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Cold atmospheric pressure gas plasma enhances the wear performance of ultra-high molecular weight polyethylene

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ABSTRACT

Ultra-high molecular weight polyethylene (UHMWPE) is frequently employed in joint replacements because of its high biocompatibility; however, this material does not exhibit particularly strong wear performance, thus potentially reducing the longevity of such devices. Numerous techniques have been investigated to increase the resistance to wear of UHMWPE, but they are all based on expensive machinery and require a high level of safety precautions. Cold atmospheric pressure gas plasma treatment is an inexpensive process that has been used as a surface modification method and as a sterilization technique. We demonstrate for the first time that a helium/oxygen cold atmospheric pressure gas plasma can be used to enhance the wear performance of UHMWPE without affecting the cytocompatibility of the material. The exposure to a cold atmospheric pressure gas plasma results in a greater level of crosslinking of the polyethylene chains. As a consequence of the higher crosslinking, the material stiffness of the treated surface is increased.

1. Introduction

Modern approaches to degenerative joints diseases are total joint replacement (TJR) and total disc replacement (TDR). These techniques have become increasingly popular due to the benefits of an enhanced life quality post operation and increasing life expectancy. The future will see a growing number of joint replacements because of the increasing average age of the population and the confidence in achieving high levels of activity [1,2].

The longevity of replacement joints and discs is a key factor in determining the success of such operations, which is mainly affected by the wear performance of the implant material [3,4]. Hence, the implants must be engineered to maximise wear performance, thus alleviating wear-related biological reactions [5,6]. To this end the choice and availability of implant materials is of central importance. Despite significant research effort and the application of new bearing materials such as carbon-fibre-reinforced and poly(ether ether ketone) [7,8], ultra-high molecular weight polyethylene (UHMWPE) remains the main bearing material of choice in knee and hip arthroplasty, because of the simplicity of the fabrication process, the biocompatibility and the low friction [9]. Nevertheless, UHMWPE is not wholly satisfactory. For example, present UHMWPE materials show high material loss due to relative motion between articulating surfaces. This leads to prosthesis failure due to adverse biological reactions to polyethylene debris particles, called osteolysis [6,10–14].

Therefore, there is a need to develop better-performing polymeric materials and/or improve the present UHMWPE materials to reduce wear and adverse reactions to wear particles whilst retaining bone and natural function. The traditional ways of improving wear performance of UHMWPE are by techniques such as gamma or electron beam irradiation followed by thermal stabilization (annealing or re-melting) [15]. The main disadvantages of these techniques are that wear resistance is accompanied by a decrease in bulk mechanical properties, such as toughness, tensile strength and fatigue performance [16]. This could be a serious problem for orthopaedic devices exposed to high stresses or large cyclic contact stresses as in the case of total knee replacement. Among other recent techniques of UHMWPE modification are the use of fibres [17], ion implantation [18,19] and argon plasma [20] and rapid heavy ion beam irradiation [21]. These techniques normally require a thermal stabilization step to eliminate the residual reactive species present in the materials, whose activity could result in reaction products with a detrimental effect on the overall performance of the treated material. In addition, such processes are expensive as they have to be carried out in complex machines.

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Ionized gases or gas plasmas have been an essential surface processing technology used extensively for microelectronics fabrication and surface coating [22]. At low gas temperatures they are very effective in facilitating the modification of surface chemistries and functionalities by means of ions, electrons, and chemically reactive species (usually atoms and small molecules) that are produced in an electrical discharge. In fact, low temperature gas plasmas have been used to treat UHMWPE materials [23]. The majority of commercially available gas plasma systems are based on operation at reduced gas pressures (from the ambient pressure of 760 torr), which is achieved in a vacuum chamber. However, it is now possible to generate near room temperature, chamber-free gas, plasmas at atmospheric pressure [24–26], thus offering a cost-effective and versatile surface processing technology for treating three-dimensional objects of dielectric, metallic, colloid and composite materials [27]. Commonly known as cold atmospheric pressure plasmas (CAP), they have already been used as a surface modification technique [28,29]. More recently medical applications in skin and wound cleaning and blood cauterization have been developed [30,31].

In this contribution we report an experimental study to establish whether a cold atmospheric pressure plasma produced from helium mixed with different amounts of oxygen (0–0.5%) offers an effective and beneficial approach to treatment of UHMWPE in the context of total joint and disc replacement. A second benefit of such a technique is the antimicrobial properties of cold gas plasmas that allows simultaneous wear performance enhancement and material sterilization [32–35]. Therefore, cold atmospheric pressure plasmas offer multiple benefits to surface treatment of UHMWPE. An additional objective of this work was to establish whether a cold atmospheric pressure gas plasma could enable effective sterilization of UHMWPE materials at the same time as enhancing the surface functionalities. Whilst low temperature plasmas are known to be capable of effectively modifying surfaces and efficiently sterilizing materials, it is so far unknown whether these two properties could be achieved simultaneously by near room temperature ambient pressure plasmas of non-toxic gases such as a helium/oxygen admixture.

