Helical and Retrograde Secondary Flow Patterns in the Aortic Arch Studied by Three-Directional Magnetic Resonance Velocity Mapping

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Background. Helical and retrograde secondary flows have been recorded in the aorta, but their origins and movements in relation to the arch have not been clarified. We set out to do this using magnetic resonance velocity mapping.

Methods and Results. Three-directional phase contrast cine magnetic resonance velocity mapping was used to map multidirectional flow velocities in the aortas of 10 healthy volunteers. Computer processing was used to visualize flow vector patterns in selected planes. Right-handed helical flows predominated in the upper aortic arch in late systole, being clearly recognizable in 9 of the 10 subjects. Nonaxial components of velocity in this region reached 0.29 m/s (±0.05 m/s) as axial velocities declined from a peak of 1.0 m/s (±0.1 m/s). Helical flow patterns in the upper descending aorta varied between subjects, apparently depending on arch curvature. End-systolic retrograde flow originated from regions of blood with low momentum, usually along inner wall curvatures. Flow studies in a curved tubular phantom showed right-handed helical flow in the upper "arch" when the inflow section was positioned to simulate ascending aortic curvature, and retrograde flow occurred along the inner wall at end systole during pulsatile flow.

Conclusions. Helical and retrograde streams are consistent features of intra-aortic flow in healthy subjects that result, at least in part, from the curvature of the arch and the pulsatility of flow in it. They may have significance in relation to circulatory dynamics and the pathogenesis of atheroma in the arch. (Circulation. 1993;88[part 1]:2235-2247.)

Key Words • flow • mapping • aorta

In this study, we used magnetic resonance phase shift velocity mapping,1-5 which has unrivaled capacities for noninvasive acquisition of multidirectional blood velocity data,6-9 to investigate the distribution of secondary flow patterns in the aortic arch in healthy subjects. Computer image processing was used to combine information from pairs of velocity maps to produce vector maps of flow distributions in planes aligned with and transecting the aortic arch.10,11 Finally, a tubular phantom was devised to study, also using magnetic resonance velocity mapping, relationships between tube curvature, flow pulsatility, and patterns of helical and retrograde flow. Our aim was to answer questions regarding the nature and origins of secondary flow patterns in the aorta that do not appear to have been addressed by previous studies.12-16

The presence of helical flow patterns in the aortic arch must have been suspected by many observers contemplating the right-handed twist of the great arteries. Anyone who experiments with visualization of flow in curved tubes or channels is likely to find that secondary flows, meaning flows with relatively stable components running oblique or counter to the main forward stream, are almost unavoidable. Twisting streamlines occur frequently,17 and symmetrically paired, counter-rotating helices tend to develop at simple pipe bends.18 Transparent models have been made that simulate, as far as possible, the morphology of curved arteries so that patterns of flow could be visualized in vitro.17,19 Even when helical flows can be seen, however, accurate mapping of velocity distributions in pulsatile, twisting streams presents major difficulties. The problem is not only three-dimensional or even four-dimensional (space and time) but effectively seven-dimensional, with three separate velocity components required to specify the flow vector for each point in space-time.6,7,9

This complexity helps to explain the relative lack of data on helical flow patterns in the aortic arch in humans. Some evidence of a rotational component to flow at certain locations in the aorta has been recorded.12,20 One study used transesophageal color Doppler ultrasonography to image nonaxial blood movements in the descending aorta in humans.16,21 The authors found evidence of helical flows in the majority of subjects, with variability between individuals. The method did not allow in vivo measurement flow in the arch, but part of the study recorded right-handed helical flow in the upper arch of an aortic model.

Retrograde aortic flows, meaning blood movements running counter to the main forward stream, have been
more convincingly demonstrated,14,15,21 but the origins and distribution of the retrograde streams have not been mapped in relation to the curved geometry of the arch. The present study aims toward filling this gap.

We believed that mapping of all three orthogonal velocity components in an oblique sagittal plane aligned with the upper arch would allow us to observe the distributions of helical and retrograde flows around a significant part of the arch. Depending on what the first velocity maps revealed, we planned to acquire velocity data in additional planes in selected subjects for clarification of initial findings.

The in vitro flow studies were intended to further clarify the flow findings and to give insight into causative factors that may underlie them. The experiments using a curved tubular phantom were carried out after the studies in humans and were devised specifically to throw light on the relationships among secondary flow structures, arch curvature, and flow pulsatility.

