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Study of PDMS characterization and its applications in biomedicine: A review

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Review Article

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Abstract

Polydimethylsiloxane, also known as PDMS, has been widely used in the biomedical industry because of its biocompatible material and its biomechanical behavior is similar to biological tissues, with applications in the study of aneurysmal behavior and devices such as: Micro pumps, optical systems, microfluidic circuits. Many advances in research have been reached, but further tests are still necessary to understand the mechanical behavior and applicability of the material. For the study of PDMS behavior, two different techniques are employed: numerical and experimental. In experimental studies, it is extremely popular to use a field technique, in which the most appropriate technique to measure the field displacement of PDMS, without decorrelation, is the Digital Image Correlation (DIC) method. In this paper, we revised the most important experimental works with PDMS material and, simultaneously, we present its mechanical properties and its biomedical applications. ***DOI****: https://doi.org/10.24243/JMEB/4.1.163*

Keywords: Polydimethylsiloxane; Digital Image Correlation; clamping; hyperelastic material; biomedicine

1 Introduction

Currently, elastomers (rubbers) have been the object of study of many researchers due to some of their interesting biomechanical characteristics, such as: flexibility, chemical stability and resistance to corrosion. Among the various elastomers in the market, there is one that has come to stand out in recent years, which is the polydimethylsiloxane, also known as PDMS. This material has been applied in several industrial areas ranging from mechanics to electronics, and including biomedicine. Some of the reasons for its extensive use relate to its ease in the manufacturing process, its optical transparency, biocompatibility and its low cost. Thus, some of the most relevant PDMS applications are mechanical sensors **[1]**, electronic components **[2]**, electrochemical sensors **[3]**, medical equipment **[4]**, and biomedical research **[5]**, among others.

In this revision, it will be present the most relevant applications of PDMS in biomedicine. It is an area that is being evolved with the objective of improving techniques, materials and equipment that are able to aid help in to understand the behavior of certain pathologies and their respective treatments. Regarding biomedical applications, it

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was been shown that PDMS has a biomechanical behavior similar to some biological tissues and as a result PDMS can be qualified as a hyperelastic material. The hyperelastic behavior is characterized by the ability of some materials to undergo large deformations before their rupture. For the study of materials with this type of behavior, there are usually two different approaches: numerical and experimental. For the numerical application, it is generally used finite elements to simulate hyperelastic behavior; in this case, it is necessary to use constitutive models that are more suitable for the material studied and it's it is usually required to perform tensile tests (uni or biaxial) to better characterize the material under analysis. In the experimental approach, it is very common to use field techniques, such as ESPI (Electronic Speckle Pattern Interferometry) [6], Shearography [7] or Digital Image Correlation (DIC) [8]. However, in the case of hyperelastic materials the most suitable technique is DIC, once it allows the measurement of large displacement fields which are not possible with other field techniques without speckle decorrelation. For this reason, the experimental technique that will be adopted in this work is the DIC.

2 Polydimethylsiloxane

Polydimethylsiloxane (PDMS) is a polymer belonging to the group of silicone elastomers. It is a hyperelastic material that has a wide application in the biomedical industry, from contact lenses to medical devices, and also in the area of research and behaviors of diseases [9], thus attracting the attention of many researchers who see PDMS as a more sophisticated material which can replace previous methods and obtain more accurate data.

The synthesis of silicone was first obtained in 1950 by the Wacker Chemiecompany [10]. One of the first uses of PDMS occurred in the encapsulation of electronic components in order to extend the lifespan of the chips. With the development of technology and of behavioural studies and their characteristics, PDMS has been gaining new applications in micro and nanotechnology, and in the study of the biophysical behaviour of blood flow in microvessels [11].

2.1 Structure of PDMS

PDMS belongs to the group of siloxanes, however, in its advent, it was called silicocetones or silicones, but since as there was no double bond of Si = S, its name was later replaced by a specific nomenclature and its basic unit has become known as siloxanes. The most known material of this group is PDMS, a synthetic polymer whose main axis is made from the repetition of silicon and oxygen bonds and methyl groups [12]. Once the methyl groups may be substituted by other groups, for example, phenyl or vinyl, allowing the attachment of organic to inorganic groups, PDMS has a unique property and can be altered for different applications.

