13,700	0.32	2.28

Table 3. Elastic parameters for the cortical bone.

	Elastic parameters			Ogden parameters	
	Shear Modulus (MPa)	Poisson coefficient	Density (t/mm^3)	μ_1/α_1	μ_2/α_2
Tissue	0.69	0.495	1.438 E − 9	7.0/0.8	2.6/2.6

Table 4. Material model for human tissue.

4.1.3. Flexible EVA

Flexible EVA has high elasticity and low mechanical resistance. A reverse analysis method was adopted to extract the material properties from the experimental tests described. In the reverse method, material parameters are tuned such that numerical predictions match the experimental curves (**Figure 10**).

Table 5 summarizes the material parameters, used to characterize flexible EVA, according to the Ogden hyperelastic model, available in the commercial software LS-Dyna® and adopted in this study.

4.1.4. Rigid EVA

The inverse methodology was again adopted here, to characterize rigid EVA. **Figure 11** shows the similarity between the experimental and the numerical compression tests.

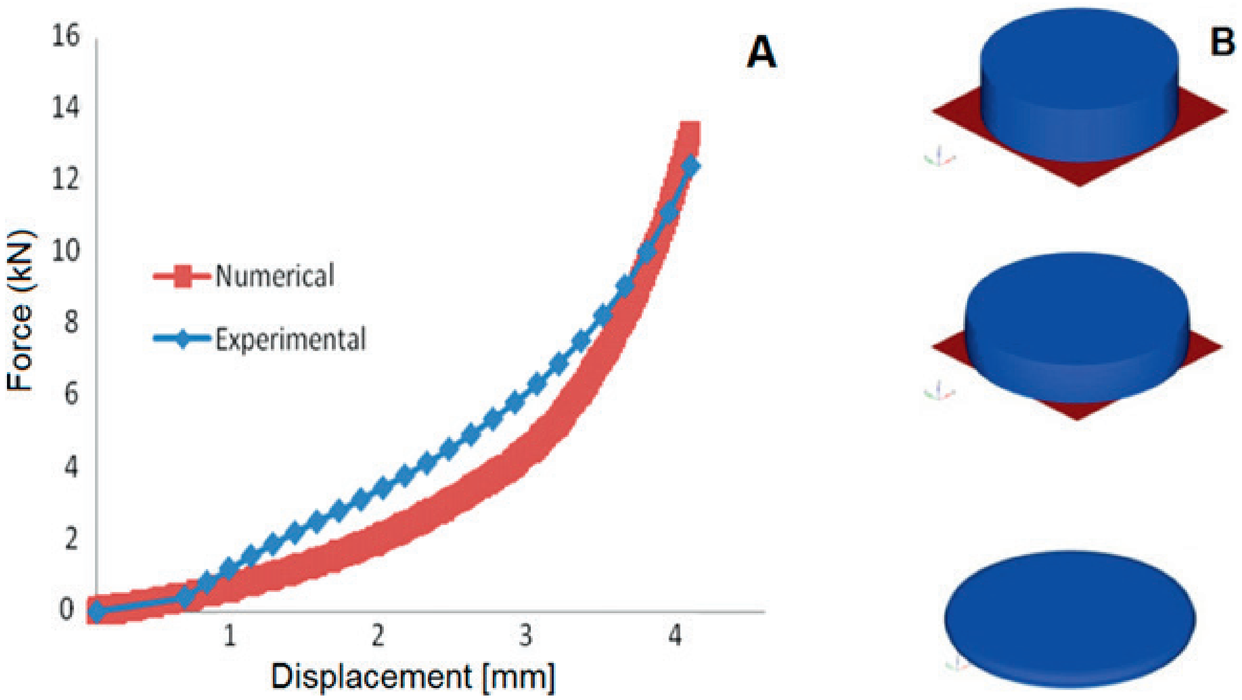

Figure 10. (A) Experimental and numerical curve for compression test. (B) Specimen configuration at different instants of the numerical analysis [6].

