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Novel formulations of ballistic gelatin. 1. Rheological properties

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ABSTRACT

Ballistic gelatin is the simulant of the human body during field tests in forensics and other related fields, due to its physical and mechanical similarities to human trunk and organs. Since the ballistic gelatin used in present has important issues to overcome, an alternative approach is the use of gelatin–polymer composites, where a key factor is the insertion of biocompatible materials, which replicate accurately the human tissues. In order to be able to obtain an improved material in terms of mechanical performances by an easy industrial-scale technology, before the verification of the ballistic parameters by shooting in agreement with military standards, one of the best and cheapest solutions is to perform a thorough check of their rheological properties, in standard conditions.

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1. Introduction

Defense industry, forensics and sport industry have identified a growing demand for the trunk form that mimics exactly the mechanic response of the human body in order to achieve, on the one hand, new and better protecting equipment, and, on the other hand, for understanding the mechanisms of injury in response to a wide range of impact and penetration phenomena. More extensive research programs on the final effects of munitions or explosives against people were initiated, mainly the assessment and validation criteria of lethal and non-lethal ammunition [1–7].

In research and development of non-lethal weapons and ammunition, the difficulty does not come necessarily from technical modalities through which the interaction with the victim takes place, but the concept of non-lethality is called into question, the armament or ammunition system being imposed a series of requirements for injury degree. An appropriate ballistic simulant must perform similarly with the human tissues, in terms of mechanical behavior, enabling observation and measurement of temporary cavity and tissue compression.

Common simulants in these types of tissue exploit involved both skin, brain, muscle, internal organs, and ballistic gelatin or various other materials, such as rubber, leather, silicone elastomers, soap, grease and clay. Over the years, various methods have been used to replace the human tissue: water, wet phone books, wet paper, clay, or transparent gel; also, animals or dead subjects [7]. Besides the latter ones, which require special credentials prior to use, although they provide the opportunity to maintain a permanent record and a transfer of energy, the materials employed lack in the viscoelastic character of human tissue, and certain simulants, such as soap and clay, are mainly inelastic and provide a cavity of permanent deformation. In this context, two main types of materials have provided successful results for the human tissue simulation: soap and gelatin [1].

Ballistic gelatin-based tissue simulants are widely used in terminal ballistics testing and represent also an important tool for assessing projectile effects in living tissues. Ballistic gelatin is also the basic building material for reconstruction in forensic ballistic injuries. However, the reliability of scientific reports associated with the use of gelatin has uncertainties because there is no agreed standard for preparing it, but only for testing it [8]. Some researchers use 10%, while others use 20% concentration ballistic gelatin at different temperatures. The validation of the materials used has been previously performed by important international research teams of FBI on human cadavers [7,9]. The question of concentration is irrelevant as long as the gelatin has been

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validated to produce results that can be extrapolated to living tissue.

However, there are studies that state that water temperature and storage time affects the physical properties of gelatin. There are also a number of parameters that can also affect the properties of gelatin. To get valid and reproducible results, production and storage conditions should remain constant.

In this context, the aim of the present study was two folded: to obtain new materials for use as simulants, and to analyze them so that forensic results obtained be reliable when compared to real cases.

2. Materials and methods

2.1. Materials

260 Bloom edible pig gelatin, 500 cSt dimethylpolysiloxane (PDMS), 25% glutaraldehyde aq.sol. (crosslinking agent) [10], min. 99% propionic acid (antifoaming agent), and food red dye were purchased from Sigma–Aldrich.

Equipment and apparatus for synthesis included a 3000 mL glass reactor with cover and mechanical stirrer, dropping funnel, thermometer, 50–2000 rpm, oil bath; molds for trunk, heart, lung, liver, kidneys; a refrigerator; a climatic chamber Angelantoni DY600C working in the range −60 to +170 °C and 0–100% relative humidity.