2.2 General properties of PDMS

PDMS is a material that has good microstructural characteristics, good manufacturing ability and a low cost. In the study of the microfluidics, it has been verified that PDMS presents higher properties than the old techniques that used materials such as glass and silicon, once the use of PDMS makes the work simpler and cheaper [13], [14]. In addition, PDMS is thermally stable, optically transparent [15], works as a thermal and electrical insulation [16], has good chemical stability and degrades quickly in the natural environment when compared to other polymers, and it presents no environmental problem.

The main disadvantage from the biomedical point of view is the difficulty of wetting its surface with aqueous solvents. This is due to the fact that PDMS presents a hydrophobic surface [17] because of its CH3 groups, which can lead to the fixation of liquid molecules and gases as fluorescent dyes **[18]** and organic solvents **[19]**.Considering this disadvantage, much effort has been devoted to improve the surface and wetting properties of PDMS **[20]**-**[22]**. Much progress has been made, for instance, the oxygen plasma treatment and the creation of a hydrophilic surface of PDMS**[23]**, however these techniques show some limitations when not revealing that the PDMS becomes temporarily hydrophilic and they do not ensure durability and stability of the coatings **[24]**, **[25]**, thus, proving that further progress is still needed in the study of the stability of PDMS treatments **[26]**.Also, one of its advantages consists in the fact that PDMS is able to chemically modify its structure, consequently opening the way to new applications and showing the need for new studies to understand its behaviour and applicability **[27]**, **[28]**.

Other important properties of PDMS are the permeability and elasticity. Permeability is the product of the solubility of a gas in a polymer and its diffusion. Siloxanes have greater permeability than most elastomers. The permeability of PDMS makes it advantageous for industrial applications in which it is necessary the separation of gases from the material, for example, in the development of artificial skins for burns **[29]**.

The good elastic capacity of silicones comes from the Si-O structure being more flexible than other conventional polymers that have C-C carbon structures. However, the flexibility of the siloxanes should not be defined solely by their ease of twisting, but also by their possibility of folding so large that it can be reversed **[12]**.

The PDMS offers a good elasticity, due to the fact that it exists in a very compact shape. Thus, when subjected to a tensile force, the polymer is stretched releasing its tension and then returns to its initial state when the load is removed.

The polymer has its elasticity determined by the ability of its regions, which are close, to slide on each other. This property is influenced by the number of existing cross links, the more cross-linked the PDMS is, the less it will be elastic **[12]**. As the PDMS is a soft material it is very sensitive to low loads. Furthermore, the PDMS is a viscohyperelastic material and the strain-rate effects are commonly observed **[30]**.

3 Biocompatibility

An important feature of PDMS is the biocompatibility, which is the ability of a material to be compatible with biological tissue.

Any material, when implanted in the human body causes an inflammatory response due to the reaction of the immune system that begins to act, with the aim of removing the strange body **[31]**, **[32]** which can lead to its encapsulation and, thus, damage the functioning of the implanted device **[33]**-**[35]**. Due to this effect, there was a need to look for materials that provide the least impact on the tissue **[36]**, which is an aspect of PDMS because it reduces the impact and interferences of the tissue response.

The fact that PDMS is biocompatible and bio-stable makes it the most studied implantable polymer. The PDMS is one of the most successful polymers, because when implanted it only causes a brief inflammatory reaction in the organism, which explains its wide use in personal care and topical skin applications. A long history of its use in medical devices, including long-term implants, has made silicones widely recognized as biocompatible. Currently, PDMS has been used as a coating on devices to be implanted in both humans and animals **[37]**, **[38]**. A prerequisite for such material is that it should not cause major inflammation after surgical intervention, and cellular behaviour should not be altered by toxic products that diffuse out of the material itself. These investigations of basic material are identified in in vitro cytotoxicity tests with standardized cell cultures. The international standard ISO 10993 "Biological evaluation of medical devices" describe test systems, procedures and evaluation schemes which classify an implant as biocompatible or not. The cytotoxicity test helps reduce animal experiments and allows the evaluation of different materials, due to standardized and application-specific cell lines **[38]**.