	μ_1/α_1	μ_2/α_2	Poisson coefficient	Shear Modulus (MPa)	Density (t/mm³)
Flexible EVA	7.0/0.8	2.6/2.6	0.48	10.0	2.0 E − 9

Table 5. The material model for flexible EVA.

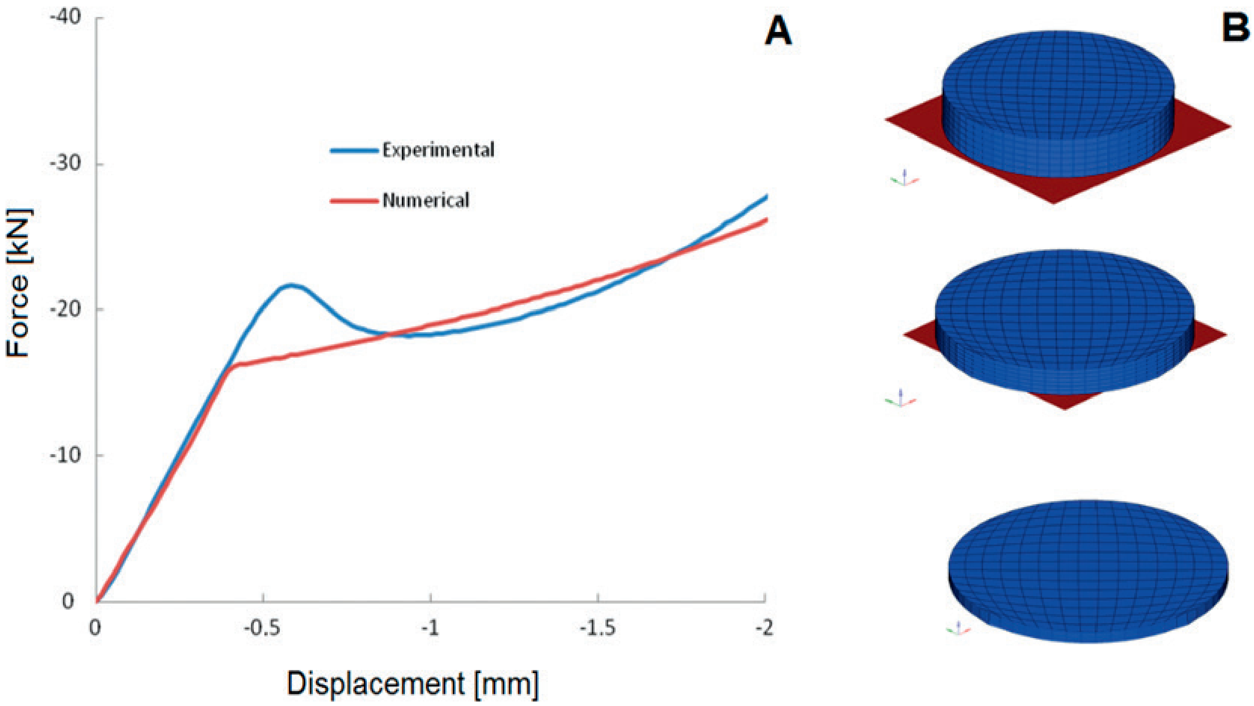

Figure 11. (A) Experimental and numerical curve for compression tests of rigid EVA. (B) Specimen configuration at different instants of the numerical analysis [37].

Table 6 shows the material parameters used for the rigid EVA, according to the Ogden model available in the software LS-Dyna®.

4.1.5. Geometry

As for numerical simulations of the human face, the geometry is a challenge, due to the great number of particularities.

To overcome this problem, a scientific partnership was established with the Renato Archer Information Technology Center (CTI Renato Archer). They provided the face images (**Figure 12**), obtained by computerized tomography (CT) and using in-house software.

	μ_1/α_1	μ_2/α_2	Poisson coefficient	Shear Modulus (MPa)	Density (t/mm³)
Rigid EVA	1.0/0.05	10.0/−4.0	0.49	175	1.2 E − 9

Table 6. Material model for rigid EVA.

