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# Attenuation of reflected waves in man during retrograde propagation from femoral artery to proximal aorta

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ABSTRACT

*Background:* Wave reflection may be an important influence on blood pressure, but the extent to which reflections undergo attenuation during retrograde propagation has not been studied. We quantified retrograde transmission of a reflected wave created by occlusion of the left femoral artery in man.
*Methods:* 20 subjects (age 31–83 years; 14 male) underwent invasive measurement of pressure and flow velocity with a sensor-tipped intra-arterial wire at multiple locations distal to the proximal aorta before, during and following occlusion of the left femoral artery by thigh cuff inflation. A numerical model of the circulation was also used to predict reflected wave transmission. Wave reflection was measured as the ratio of backward to forward wave energy (WRI) and the ratio of peak backward to forward pressure ($P_b/P_f$).
*Results:* Cuff inflation caused a marked reflection which was largest at 5–10 cm from the cuff (change (Δ) in WRI = 0.50 (95% CI 0.38, 0.62); $p < 0.001$, $\Delta P_b/P_f = 0.23$ (0.18–0.29); $p < 0.001$). The magnitude of the cuff-induced reflection decreased progressively at more proximal locations and was barely discernible at sites >40 cm from the cuff including in the proximal aorta. Numerical modelling gave similar predictions to those observed experimentally.
*Conclusions:* Reflections due to femoral artery occlusion are markedly attenuated by the time they reach the proximal aorta. This is due to impedance mismatches of bifurcations traversed in the backward direction. This degree of attenuation is inconsistent with the idea of a large discrete reflected wave arising from the lower limb and propagating back into the aorta.



## 1. Introduction

Elevated blood pressure remains the leading cause of mortality worldwide [1]. Wave reflection has been proposed as a major factor in the morphology of the aortic (central) blood pressure waveform making a large contribution to pulse pressure [2], and is an important therapeutic target in hypertension [3] and heart failure [4]. It is often implicitly assumed that there is no impediment to retrograde propagation of reflected waves [5], although theoretically this is unlikely [6,7]. A limited number of invasive studies in animals and man have shown conflicting results with regard to the importance of discrete reflected waves in the aorta [8,9], and recently the importance of large discrete reflections in the aorta as postulated by the asymmetric t-tube model has been criticised [10,11]. Alternatively, it has been proposed that the morphology of the aortic waveform may be comprehended either in terms of waves propagating in a time-varying reservoir [12], or as the summation of many diffuse waves undergoing extensive reflection, re-reflection and entrapment [13,14].

The aim of this study was therefore to examine the extent to which a large reflection generated by inflation of a thigh cuff to occlude the femoral artery could propagate backwards towards the proximal aorta and thereby to assess the likely importance of discrete reflections arising peripherally to the morphology of the aortic pressure waveform in man.

## 2. Methods

### 2.1. Study population

Twenty participants (age range 31–83 years, 6 female) undergoing routine coronary angiography at Imperial College Healthcare NHS Trust were recruited. Exclusion criteria included significant valvular pathology or significant impairment of left ventricular systolic function (ejection fraction <55%). The study protocol conformed to the ethical guidelines of the 1975 Declaration of Helsinki as reflected in a priori approval by the

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institution's human research committee and all subjects gave written informed consent prior to participation.

### 2.2. Study investigations

A standard thigh blood pressure cuff (width = 20 cm; length = 42 cm) was placed around the left thigh (the opposite side to the arterial access site) as proximally as possible. A radio-opaque marker was sited at the upper border of the cuff to aid subsequent radiological localisation. Invasive measurements of pressure and flow velocity at different sites were made following elective coronary angiography after a period of 10 min of supine rest on the catheter laboratory table.

Following coronary angiography a 0.014 inch sensor-tipped combined pressure–Doppler velocity wire (ComboWire XT 0.0, Volcano Corp., CA, USA), was positioned in the left femoral artery as close to the proximal border of the thigh cuff (identifiable by the radio-opaque marker) as possible. The sensor wire was then used to measure simultaneous pressure and flow velocity at that site and then proximally at intervals as far as possible towards the proximal aorta (typically 5, 10, 20, 30, 40, 50, 60 cm (from the cuff) and as proximal as possible in the aorta). The position of the ComboWire was measured using a calibrated sterile measure. Care was taken to ensure that high quality pressure and flow velocity signals were obtained at each location. A fluoroscopic image frame was also stored so that the position of the wire could be calculated using a quantitative measurement tool in the Medcon TCS Symphony suite (Medcon Telemedicine technology, Inc., Whippany, NJ, USA). Simultaneous recordings of pressure, velocity and ECG were acquired for a minimum of 10 s. All data were acquired at 1 kHz using an analogue-to-digital card (DAQ-Card AI-16E-4) and Labview software (National Instruments).