Methods

Subjects

Ten healthy volunteers were studied (7 men and 3 women), ages ranging from 24 to 43 years (mean, 34 years). One flow study, mapping velocity distributions through the aortic valve, was included, recorded in an additional healthy 32-year-old man. All studies were at rest, with subjects lying supine in the magnet.

Magnetic Resonance Imaging and Velocity Mapping

We used a Picker magnetic resonance machine operating at 0.5 T with modified gradient coils and a surface receiver coil. Cardiac gated transaxial multislice spin echo images were acquired, covering the region between the left ventricular outflow tract and the aortic arch. Then, an oblique spin echo image was acquired in the aortic arch plane, located by three points: one at the top of the arch and one each in the centre of the ascending and descending aorta at about right pulmonary artery level.

Three-directional cine velocity mapping was performed using a gradient echo sequence with an echo time of 14 milliseconds.15,18,22 Slice thickness was 8 to 10 mm, 40-cm field of view, with two averages of 128 phase encoding steps for each of four interleaved acquisitions: one velocity compensated, for background phase reference, and one each for measurement of velocity-dependent phase shifts in the slice select gradient, read gradient, and phase encode gradient directions. Three-dimensional cine velocity mapping in a given plane took 16 to 24 minutes, depending on heart rate, velocity maps then being produced by subtraction of reference from respective velocity encoded phase images so as to retain only velocity-related phase shifts. Each directional velocity map consisted of 16 cine frames gated from the R wave of the ECG and distributed through systole and most of diastole, successive cine frames being at 40- to 60-millisecond intervals.

Velocity Mapping Planes

The plane used for three-directional velocity mapping in all 10 subjects was the oblique sagittal plane aligned with the aortic arch (Figs 1, 2, and 3).

Velocity mapping in each of five additional planes was performed in one or more subjects, these planes being (1) a transaxial plane transecting the ascending and descending arch at the right pulmonary artery level (see lines drawn on Fig 3d), (2) a coronal plane tilted forward to transect the upper ascending arch (Figs 3d and 4), (3) a transaxial plane transecting the descending thoracic aorta at mitral valve level (Fig 3d), (4) an oblique plane through the two coronary sinuses of the aortic valve (in the additional subject; Fig 5), and (5) an oblique coronal plane through the left ventricular outflow tract and ascending aorta (Fig 6).

Velocity Vector Map Reconstruction

Software was written to combine the vertically and horizontally encoded velocity map data to produce cine vector maps displaying the distribution of flow in the image plane. (Figs 2 through 6). Local vectors were depicted as tapered streaks, the thick end pointing in the direction of flow, extending from multiple points in a rectangular matrix. The length and direction of each streak represents in-plane velocity at the point of origin.

Data Analysis

The anatomic and flow data were stored and studied in four forms.

Original magnetic resonance image format. Maps of velocity in each direction were displayed as gray-scale images (as in Fig 1). These were viewed at the console in cine mode, or analyzed frame by frame, using a cursor to interrogate pixel values in different regions. Standard software allowed profiles of velocity along any chosen line to be drawn automatically.

Velocity maps. With velocity profiles superimposed, maps were transferred to film hard copy, a convenient form for comparison of findings during the process evaluation.

Cine vector maps. Maps were viewed at a computer console.

Numeric records of peak velocity. Records measured by drawing velocity profiles across the arch, but avoiding exceptionally high or low pixel values, were used to compare flow at different gating delays, at different locations and in different directions (Table).