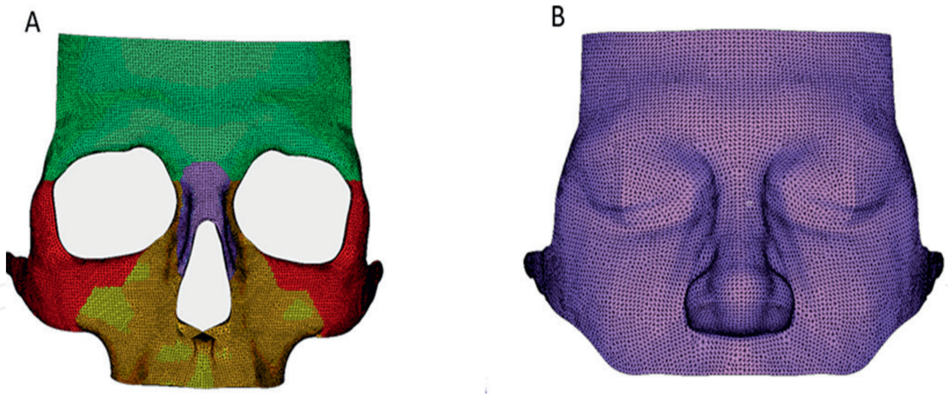

Figure 12. (A) The bone and (B) soft tissue configuration of the face, obtained from CT [37].

4.2. Numerical analyses

Using the material and geometrical parameters defined so far, it is possible to perform complex numerical analyses of the face, with different load conditions. Here, software LS-Dyna was used. The mesh generation and data analyses were performed with the pre- and post-processors HyperMesh and HyperView, respectively [38, 39].

4.2.1. EVA as nasal protector for sport

Coto et al. [6] studied the performance of EVA nasal protectors undergoing the impact of a rigid ball in the face with a 3D FE model (**Figure 13**). The material used was a combination of 1 mm of rigid EVA with 2 mm of flexible EVA. The author concluded that the proposed protector could absorb and dissipate the energy from the impact of a ball with mass of 0.025 kg at initial velocity of 20 m/s. The energy is high enough to fracture the nasal bone if there is no protector (**Figure 14**).

According to Coto et al. [37], rigid EVA reduced the velocity of impact and the flexible EVA increased the time interval of the impulse, thus decreasing the peak load transmitted to the bone.

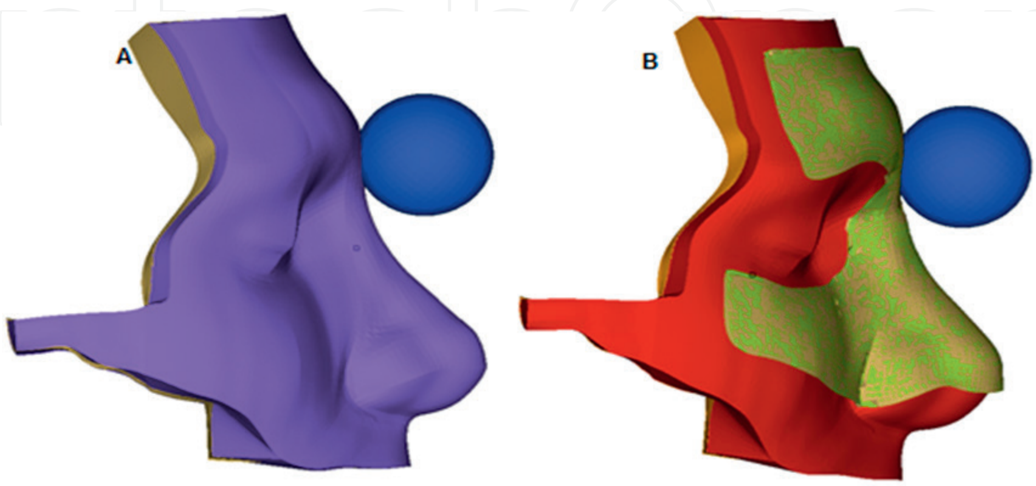

Figure 13. FE model. (A) Without the protector. (B) With the protector. Figure is extracted from Coto et al. [37].