Measurements were made before, during and after inflation of a cuff on the left thigh to 50 mm Hg above systolic pressure. Consistent with previous reports [15], we confirmed that cuff inflation abolished flow in the popliteal artery using Doppler ultrasound. The cuff remained fully inflated for at least 10 s. Recordings were ensemble averaged using the ECG peak R wave as the fiducial point and taking account of offsets introduced by signal processing by the Combiwire console. Analysis was performed offline using custom-written software in Matlab (Mathworks, Natick, MA). Pressure separation and measurement of wave intensity was performed as described previously [16], but when occlusions were imposed the wave speed from the non-occluded condition was assumed due to the likelihood of early reflected waves complicating the pressure–velocity relationship [17]. Peak pressure, peak velocity, peak wave intensity and wave intensity time integral (i.e. wave energy) were quantified. The magnitude of wave reflection was quantified in two ways: 1) as the wave reflection index (WRI) which was calculated as the ratio of the energy of the reflected backward compression wave (BCW) to the incident forward compression wave (FCW); and 2) as the ratio of the peak backward to forward pressure ($P_b/P_f$) after pressure separation (Fig. 1). Apparent reflection time was calculated as the half the time interval between the peak of FCW and the BCW divided by the local wave speed. Reproducibility of measurements has been published previously; [18] the within patient standard deviation of difference was 4 mm Hg and 6 cm·s$^{-1}$ for pressure and flow respectively.

### 2.3. Numerical modelling

Pressure and flow waveforms were simulated using a nonlinear one-dimensional model of pulse wave propagation in the 55 larger systemic arteries in the human as previously described [14]. The flow rate prescribed at the root of the network was based on in vivo measurements at the aortic root and inflation of the cuff was assumed to cause complete occlusion of the artery. Arteries were simulated as thin, homogeneous, incompressible, elastic tubes, in which each section is independent of the others, and the blood was assumed to be a homogeneous, incompressible Newtonian fluid with a density of 1050 kg·m$^{-3}$ and a viscosity of 4 mPa·s. Local wave speeds were calculated using the parameters of the model at mean pressure. Pressure signals were calculated by solving the linear one-dimensional equations of pulse wave propagation in the elastic vessels of the 55-artery network using a wave tracking algorithm [14]. Only waves equivalent to a pressure >0.01% of the initial pressure were computed.

### 2.4. Statistical analysis

Statistical analysis was performed using SPSS 17.01 (SPSS Inc, Chicago, Ill, USA). Continuous variables are reported as mean and standard deviation for sample characteristics and mean (95% confidence interval) for results. Statistical comparisons were made using a paired Student's t-test; p values < 0.05 were considered significant.

## 3. Results

Patient characteristics are summarised in Table 1. The mean age was 62 years, the majority were male and most were receiving lipid

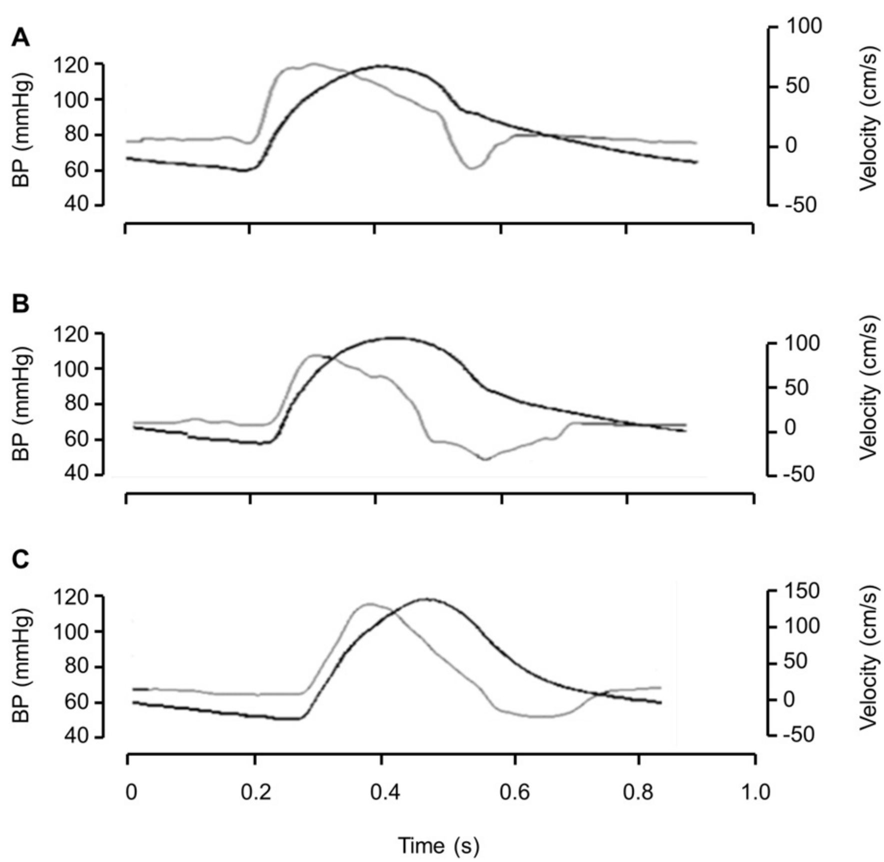


**Fig. 1.** Traces of simultaneous pressure and flow velocity waveform recordings under control conditions (without cuff inflation) from three different locations in the arterial tree. Pressure (black line) and flow velocity (grey line) were acquired using an intra-arterial sensor wire. The recordings were made in A) the proximal aorta, B) the abdominal aorta proximal to the aorto-iliac bifurcation and C) the left femoral artery. Time zero corresponds to the peak of the R-wave of the ECG.