2. Materials and methods

2.1. CAP source and treatment of the UHMWPE sample

The cold atmospheric pressure plasma source was made of a capillary as the powered electrode and a downstream ring electrode (Fig. 1). The capillary electrode was housed within a quartz tube having an inner diameter of 1.5 mm, slightly larger than the outer diameter of the capillary electrode, and its tip was recessed by 1.5–2 cm from the end of the quartz tube. The ring electrode was wrapped around the outside of the quartz tube near the nozzle. A helium (99.99%) flow of 5 slm (standard litre per minute) and an oxygen flow of 10 sccm (standard cubic centimetre per minute) were combined before being passed through the capillary electrode, which doubled as the gas inlet. The two electrodes were energized by a purpose built high voltage alternative current (a.c.) power supply with a peak to peak voltage of 8 kV and an excitation frequency of about 20 kHz.

The axial separation of the capillary electrode and the ring electrode are used to produce an axially directed electrical field upon the application of an external voltage, with the gas flow also in the axial direction. Because of the alignment of the electrical field and the gas flow in the axial direction this type of CAP source is often known as a linear field device [36], the details of which have been reported previously [25]. Under the influence of an applied a.c. voltage the helium/oxygen mixture is broken down to form an electrical discharge inside the quartz tube. This gas plasma appears as a light emitting plume extending from the quartz tube, commonly known as a CAP jet or simply plasma jet. It is known that linear field plasma jets have a long plume length and effective application efficiency [36], and as such this study employed a linear field plasma jet as described above. Under the experimental conditions considered in this study the plasma plume was more than 1 cm long and its gas temperature was always below 27 °C. Samples to be treated were placed on a sample holder which was grounded electrically and the sample was fixed at 1 cm directly downstream of the quartz nozzle. The holder was rotated so that the entire UHMWPE was exposed to the CAP jet plume in turn. The samples were exposed to the plasma plume for 2, 7.5 and 15 min.

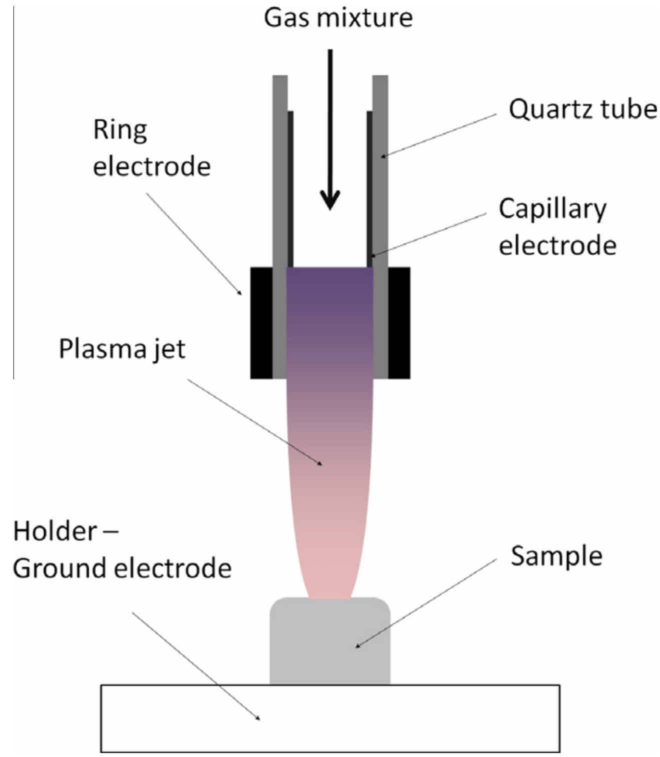

Fig. 1. Schematic representation of the cold atmospheric gas plasma rig.

The treated samples were kept at room temperature and subjected to material and surface characterization within 1 day. Wear testing was also initiated in the same time interval.

2.2. Wear testing

Wear testing of UHMWPE (GUR 1020, Hoechst, Germany) was performed using a single station pin on plate in-house built wear simulator under constant load applied under lubricated conditions. Pins were machined from ram extruded crosslinked (4 Mrad) UHMWPE while metallic plates were made of medical grade wrought cobalt–chromium alloy (according to ASTM F1537) and polished to an average surface roughness $R_a \approx 0.01$ µm. Before wear testing all samples were soaked in distilled water at room temperature for 2 weeks, to saturate them. The lubricant employed in all wear tests consisted of 25 vol.% bovine serum (Harlan Sera-Lab, Loughborough, UK) in sterile water with 0.1% (w/v) sodium azide to inhibit the growth of bacteria. The lubricant was changed every week and serum samples were collected for wear debris analysis. Control pins were soaked in lubricant for the