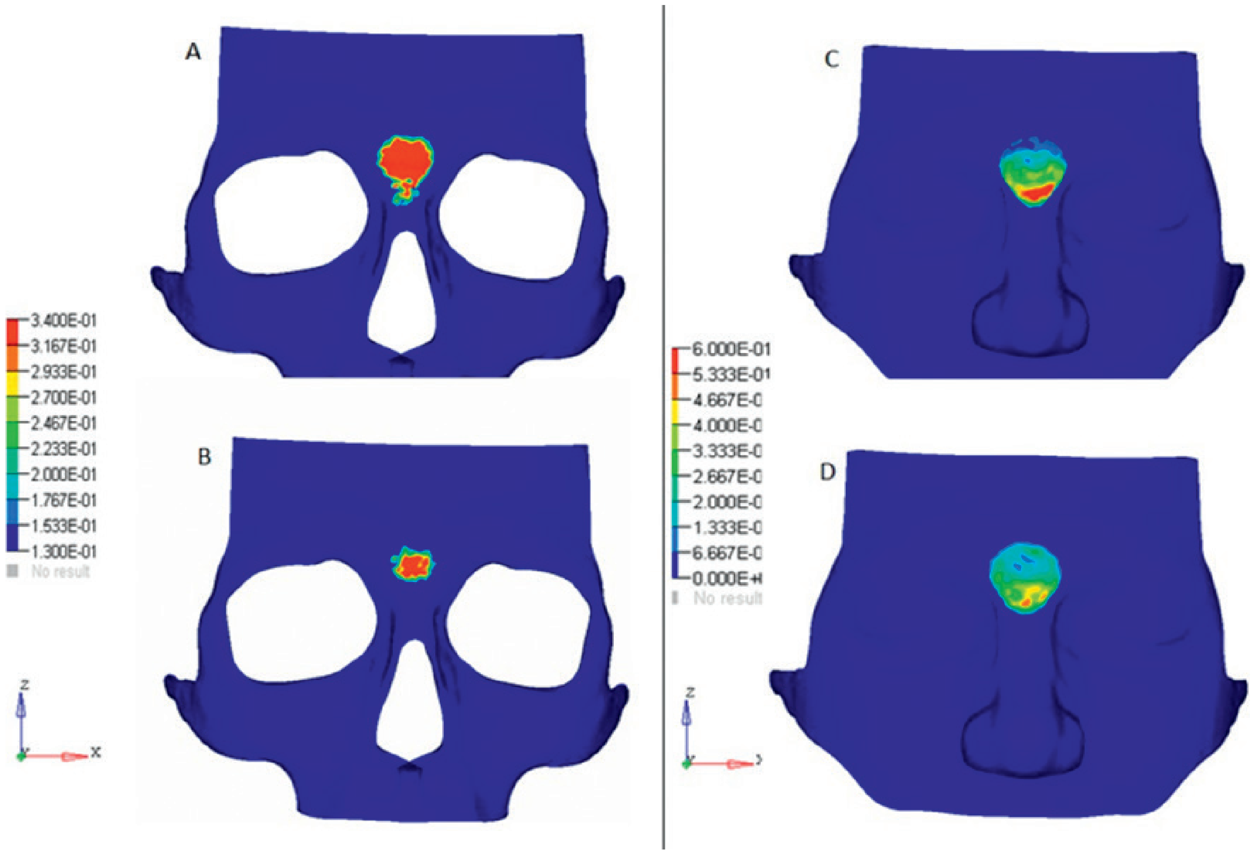

Figure 14. (A, B) Normal compressive stress in the bones of the frontal region, after impact, (A) without and (B) with nasal protector. (C, D) Normal compressive stress in the soft tissue of the frontal region, after the impact, (C) without protector and (D) with protector. Figure is extracted from Coto et al. [37].

