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Grinding wheel motion, force, temperature, and material removal in rotational atherectomy of calcified plaque

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ABSTRACT

This study investigates the grinding wheel motion, force, material removal, and temperature in rotational atherectomy (RA). RA utilizes a metal-bond diamond wheel to remove plaque from arteries to treat cardiovascular diseases. As a plaque surrogate, a bone workpiece was placed in a vessel simulator and subjected to RA with a wheel rotational speed of 160,000 rpm. This grinding process was monitored by a high-speed camera, a dynamometer, and embedded thermocouples. The results show this process has a 108 Hz wheel orbital frequency, an oscillating grinding force of 0.23 N, 90% debris smaller than 31 µm, and a 4.1 °C temperature rise.

1. Introduction

Rotational atherectomy (RA), as shown in Fig. 1, is a grinding process to remove plaque from arterial walls to restore blood flow. RA utilizes a high-speed metal-bond diamond grinding wheel (1.25–2.5 mm diameter and up to 210,000 rpm [1]) for the treatment of several cardiovascular diseases, e.g. the calcification (hardening) of plaque, arterial bifurcation, ostial stenosis, and in-stent restenosis in which RA is preferred over traditional angioplasty [2]. The grinding wheel is driven by a long flexible drive shaft and rotates around a stationary guidewire (0.23 mm diameter). The shaft rotates within a sheath where saline flows (marked by arrows in Fig. 1) for lubrication and cooling. Blood flows outside the sheath.

Clinically, RA has high complication rates [1]: restenosis – the regrowth of the plaque after RA – occurs in over 50% patients; and other complications include myocardial infarction, dissection, perforation, slow-flow/no-reflow, vasospasm, and grinding wheel entrapment. Extensive clinical studies have been conducted to lower complication rates. A current universally accepted protocol suggests an initial grinding wheel size of 1.25–1.5 mm with a rotational speed ranging from 135,000 to 180,000 rpm [3]. Safian et al. [4] suggested avoiding excessive rotational speed decreases (>5000 rpm) as this indicates large grinding forces that may damage healthy tissue. Kini et al. [5] recommended a plaque grinding time between 20 and 30 s to prevent vessel dissection and thermal damage, with a grinding wheel diameter less than 70% of the treated artery diameter to avoid over-stretching the lesion. Lin et al. [6] found that advancing the grinding wheel across long, angulated, and heavily calcified lesions may cause a steep decrease of the rotational speed and entrap the wheel, suggesting a slow and steady advance of the wheel for less than 15 s.

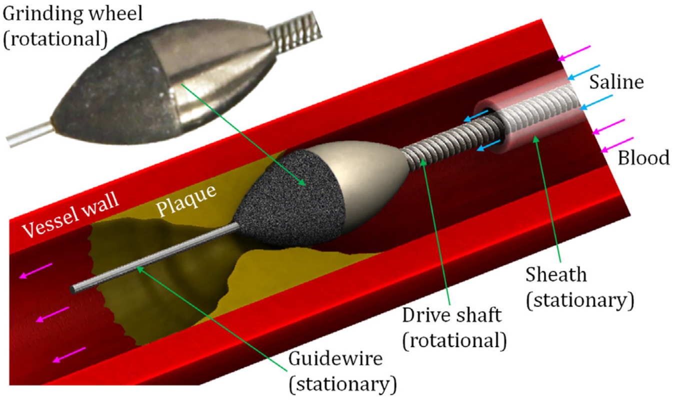

Fig. 1. Rotational atherectomy – the plaque grinding process.

Engineering studies in RA have thus far been limited to investigation into grinding wheel design and rotational speed. For instance, Kim et al. [7] modified the grinding wheel surface by laser engraving to reduce microcavitation and tissue damage. Nakao et al. [8] created micro-blades on the wheel surface to replace diamond abrasives. Reisman et al. investigated the effects of rotational speed on platelet aggregation [9] and tissue thermal injury [10]. However, our review of the literature has found that there is a lack of knowledge in the grinding process and plaque removal mechanism in RA.

