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Application of atmospheric pressure plasma on polyethylene for increased prosthesis adhesion

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ABSTRACT

Biopolymers are often subjected to surface modification in order to improve their surface characteristics. The goal of this study is to show the use of plasma technology to enhance the adhesion of ultra-high molecular weight polyethylene (UHMWPE) shoulder prostheses. Two different plasma techniques (low pressure plasma activation and atmospheric pressure plasma polymerization) are performed on UHMWPE to increase the adhesion between (1) the polymer and polymethylmethacrylate (PMMA) bone cement and (2) the polymer and osteoblast cells. Both techniques are performed using a dielectric barrier discharge (DBD). A previous paper showed that low pressure plasma activation of UHMWPE results in the incorporation of oxygen-containing functional groups, which leads to an increased surface wettability. Atmospheric pressure plasma polymerization of methylmethacrylate (MMA) on UHMWPE results in a PMMA-like coating, which could be deposited with a high degree of control of chemical composition and layer thickness. The thin film also proved to be relatively stable upon incubation in a phosphate buffer solution (PBS).

This paper discusses the next stage of the study, which includes testing the adhesion of the plasma-activated and plasma-polymerized samples to bone cement through pull-out tests and testing the cell adhesion and proliferation on the samples. In order to perform the pull-out tests, all samples were cut to standard dimensions and fixed in bone cement in a reproducible way with a sample holder specially designed for this purpose. The cell adhesion and proliferation were tested by means of an MTS assay and live/dead staining after culturing MC3T3 osteoblast cells on UHMWPE samples. The results show that both plasma activation and plasma polymerization significantly improve the adhesion to bone cement and enhance cell adhesion and proliferation. In conclusion, it can be stated that the use of plasma technology can lead to an implant with improved quality and a subsequent longer lifespan.

1. Introduction

Total shoulder arthroplasty (TSA) is commonly used as treatment for diseases of the glenohumeral joint, such as symptomatic osteoarthritis, rheumatoid arthritis or avascular necrosis [1,2]. The shoulder joint is a ball-and-socket joint, which consists of two main parts: the humerus (upper arm) and the glenoid cavity (located in the shoulder blade). An anatomical TSA mimics this anatomy and therefore also consists of a humeral and glenoid component. The former is a modular system containing a stem and a rounded head or ball, usually made of titanium or a cobalt–chromium alloy. The latter component is a concave socket made of ultra-high molecular weight polyethylene (UHMWPE). The major problem concerning total shoulder replacements today is the loosening of the glenoid component [3]. The standard for fixation of a full-UHMWPE component is using bone cement, usually a polymethyl methacrylate (PMMA) resin. Other techniques such as the use of metal-backed components and full-UHMWPE components without bone cement can be applied based on the patient's requirements [4]. However, in spite of these additional techniques and the fact that the glenoid component can come in different geometrical designs, e.g. pegged or keeled, the incidence of glenoid component loosening is still too high and accounts for about 80% of all complications [2–4]. The region of failure is mostly the interface between the glenoid component and the PMMA bone cement [3]. This is mostly due to the nature of the used material. Although UHMWPE has excellent mechanical properties, it is an inert and non-polar material. As a consequence, it is difficult to adhesively bind UHMWPE [5]. By improving the adhesive properties of medical grade UHMWPE using surface modification, it can be possible to improve the lifespan and quality of a shoulder implant.

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The literature shows extensive research, using plasma technology, on the improvement of the wettability and adhesion of polymer surfaces [6–12]. Plasma activation has been widely used in the past to introduce functional groups such as hydroxyls and alkanoates onto polymer surfaces, making them less inert and more polar. Research has shown that an increase in wettability can also lead to an increase in cell adhesion and proliferation [10,13,14]. Another plasma-based surface modification technique is plasma polymerization which is a method to produce thin polymer films on a substrate, allowing changes in the surface properties by depositing a coating. The produced plasma polymerized films are in general pinhole-free, highly cross-linked, insoluble in nearly all solvents and also strongly adhere to numerous substrates [15–21].

The goal of this study is to show the potential of plasma technology as a surface modification technique to enhance the adhesion of UHMWPE shoulder prostheses. Low pressure plasma activation as well as atmospheric pressure plasma polymerization of methyl methacrylate (MMA) will be performed on medical grade UHMWPE to (1) increase the adhesion between the polymer and PMMA bone cement and (2) to enhance the cellular interactions with UHMWPE. Plasma polymerization of MMA will result in the deposition of a plasma-PMMA (PPMMA) thin film on a pre-activated UHMWPE surface. This intermediate layer will show a chemical composition similar to the bone cement used in TSAs and may therefore improve the adhesion between the implant and the bone cement. Both plasma activation and plasma polymerization experiments will be performed using a dielectric barrier discharge (DBD) at medium pressure and atmospheric pressure respectively. DBDs are known for their easy formation of a stable discharge and their scalability. The efficiency of medium pressure DBDs has already been demonstrated in the field of plasma activation as well as plasma polymerization [9,10,16,19,21,22]. In a previously published paper, results and insights in UHMWPE plasma surface modifications have already been described by using a varied set of analysis techniques [23]. Low pressure plasma activation of UHMWPE resulted in the incorporation of oxygen-containing hydrophilic functional groups, which led to an increased surface wettability. Atmospheric pressure plasma polymerization of MMA on UHMWPE resulted in a PMMA-like thin coating, which could be deposited with a high degree of control of chemical composition and layer thickness. The deposited thin films also proved to be relatively stable upon incubation in a phosphate buffer saline (PBS) solution.