4.3. Study of EVA to protect the zygomatic bone

The zygomatic bone forms the prominence of the cheek, part of the lateral wall and floor of the orbit. Due to its location and prominence, it presents a high risk of fracture [39–41]. The thickness is not constant in its extension. The zygomatic bone is composed of cortical and spongy bone in the thicker portion, and in the region near the frontonasal suture, it is almost exclusively formed by the cortical bone [41].

A simplified geometry of overlapping discs with a 100-mm radius was considered. The layers were composed of bone tissue (zygomatic bone portion, lower malar portion, near the nasal front suture), soft tissue and three proposed rigid and flexible EVA combinations, according to **Table 7**.

	Flexible EVA (thickness, mm)	Rigid EVA (thickness, mm)	Flexible EVA (thickness, mm)
G1	2	1	1
G2	3	1	–
G3	2	1	–

Table 7. Configurations analyzed for rigid and flexible EVA.

Figure 15 shows the geometry for G1. An extra configuration formed only by the cortical bone and soft tissue was also included in the analyses as a control group (CG) as shown in **Figure 16**.

Figure 16 also shows the projectile, here represented by a golf ball, with parameters obtained in Bartlett et al. [43] (**Table 8**). The ball had a velocity of 10 m/s at the instant of impact.

The parameters used for the cortical bone, soft tissue, flexible and rigid EVA are in **Tables 3–6**, respectively. The thicknesses of bone and soft tissue were 10.3 mm [42] and 12.3 mm [43], respectively.

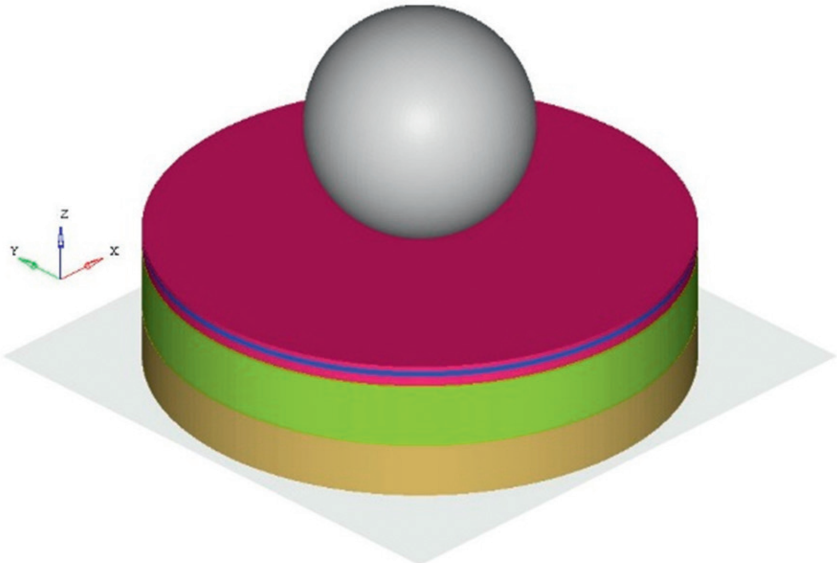

Figure 15. Simplified geometry (Group G1), soft EVA, rigid EVA, soft tissue amd bone.