In Vitro Flow Model

A single flexible plastic tube, 3 cm in diameter and 80 cm in length, was used. It was of the type with wall corrugations that allow relatively tight curvature without kinking. The corrugations, at 3-mm intervals, were small in relation to tube diameter. Part of the tube (the arch) was secured with curvature in a single plane simulating that of the upper aortic arch. Proximal to this, a 30-cm length of the tube was secured either in plane with the arch, aligned with its ascending limb (the flat arch), or arranged so as to curve into the arch plane from its “left” side, simulating entry from the aortic root (the twisted arch). Water, with dissolved copper sulfate, was propelled through the tube by a centrifugal pump delivering continuous flow. Pulsatility could be induced in the tube section by intermittent compression of a flexible chamber connected to a side opening at the tube’s proximal end. Compression of the chamber was achieved by a lever mechanism, moved to and fro by a line to the rotating arm of a motor located outside the
Fig 1. Vertical and through-plane velocity map frames from all 10 subjects. The planes are aligned with the aortic arch, viewed from the left. Images on the left of each pair show peak axial flow (early to mid systole), white representing velocity up the image and black down. Images on the right of each pair show peak through-plane flow in mid to late systole, light gray representing movement away from the viewer and dark toward. Flow entering the plane from the aortic root and flow in the right pulmonary artery are light as they move away from the viewer. A light strip against the inner wall of the upper arch with a broader dark region above it is a consistent finding, clearly identifiable in 9 subjects, less so in patient 10. This pattern indicates the clockwise rotation (viewed in the direction of forward flow) of a right-handed helical flow pattern. Notice variations in arch curvature. Size variations depend on body size; subjects 2, 3, and 5 are women.

magnet. A second flexible capacitance chamber connected to a side opening at the distal end of the arch tube allowed pulsatility of flow in the test section to be induced, free of the inertial damping effect of fluid in several meters of tubing leading back to the pump, which also had to be located outside the magnet. Mean flow rate was adjusted by a gate valve, and the frequency and amplitude of flow pulsatility were adjusted by setting the rotation rate and length of the rotor arm and by adjustment of the tension in the connecting line.
Flow vector components in planes aligned with and transecting the upper arch were mapped by magnetic resonance, as described above. Both continuous flow and pulsatile flow experiments were performed through flat and twisted arrangements of the arch. For cine imaging of the cycle of pulsatile flow, gating (equivalent to cardiac gating) was achieved through an electric circuit closed at each contact of the driving rotor arm with a second conductor. Sixteen frames were acquired per cycle.

Continuous flow was maintained at a rate of 12 L/min. Pulsation was superimposed at a rate of 30 beats per minute, adjusted to give a peak of forward flow rising to 28 L/min (flat arch experiment) and 22 L/min (twisted arch experiment), with a slight reversal of net flow in the diastolic phase. Peak axial velocities during the systolic phase of pulsatile flow reached 0.5 m/s.

Results

The images in Figs 1 through 6 have been selected to illustrate the principle in vivo flow findings, some of which are schematically drawn in Fig 7. Before we describe them, however, we will draw attention to certain anatomic features and define the terms that we use to describe arch anatomy and patterns of flow.
Fig 3. Transition from right-handed to left-handed rotation (in subject 1, a subject with relatively acute distal arch curvature). Numbers indicate gating delays, in milliseconds from R wave. a, Vertically encoded velocity map, mid-systolic frame, showing flow separation (labeled “s”) and local retrograde flow in the distal arch. b, Corresponding through-plane velocity map (dark toward viewer, light away). The velocity distribution indicates right-handed helical flow in the ascending and upper arch, but left-handed rotation (with respect to forward flow) is beginning to develop in the distal arch. c, The spin echo image shows the slight dilatation of the ductus diverticulum (arrowed). d, A late systolic through-plane velocity map, 110 ms later than b, showing that at this stage, as axial flow declines, there is right-handed rotation in the ascending and upper arch, but left-handed rotation in the descending arch. The four vector maps show nonaxial blood movements in planes transecting the arch at levels indicated by the lines on the velocity map. The vector maps are all viewed as if looking in the direction of forward flow, i.e., from below on the ascending side and from above on the descending side and are orientated with the subject’s right side to the right of the vector map.

Arch Anatomy
The extent to which the aortic arch was found to lie in a single plane can be judged from the images in Fig 1. The ascending aorta entered this plane, which we call the arch plane, from its left side, at a level just below that of the right pulmonary artery. We refer to the ascending aorta from this point up to the origin of the first (right) brachiocephalic artery as the ascending
FIG 4. Flow into the first branch of the arch. This vector map obliquely transects the ascending arch of subject 7, showing systolic flow into the right brachiocephalic artery.

The region from the first branch to the point at which arch curvature begins to straighten to become the descending thoracic aorta, we call the upper arch.

In one subject (subject 10, as numbered in Fig 1), the aorta was unusually flat, with nearly all of the ascending aorta, including part of the sinus of Valsalva, lying in the arch plane.