3.1 Structural Biocompatibility

Superficial biocompatibility describes only one aspect of this feature. On the other hand, structural biocompatibility refers to the mechanical interaction between the implant and the surrounding tissue, including weight, shape and flexibility (Young's module). Therefore, non-mechanical adaptation of the material to the tissue causes inflammation once a material with mechanical properties incompatible with the tissue is implanted as reacting cells begin to react, and subsequently, the implant gets involved. Hyperelastic polymers possess large modules of elasticity and have attractive properties in comparison to structural biocompatibility [38].

3.2 Biostability

The period that an implant stays in the human body is usually long. Biostabilityis linked with the integrity of the material throughout its stay in the body, where metals should not suffer corrosion and the coating should not deteriorate. In polymers, hydrolytic, oxidative and enzymatic degradation can occur and can be accelerated by changes in pH and stress in the integrated interconnect lines. In vitro immersion experiments, for example, in physiological saline, Ringer's or in means of cell culture, it is allowed a first approach of the biostibility of the materials which are often performed at higher temperatures to accelerate the diffusion processes, and thus has an influence on aging and in the meantime until failure [38].

4 Medical Applications of PDMS

Due to its characteristics of biocompatibility, chemical stability, transparency and mechanical elasticity, PDMS has been widely used in biomedical devices such as catheter and drainage tubing, dialysis membrane [39], micro pumps [40], micro valves [41], and are often found in fluidic circuits [42]-[44], and optical systems (adaptive lenses) [45]-[47]. It has also been used as research material, helping to understand the behaviour of diseases, for instance, aneurysm and their respective treatments, [9], [48] and in implants [49], [50].

4.1 Use of PDMS in Aneurysm Evaluation

An aneurysm occurs when the artery wall weakens, with saccular dilatation [51], the causes of wall weakening are still unknown. It may originate in congenital defects, atherosclerotic changes, traumatic or infectious emboli. Some other factors that may be related to the appearance of an aneurysm are hypertension, smoking, excessive alcohol use, increase in age, and it also tends to have a higher occurrence in females. The rupture of an aneurysm may represent a very high risk of death [52], as it estimates that 2.6% of the general population has an intracranial aneurysm and accounts for almost 85% of subarachnoid hemorrhages [53].

Several studies have been done to understand the hemodynamic behaviour of blood cells in the artery, however, hemodynamic studies are still lacking to understand the mechanical effects on the expansion of the aneurysm walls.

Recently, a study conducted by Rodrigues et al [9] developed and fabricated a model of intracranial aneurysm using a 3D printer and PDMS material to simulate the mechanical behavior of blood vessels. The aneurysm displacement fields were obtained using the digital image correlation technique (DIC) and the results of the tests were used to validate numerical simulation using finite element method.

4.2 Use of Injectable PDMS for Aneurysm Repair

As already seen, an aneurysm is the weakening of the arterial walls, making them thin and at great risk of rupture, thus, the aneurysms which did not suffer rupture and when discovered in time are usually repaired. One complication that affects the success of such repairs is the migration of the stent graft, which can cause type 1 endoleak or even rupture of the aneurysm.

Recently, a method of excluding an aneurysm was proposed, which consists of injecting a biocompatible elastomer (PDMS) into the aneurysm region, reducing wall tension and consequently, aneurysm rupture [48], [54], [55].

5 Digital Image Correlation

In order to study the mechanical behaviour of materials, it is necessary to measure quantities, such as stress and displacement. The Digital Image Correlation (DIC) technique is an optical method, without contact, which basically consists of obtaining images of an object with a random pre-established pattern, making its records and comparing the images in two distinct states, not deformed and deformed, in order to determine the displacement field. Nowadays, this technique is becoming attractive due to the simplicity of the equipment, when compared to other methods of displacement analysis, besides being a method which is able to measure with high precision displacement fields and not only punctual displacements. The possibilities of using this method are very wide due to the fact that it is able to measure small displacements in micro and nano scale and also measure great displacements of diverse dimensions. The DIC technique has been used in both studies of hyperelastic polymers[56]-[58] and in the analysis of the mechanical behavior of various materials used in industries [59], [60].