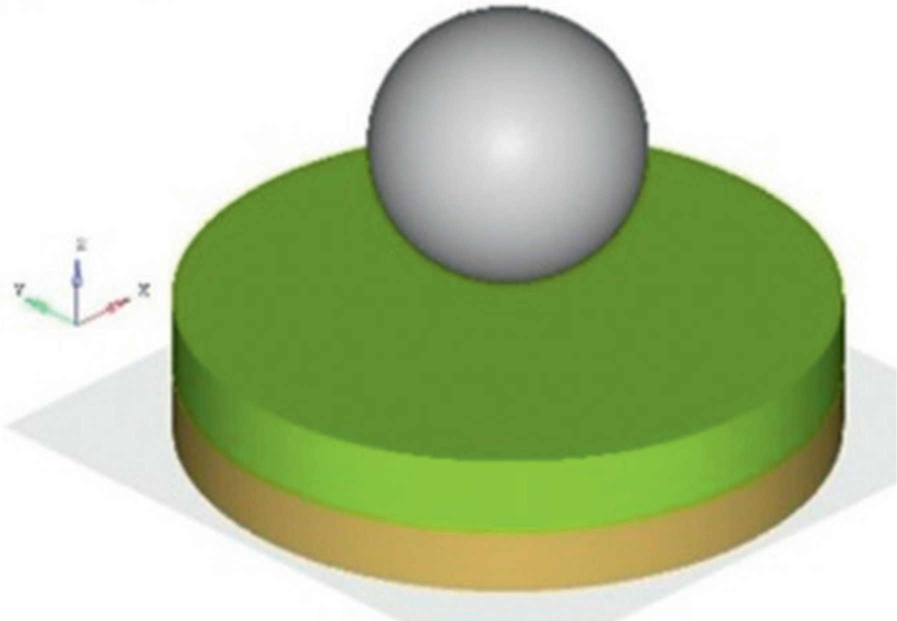

Figure 16. Control Group (CG), soft tissue and zigomatic bone.

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	Young Modulus (MPa)	Poisson coefficient	Density (t/mm³)	Radius (mm)	Velocity (m/s)
Golf ball	392	0.45	1.15 E − 9	21	10

Table 8. Geometric and material characteristics of the projectile.

The analyses were performed by the LS-Dyna software. The minimum compression stress was controlled. The maximum pressure allowed for the bone and the EVA (rigid or flexible) was of 2.7 MPa and 5.0 MPa, respectively. The friction value considered was 0.5 between ball and soft tissue.

5. FEA results

Figure 17 shows the pressure for the CG. The figure shows the high level of pressure at the zygomatic bone, exceeding the failure limit of 2.7 MPa.

According to the analyses, the results showed that in the three models proposed, there was the maximum performance of EVA, but the best protection to the studied bone is given by the G2 model. **Figure 18** shows the pressure profile in the EVA for G1 and G3.

Figure 19 shows the energy conversion during impact in G2.

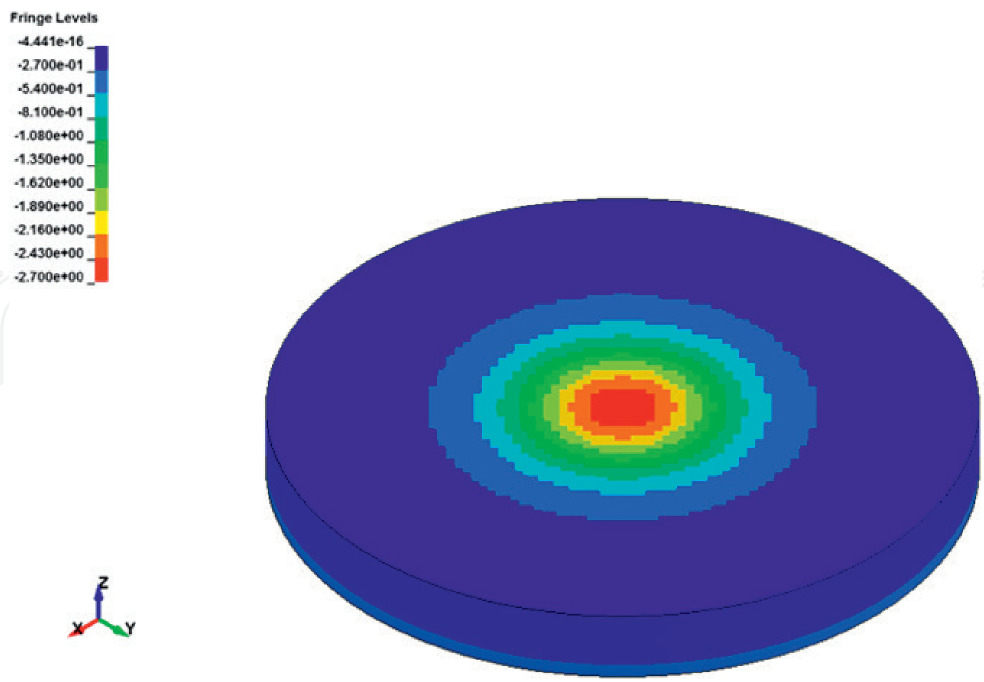

Figure 17. Pressure for the CG.

