Changes in aortic rotational flow during cardiopulmonary bypass studied by transesophageal echocardiography and magnetic resonance velocity imaging: a potential mechanism for atheroembolism during cardiopulmonary bypass

Abstract The human aorta is a curved conduit with a complex three-dimensional geometry. The curvature influences axial velocity distribution and introduces transverse velocity components. Rotational flow in the aorta can be demonstrated during normal pulsatile flow using transesophageal echocardiography. Cardiopulmonary bypass may affect the pattern of rotational flow in the aorta and thus influence the generation of atheroemboli. We investigated rotational flow in the descending aorta using color flow mapping and pulse-wave Doppler on transesophageal echocardiography before and during cardiopulmonary bypass. We correlated our findings with magnetic resonance velocity imaging in a model of a human aortic arch connected to a cardiopulmonary bypass circuit. Before cardiopulmonary bypass, rotational flow in the descending aorta was seen in 37 of 40 patients (93%). In the majority of these patients, rotational flow was in the clockwise direction during systole, looking in the direction of flow (30 of 37 patients, 81%, $P < 0.01$ vs counterclockwise rotation). During cardiopulmonary bypass, there were almost equal numbers of patients with clockwise (18 patients) and counterclockwise rotation (19 patients). Forty-seven percent of patients with clockwise rotation before cardiopulmonary bypass developed reversal in the direction of rotation to counterclockwise during cardiopulmonary bypass. Twenty-nine percent of patients with counterclockwise rotation developed reversal of the direction of rotation during cardiopulmonary bypass. The transverse velocity component increased during cardiopulmonary bypass regardless of the direction of rotation. We also demonstrated clockwise rotation in the descending aorta of a human aortic arch model connected to a cardiopulmonary bypass circuit using magnetic resonance velocity mapping. Before cardiopulmonary bypass, rotation was predominantly clockwise, while during cardiopulmonary bypass, there was no preferred direction of rotation. The geometry of the aorta, which is fairly constant in all patients, imposes handedness to aortic flow before cardiopulmonary bypass. However, during cardiopulmonary bypass, other extrinsic factors such as aortic cannula orientation may influence the direction of rotation. The change in direction of rotational flow and increase in its transverse velocity component during cardiopulmonary bypass may have implications for atheroembolism and arterial branch perfusion during extended periods of non-pulsatile flow.

Key words Aorta · Blood flow · Cardiopulmonary bypass · Embolism · Transesophageal echocardiography

Introduction

Refinements in surgical and anesthetic techniques continue to reduce operative mortality and cardiac morbidity in patients undergoing coronary artery surgery. However, neurological complications remain an important cause of mortality and long-term disability, especially as an increasing number of elderly patients are undergoing coronary artery surgery. The most devastating neurological complication, perioperative stroke, occurs in between 2% and 5% of patients undergoing coronary artery surgery and is dependent on age.1,2 The embolization of atheroma from the aorta is an important cause of ischemic stroke.4 Identification of an atherosclerotic ascending aorta by the surgeon is the single most significant marker for an adverse cerebral outcome.5 One of the mechanisms for dislodgement of atheroma is the effect of the jet from the aortic cannula on the aortic wall, or the “sandblast effect.”6,7 The axial component of the high-velocity jet directed into the aorta by the aortic cannula

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during cardiopulmonary bypass is generally considered to be responsible for generating such atheroemboli.

The aorta with its arch is a complex three-dimensional structure and its geometry may influence blood flow patterns both in the axial and transverse direction during cardiopulmonary bypass. Transesophageal echocardiography with its Doppler flow capability allows the flow in the descending aorta to be studied intraoperatively, and because of the relation of the probe to the aorta the transverse component of blood flow can easily be investigated. We therefore studied blood flow patterns in the descending aorta using color flow and pulse-wave Doppler during cardiopulmonary bypass for coronary artery surgery. To investigate the Doppler correlations of transesophageal echocardiography in greater detail, we also used magnetic resonance velocity mapping to study flow in a model of the human aorta connected to a cardiopulmonary bypass circuit.

Patients and methods

Patients

We studied 40 patients (mean [SD] age 63 [8] years; 35 men, 15 women) undergoing routine coronary artery bypass grafting for stable angina. The patients had greater than 75% stenosis in at least two epicardial coronary arteries and a left ventricular ejection fraction greater than 50% as assessed by contrast angiography. Patients with unstable angina or myocardial infarction within the previous 6 months were excluded. The protocol was approved by the Ethics Committee of the Royal Brompton Hospital, and informed consent was obtained from all patients. There were no side effects.

Operative procedure

General anesthesia was induced with alfentanil and maintained with enflurane. Cardiopulmonary bypass was established with an ascending aortic 26-F type 14 aortic cannula (Sorin Biomedica UK, Gloucester, UK) and single right atrial (two-stage) cannulation with systemic hypothermia (Crawley, West Sussex, UK) was used. Aortic cross-clamp was removed and the proximal anastomoses were complete, the aortic cross-clamp was removed and the proximal anastomoses fashioned with a side-biting clamp on the aorta during myocardial perfusion. Immediately prior to release of the aortic cross-clamp, a 5-min period of warm reperfusion (600 ml of potassium-enriched blood at 37°C via the coronary sinus catheter) was administered, while the patient’s core temperature was 35°–37°C.

Protocol

A 5-MHz multiplane transesophageal probe was inserted after induction of anesthesia and connected to a Hewlett-Packard Sonos 2500 echocardiographic system (Hewlett-Packard, Andover, MA, USA). The descending aorta was then brought into view at a level approximately 5 cm from the aortic arch. The presence or absence of atheromatous plaque or intimal thickening was noted and categorized according to the classification suggested by Kronzon et al.: grade 1, mild intimal thickening; grade 2, extensive intimal thickening; grade 3, sessile atheroma protruding less than 5 mm into aorta; grade 4, atheroma protruding more than 5 mm into aorta; and grade 5, mobile atheroma.

At baseline, the presence of systolic rotational flow was noted by the Doppler color flow appearance of hemicircles of red and blue in the aorta (Fig. 1). The direction of rotation was noted. Clockwise rotational flow from the perspective of looking along the direction of flow gives the appearance of a red hemicircle on the left side of the echocardiographic image and blue on the right, representing flow toward and away from the transducer, respectively.

The pulse-wave Doppler cursor was then positioned in the center of each hemicircle to enable the transverse velocity component of flow to be measured. The probe was adjusted so that the aorta appeared as circular as possible to avoid measuring tangential flow. The transesophageal probe was left in situ until cardiopulmonary bypass was established. When cardiopulmonary bypass was established on full flow, the direction of rotational flow was again noted and the pulse-wave Doppler measurements repeated.

Magnetic resonance velocity mapping of flow in an aortic arch model

We set up a cardiopulmonary bypass circuit that was connected via an aortic cannula to the ascending aorta of a rigid model of a human aortic arch to simulate aortic cannulation during cardiac surgery. The aortic arch model was made from a cast derived from the aorta of a female subject, and was made of a synthetic polymer (Ranier Technology, Cambridge, UK). The model was constructed with a cannula access port in the anterior aspect of the aorta, in the position where aortic cannulation for cardiopulmonary bypass would normally be performed. The aortic cannula (26-F cannula, 0.75-inch perfusion tubing) was then secured to the aortic model and connected to a Stockert SIII roller pump. Copper sulfate solution was used to fill the aortic arch model.