2.2. Composite synthesis and molding

Non-crosslinked gelatin solutions stored below 30 °C form reversible physical gel networks. Incubation at 37 °C causes destruction of the physical network of gelatin, since the protein chains change from helix to random coil when heated above the sol–gel transition temperature [11], and it starts to degrade if not stabilized by crosslinking. The raw materials were chosen so that parameters as time and temperature stability be achieved. They were dosed accordingly to Table 1 (demineralized water:gelatin:glutaraldehyde:PDMS:propionic acid mixture). Gelatin is added to the water at 65 °C, in small portions, under vigorous stirring. After its complete dissolution, PDMS and propionic acid were added. Red dye has been added to the compositions meant for the organs, while for the torso no dye has been introduced. The final step consisted in the quick addition of the crosslinking agent, its homogenization in the mixture and the mixture loading in molding shapes, accordingly to their further processing purpose. All the tests were performed at least in triplicate and the results given are the average of the values obtained. The molded composites were cooled to room temperature.

In order to establish their degradation and biodegradation behavior, samples were submitted to various temperatures: −10 °C, +23 °C and 60% relative humidity, 4–7 °C and 16 °C (the temperature from laboratory), the materials being submitted further to analyses and tests and the results obtained for the aged samples were compared with the results obtained for freshly prepared samples.

Table 1
Composition of the hybrid composites (%wt).

No.	Demineralized water	Gelatin	Glutaraldehyde	Propionic acid	PDMS
1	90	10	–	–	–
2	85	15	–	–	–
3	80	20	–	–	–
4	88	10	0.5	0.5	1
5	83	15	0.5	0.5	1
6	78	20	0.5	0.5	1
7	87	10	0.5	0.5	2
8	82	15	0.5	0.5	2
9	77	20	0.5	0.5	2

2.3. Determination of hybrid composites density

The inhomogeneity in a material is due to its different degree of crystallinity in the areas of material, loss of plasticizer, solvent absorption, etc.

Tests for density determination were made in demineralized water on swelled hybrid composite samples at 25 °C and 50% relative humidity.

2.4. Determination of the swelling degree of the hybrid composite samples

The determination of the swelling degree of these materials was carried out by immersing dried samples of hybrid composite in demineralized water at 25 °C. The degree of swelling was determined from the formula:

$$SR = \frac{m_t - m_0}{m_0} \cdot 100(\%)$$

where SR – swelling rate; m_0 – initial mass of dried sample; m_t – sample weight after the swelling in distilled water at preset time. The swelling equilibrium was reached when the hydrogel mass remained constant.

2.5. Thermogravimetric analysis of the gelatin-based hybrid composite gels

Thermogravimetric measurements of hybrid composites were carried out at a 10 °C/min. heating rate in a nitrogen atmosphere, from room temperature up to 420 °C, using Instruments TGA Q500 from TA equipment.

2.6. Evaluation of the rheological properties of hybrid composites (G′ and G″ moduli determination)

Rheological tests were performed with a rotational rheometer Kinexus Pro Malvern using a temperature control unit. In oscillating mode, a parallel plate and geometric measuring system were used, and the gap was set according to the force value. After the sample was properly placed on the plate, the test took place with one of the three test temperatures: 5 °C, 23 °C and 37 °C. The frequency was set from 510 to 0.1 Hz. The elastic modulus (G') and the viscous modulus (G'') were recorded, and the phase angle was determined. The phase angle is the phase displacement between deformation and response in a dynamic-oscillatory test, with values between 0° and 90°, where 0° value implies the elastic behavior of the material and a 90° value – a viscous behavior of the material, between these values the materials behavior being viscoelastic.

3. Results and discussion

There is a wide range of articles and opinions on the type of simulants that should be used in ballistic forensic tests, but the assessment of the material properties versus human properties is difficult to perform due to deontological and law issues to overcome. Data measurements or hybrid finite element and finite/discrete element analyses of human/animal tissues or organs physical parameters are given very roughly in the literature [9,12,13]. Quantitative values for many organs elasticity parameters are not known yet [12,13]. Young modulus for bovine liver,

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