Depending on its application, the digital image correlation can be divided into three different forms: 2D which determines in-plane displacement field [61], 3D measurement system can be used to determine in-plane and out-ofplane displacement fields [62] and its most recent use of Digital Volume Correlation, which is a technique that uses Xray computed tomography and thus determines deformations in the entire body [63]. The equipment set-up consists in the use of high resolution CCD cameras (charged-coupled devices), one or two cameras for 2D and 3D measurements, respectively, non-special lighting, and a computer with image correlation software, as shown in Fig. 1.

The changes in the images can be described by the same concepts of the continuum theory which governs the deformation in small areas. In the field of experimental mechanics, this initial concept was refined and incorporated into numerical algorithms to extract from the sequence of images the value of the deformation. The digital recording of the images has been carried out with several patterns: among them: lines, grids, points and matrices. A widely used method is that which uses random pattern, comparing sub-regions along the sequence of images [64].

***Fig.1 3D Digital Image Correlation set-up.**[9]*

This technique tracks the pixel blocks of the sub-regions, allowing the measurement of surface displacement, and thus, generating the vector field displacement. The method to perform effectively, it is necessary that the pixel blocks be random and unique with a range of contrast levels and intensity.

The correlation calculation is done by comparing the images of the body before suffering the deformation and after the deformation, mapping the initial and final position of the points, and as a result, determining its displacement field, according to the scheme shown in Fig. 2. The correlation of the two images (reference and deformed) is given by the equation (1) and the components of displacement vector are determined by the equations (2) and (3) [65].

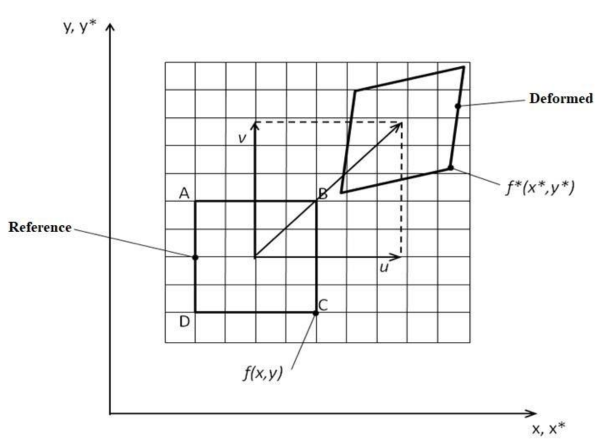

Fig.2Variation of the initial state (reference) to the final state (deformed)**[66]**.

$$C^*(u^*,v^*) = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}[f(x_i,y_j)-\bar{f}]\left[g\left(x'_i,y'_j\right)-\bar{g}\right]}{\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n}[f(x_i,y_j)-\bar{f}]^2}\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[g\left(x'_i,y'_j\right)-\bar{g}\right]^2}} \quad (1)$$

In which

$$x' = x + u_0 + \frac{\partial u}{\partial x}\cdot dx + \frac{\partial u}{\partial y}\cdot dy \quad (2)$$

$$y' = y + v_0 + \frac{\partial v}{\partial x}\cdot dx + \frac{\partial v}{\partial y}\cdot dy \quad (3)$$

The value of the pixels of the undeformed image is presented by the function f(x, y) and the image of the deformed image is presented by the function g(x ', y'), $\bar{f}$ and ḡ are average values of the images, e u e v are the central components of displacement in the x and y directions, respectively.

The DIC method, as well as other field techniques, has some advantages and, what it stands out is that any object can be measured, independent of its temperature, there is no need for special light, the optical apparatus used is simple, it is a non-destructive method, has a low cost and can be used with many types of materials, such as metals, polymers, composites, biologicals, and others.

6 Conclusions

PDMS has become a widely used biomedical material. In this article, it is presented the relevance of PDMS in different medical applications and new techniques, as well as in the study of aneurysm behaviour, showing the importance of PDMS in the present and future of biomedicine.To advance the application of the PDMS in the study of the aneurysm, we intend to perform new mechanical tests and optimize the technique of manufacture of the aneurysm model. The best way to characterize this material is to use optical field techniques, with the digital image correlation method being the most suitable for application to materials with a hyperelastic behaviour which is intrinsic to the PDMS.

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