Understanding the grinding wheel motion, force, debris size, ground surface, and temperature is critical to ultimately improving RA techniques and devices. Because of the high rotational speeds, the flexibility of the drive shaft, and poor visibility and accessibility of the grinding site within arteries, investigation of these grinding mechanisms is and has been challenging. To address these issues, this study investigated the RA grinding process within a semi-transparent soft tissue-mimicking phantom embedded with a

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ring-shape bovine bone workpiece as a plaque surrogate. To measure the grinding wheel motion, force, and temperatures during the grinding process, a high-speed camera, piezoelectric dynamometer, and embedded thermocouples were utilized, respectively.

RA device and experimental setup and design are first introduced. Results on grinding wheel motion, force, debris size, surface topography, and temperatures of the blood-mimicking fluid and plaque surrogate are presented and discussed.

2. Experimental setup

The experimental setup, as shown in Fig. 2, consists of three modules: (1) a rotational atherectomy device, (2) tissue phantom, and (3) measurement system.

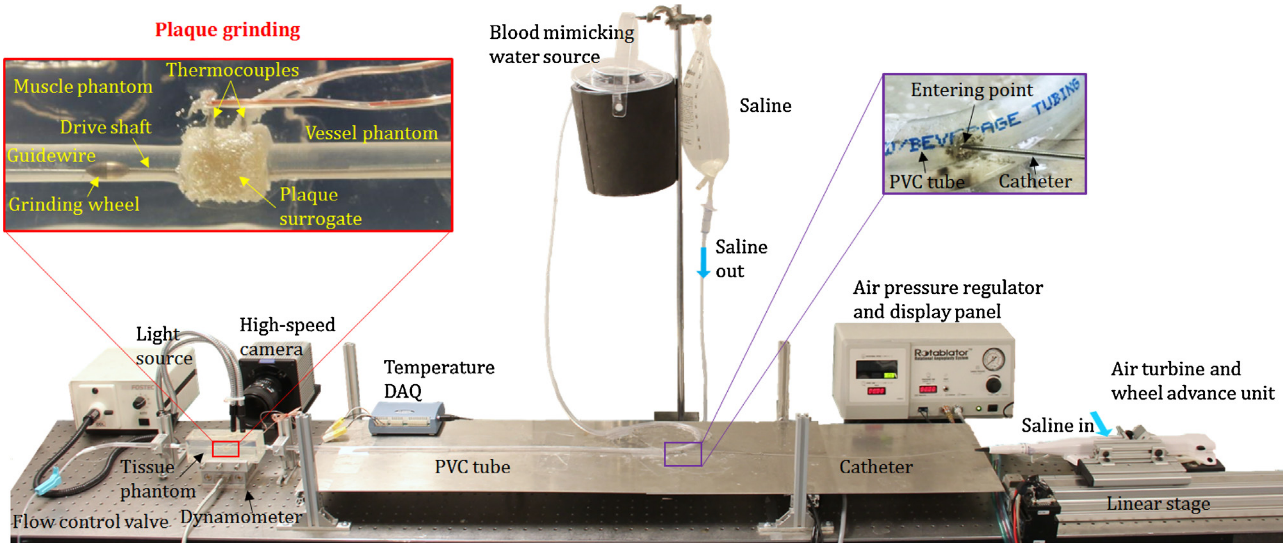

Fig. 2. Experimental setup.

2.1. Rotational atherectomy device

The RA device, Rotablator^{TM} by Boston Scientific, includes a catheter, an air turbine, a grinding wheel advancing unit, and an air pressure regulator with an information display panel.