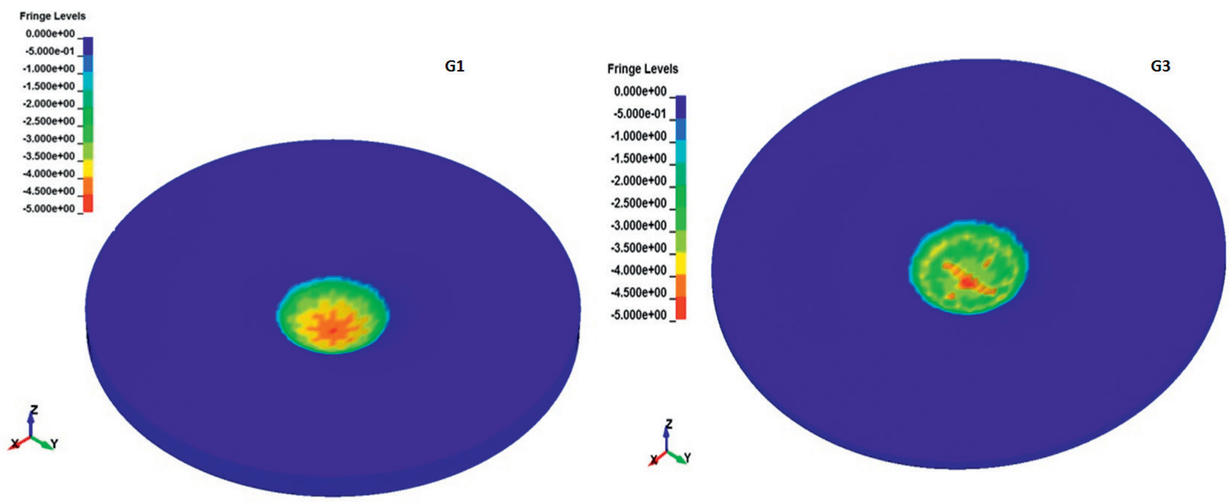

Figure 18. Results of pressure profile in the protector for G1 and G3, respectively.