This paper however will discuss the next stage of the study, which is testing the effect of plasma technology on characteristics that are important towards the application to a shoulder prosthesis. This includes testing the adhesion of plasma-activated and plasma-coated samples to bone cement through pull-out tests and testing the cell adhesion and proliferation on plasma-modified samples.

2. Materials and methods

2.1. Chemicals and materials

For the plasma polymerization experiments, MMA (99%, 30 ppm MEHQ as inhibitor) was purchased from Sigma-Aldrich (Belgium) and used as such. Dry air, argon (Ar), helium (He) and nitrogen (N_2) (Alphagaz 1) were purchased from Air Liquide (Belgium). Specifically for the cell tests, an UHMWPE film purchased from Goodfellow Cambridge Ltd. (England) with a thickness of 0.5 mm is used as substrate. All other experiments are performed on medical grade UHMWPE pieces with a thickness of 4 mm, which were mulled from a Chirulen 1020 plate purchased from Quadrant EPP Belgium. The bone cement was obtained from Huge Dental Material Co. (China) and consists of a PMMA resin and an MMA liquid component. Upon adding the liquid component to the PMMA resin, a bone cement paste with a curing time of 20 to 30 min is formed.

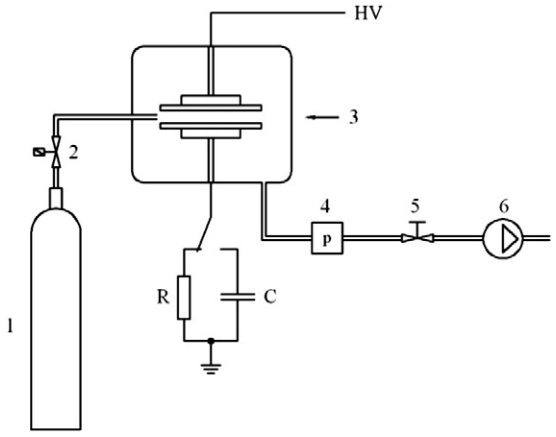

Fig. 1. Schematic representation of the DBD plasma activation reactor. 1: gas bottle; 2: mass flow controller; 3: DBD plate reactor; 4: manometer; 5: pressure valve; 6: oil pump.

2.2. Plasma methods

Both plasma activation and plasma polymerization experiments are performed in a DBD reactor. Fig. 1 shows the schematic of the DBD reactor used for activation. The discharge is generated between 2 circular copper electrodes, which have a diameter of 65 mm and are covered by a glass plate. The gap between the electrodes is 7 mm. The lower electrode is connected to earth through a 50 Ω resistor or a 10 nF capacitor, while the upper electrode is connected to a 5 kHz AC high voltage power source. The UHMWPE samples are fixed on the lower glass plate using tape followed by pumping the reactor to 0.1 kPa using a rotary vane pump. Subsequently, the reactor is filled with the gas of choice at a rate of 3 standard liters per minute (slm) until a pressure of 90 kPa is reached. At this sub-atmospheric pressure, the plasma reactor is flushed at 3 slm with the working gas for 3 min to obtain a controllable gas composition. Finally, the pressure is lowered to 5.0 kPa, the gas flow is adjusted to 1 slm and plasma activation is performed by turning on the plasma source for a specific time interval.

Plasma polymerization experiments are done in a second DBD reactor, which is schematically presented in Fig. 2. The discharge is generated between 2 circular copper electrodes with a diameter of 55 mm, which are both covered by a glass plate. The gas gap between the

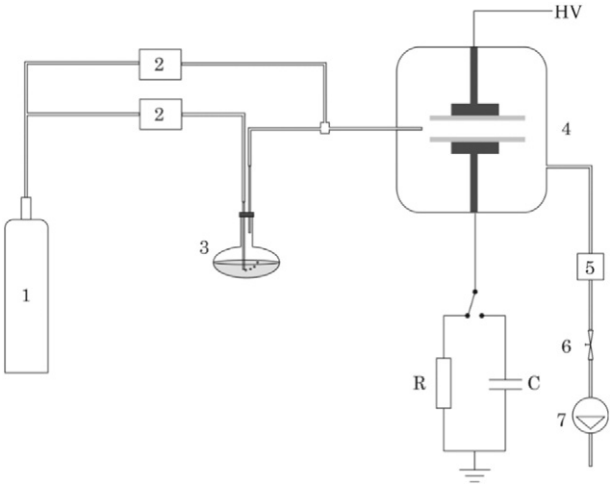

Fig. 2. Schematic representation of the DBD plasma polymerization reactor. 1: gas bottle; 2: mass flow controller; 3: gas bubbler containing MMA; 4: DBD plate reactor; 5: manometer; 6: pressure valve; 7: oil pump.