The catheter, as shown in Fig. 3, is inserted into the artery during RA. The stationary guidewire extends from the air turbine through the drive shaft and grinding wheel to beyond the plaque (Fig. 1). The guidewire guides the rotation and translation of the grinding wheel and drive shaft. As illustrated in the cross-section A-A in Fig. 3, the catheter consists of a stainless steel guidewire (0.23 mm diameter), a drive shaft (0.65 mm outer diameter (OD)), and a sheath (1.43 mm OD, 0.2 mm thick). The drive shaft connects the grinding wheel and air turbine and is made of three helically wound 0.18 mm diameter stainless steel coils. The shaft rotates inside a stationary Teflon sheath. The friction between the drive shaft, the guidewire, and the sheath is reduced by flowing saline inside the sheath (shown in Fig. 1). The grinding wheel, as shown in Fig. 3, is an ellipsoid with the distal half coated with diamond abrasives with an average size of 10 μm, as shown in the scanning electron microscope (SEM) image. A 2.5 mm diameter grinding wheel was used in this study.

The air turbine drives the grinding wheel from 6000 to 210,000 rpm. An advance knob, as shown in Fig. 2, enables the manual movement of the grinding wheel in the axial direction during the procedure. In this experiment, the knob was driven by a linear stage to control the wheel axial motion. An air pressure regulator sets the rotational speed of the grinding wheel.

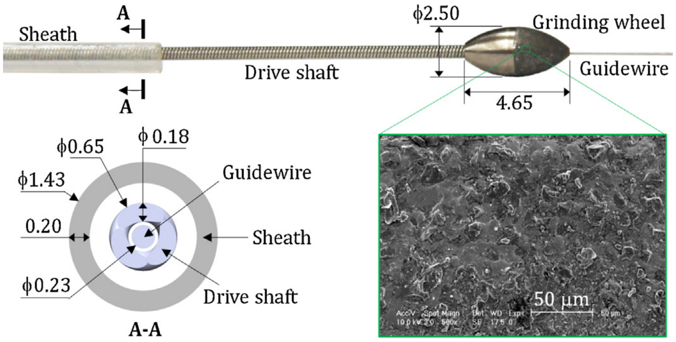

Fig. 3. Catheter and grinding wheel dimensions, catheter cross-section, and SEM image of the metal bond diamond wheel surface (Unit: mm).

2.2. Tissue phantom

A tissue phantom, shown in Fig. 4, was fabricated to simulate a lesion in the popliteal artery [11]. The phantom consisted of a ring-shape plaque surrogate made from a bovine femoral bone, the vessel phantom (PVC with 45 kPa Young's modulus), a rigid acrylic shell, and a muscle phantom (PVC with 8 kPa Young's modulus) in between the vessel phantom and acrylic shell.

This phantom was connected to a blood mimicking water source via a PVC tube (9.53 mm OD and 1.59 mm thickness). The RA catheter was inserted into the PVC tube to give the grinding wheel access to the plaque surrogate, as shown in Fig. 2. Water at 37 °C flowed through the PVC tube and the tissue phantom at 30 mL/min to simulate blood flow.

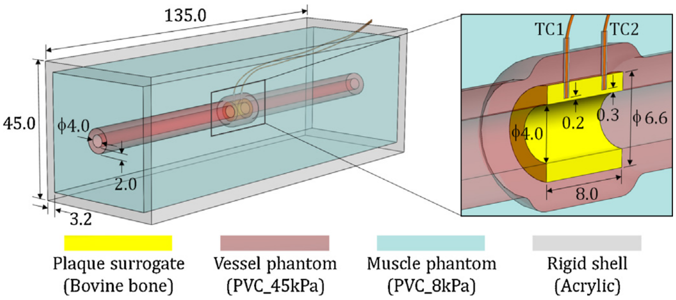

Fig. 4. Tissue phantom design, material, and dimensions (Unit: mm).

2.3. Measurement system

As shown in Fig. 2, a high-speed camera (Model FASTCAM-1024PCI by Photron) was used to record the grinding wheel motion through the semi-transparent portion of the phantom at a rate of