The upper arch curvature varied between subjects from one that continued to ascend for about 3 cm beyond the left subclavian artery branch before turning fairly tightly downward (subject 1) to more smoothly rounded curves in subjects 7 through 9.

A relatively common anatomic feature was the slight bulge of the aortic wall just distal to the point where the arch turns downward. This bulge is known as the ductus diverticulum. It was identifiable in spin echo or late systolic cine images in subjects 1 through 6 (for example, see upper-right-hand images in Figs 2 and 3). We will refer to this anatomic region, whether a bulge is apparent or not, as the distal arch.

Of the three brachiocephalic branches (innominate, L common carotid, and L subclavian arteries), the origins of at least two of the branches could be identified in 9 of the 10 subjects (see Fig 1). (In subject 5, metal caused local magnetic field distortion and degradation of the top of the velocity map images.) The origins of these branches were angulated in the direction of upward and forward flow.

Flow Terminology

We use the term helical flow to refer to fluid movement in which axial and rotational movements coexist in such a way that streamlines would be found to trace helical paths. Helices are referred to as right handed if their rotation, like that of a corkscrew, is clockwise when viewed in the direction of forward movement. Helical flow was recognized in our study by correlating information on axial and nonaxial velocity distributions in the selected image planes.

When helical flow is also pulsatile, the slope of helical streamlines changes through the cycle. At end systole and after, when axial velocities are low or reversed, rotational movement may dominate; we refer to this as rotational flow (although oblique streamlines, moving in forward and/or reversed directions, may be present).

FIG 5. Secondary flow patterns above the aortic valve. This is a late systolic vector map, located through the two coronary cusp sinuses. It shows recirculating flows accommodated by the sinuses that contribute to efficient valve closure at end systole.
Fig 6. Left ventricular outflow and ascending aorta, viewed from the front (subject 1). Through-plane velocities are shown above (dark toward, light away; PT, pulmonary trunk). In-plane vectors are shown below, in three late to end-systolic frames (numbers represent gating delays in milliseconds from R wave). Through-plane (helical) flow is not obvious in the ventricular outflow tract but develops in the ascending aorta, with a light stream sweeping away from the viewer along the inner curvature. This is also the location of a retrograde movement at end systole (labeled R). Local recirculation can be identified in the left coronary cusp, with the retrograde stream extending down to this cusp in the final frame.

The term skewed will be used to refer to an asymmetric axial velocity profile in which the peak axial velocity is located closer to one wall than the other.

Streamlines are imaginary lines through the flow field at a given moment in time, aligned at all points with the local velocity vector.

Fig 7. Schematic drawings to illustrate typical aortic arch flow development. a, Early systole. During acceleration, highest axial velocities begin along the shortest flow path, close to the inner curvature (cylindrical arrows). Axially directed flows through the remainder of the arch and its branches have not been drawn. b, Mid to late systole. The highest velocity stream migrates outward, and secondary helical flows develop. Where streamlines separate from the inner wall of the distal arch, the separation zone is filled by oblique retrograde streamlines, curling back toward the viewer from the further wall. c, End systole. Combinations of rotational and recirculating secondary flows persist after aortic valve closure. The drawing is intended to indicate averaged streamlines, although instability of flow and beat-to-beat variation is likely at end systole.
Turbulence is a region of complex flow containing multiple, small-scale eddies and countereddies whose distribution and movements are chaotic.

**Velocity Maps in the Aortic Arch Plane**

In Fig 1, pairs of velocity map frames from each of the 10 subjects illustrate the overall similarity of flow patterns between individuals.

**Development of arch flow.** Fig 2 shows frames spanning the period of systole in subject 4, chosen for illustration because the flow patterns in this subject were reasonably typical, not at one of the extremes of variability. Comparison of the images reveals the sequential development of axial, helical, and retrograde flow. Velocity profiles drawn across selected regions of the arch also changed progressively through the course of systole, showing stages that were broadly similar in all 10 subjects (represented schematically in Fig 7). In early systole (at 100- to 150-millisecond gating delay from the R wave of the ECG), as intra-aortic blood was being accelerated, forward, axial velocities developed across the width of the vessel, but with marked skewing of the profile, with highest velocities close to the inner wall of the arch. In mid systole (150- to 250-millisecond gating delay), the region of maximum axial velocity migrated outward, away from the inner wall, reaching a peak axial velocity of between 0.8 and 1.2 m/s (see Table). An oblique stream moved into the region close to the inner wall of the upper arch, beginning to establish a right-hand helical pattern of flow in this region, with nonaxial velocities reaching their peak after peak axial flow. Separation of the forward stream from the inner wall of the distal arch was seen in all subjects, although it was relatively slight in subject 9, with an unusually rounded arch. Separation was marked by local retrograde flow moving back into the separation zone (marked “s” in Fig 3a). This is the region in which retrograde flow was first seen. In late systole and diastole (250-millisecond gating delay onward), as net forward flow declined, secondary helical and retrograde flows persisted, with relatively low velocities that continued through early diastole, or through the whole of diastole in some cases (subjects 1, 2, 3, and 9).