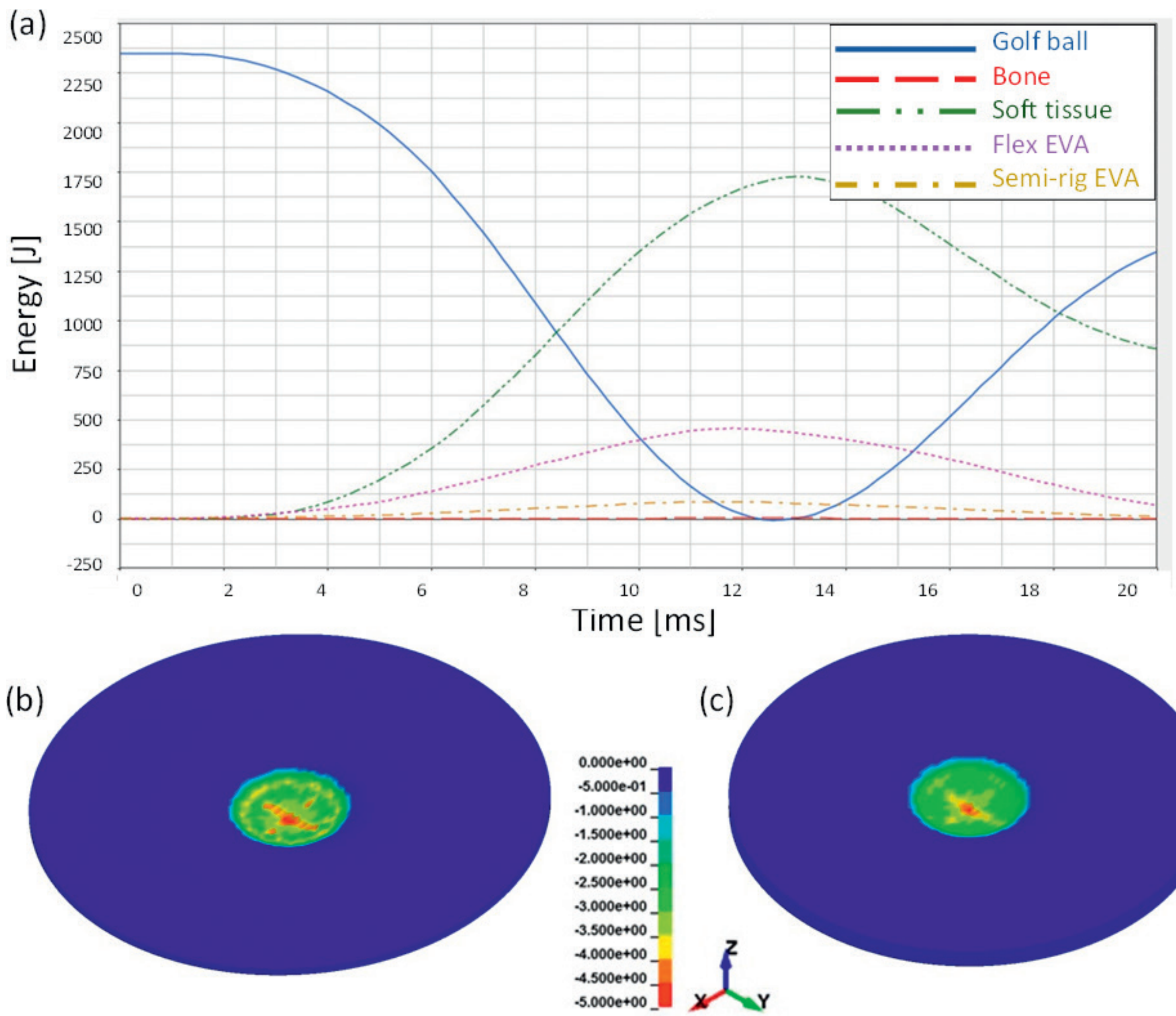

Figure 19. (a) Energy conversion during impact for G2; pressure in the (b) semirigid and (c) flexible EVA.

6. Conclusions

In human health science research, the study of materials that may replace organs is in constant evolution. Particularly in dentistry, the material should be easy to manipulate, esthetically acceptable, stable to use in the oral environment, in the presence of saliva and chewing conditions and low cost. Moreover, mechanical, physical, chemical and biological properties of any material used in the area must be known.

EVA was the object of this study. It is a thermoplastic copolymer derived from petroleum.

Initially, the material was studied in the mouth environment, and it was mechanically and chemically characterized. Finally, the material is molded and applied to facial protection.

The application is numerical, since studies in the biological area involving impact have become impossible to perform *in vivo*. FEM is a powerful tool, able to virtually mimic different complex phenomena. The quality of the results strongly depends on the correct material characterization, precise geometry of the analyzed structure and real boundary conditions (initial velocity of the projectile, displacement restrictions in the system).

The facial protector was tested during the impact of a golf ball in the nasal bone and, through a simplified model, in the zygomatic bone. The proposed protector is able to amortize the impact, and its configuration does not compromise peripheral view and does not cause discomfort to the athlete.

Author details

Reinaldo Brito e Dias[1], Neide Pena Coto[1]*, Gilmar Ferreira Batalha[2] and Larissa Driemeier[2]

*Address all correspondence to: neidecoto@gmail.com

1 School of Dentistry, University of São Paulo, Sao Paulo, Brazil

2 School of Engineering, University of São Paulo, Sao Paulo, Brazil

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