**Helical flows in the upper arch.** The through-plane velocity maps in Fig 1 show evidence of helical flows in the arch of all 10 subjects, with right-handed helical flow dominating in the upper arch of all subjects except subject 10. The nonaxial velocities in the upper arch peaked at between 0.15 and 0.4 m/s, with a mean of 0.28 m/s, ie, about one third of peak axial velocity. Because nonaxial, rotational flow reached its peak as axial flow declined, and continued, to a varying extent, after it had ceased, the direction of streamlines must have varied greatly through the cycle, from predominantly axial in early systole to predominantly rotational by end systole. The core or axis of the helix was generally located eccentrically in the ascending and upper arch lumen, first appearing toward the inner wall, then moving round to the subject’s right side (Figs 1 and 3).

In the 10th subject (who was the subject with an unusually flat arch), the helical pattern in the upper arch was barely recognizable in the through-plane velocity map. In the ascending arch of this subject, however, a central white band is flanked by two dark ones. This suggests the presence of paired, counterrotating helices, the central zone moving away from the viewer while both peripheries are moving toward.

Similar dark/light/dark patterns suggest the presence of paired counterrotating flows in the proximal descending aorta in several of the through-plane velocity map frames in Fig 1, and examination of other cine frames indicated that this pattern occurred, transiently, in all subjects in the distal arch. **Helical flows in the descending arch.** There were differences between subjects in the way that helical flow, predominantly right-handed in the upper arch, contin-
ued over into helical flows in the descending aorta. Subject 1, with marked angulation of the distal arch, developed the strongest left-handed rotation in the descending aorta, as viewed in the direction of systolic forward flow (Fig 3). Left-handed rotations also developed in the descending arch of all the remaining subjects except 9 and 10. No net rotation was measurable in the descending aorta of subject 10. Subject 9 (with a smoothly rounded arch) was the only subject in whom the right-handed helical rotation of the upper arch continued to dominate, redirected downward, in the descending limb.

Flow-related signal intensity variations. Gradient echo signal intensity images showed variations of brightness with location and timing. Brightest signal occurred where there was through-plane movement of blood. There was relatively little evidence of signal loss attributable to turbulence (Fig 2, upper row).

Vector maps in transaortic planes. Velocity vector maps acquired in planes transecting the aorta showed evidence of helical or rotational flow, supporting the findings described above. Fig 3d shows the change from right-handed ascending to left-handed descending rotations demonstrated by maps of vectors in planes transecting the arch as well as by maps of velocity components through the arch plane.

Vector maps were also acquired across the descending aorta posterior to mitral valve level in subjects 5 and 9. In both cases, these confirmed the directions of rotation that had been observed in the descending aorta in maps of velocity through the arch plane: left-handed in subject 5, and right-handed in subject 9.

Fig 4 shows a systolic vector map in a slightly oblique cut through the upper ascending aorta, tipped to lie in plane with the origin of the right brachiocephalic artery (subject 7). It illustrates continuity between helical intra-aortic flow and branch flow.

Retrograde streams. End-systolic retrograde flow was visible down the inside curvature of the ascending arch in all cases (seen as downward movement in vertically encoded velocity maps in the arch plane).

Local retrograde flow inside the distal arch separation zone was seen at mid to late systole in all subjects, although it was least marked in subject 9. In most cases, this recirculating region extended back further at end systole to give a retrograde stream round the inner curvature of the upper arch (labeled “R” in Fig 2). There was, however, variability in the upper arch region: in subject 1, retrograde flow appeared on the outside of the bend at the top of the arch, close to the origins of the brachiocephalic branches, and in subjects 2, 7, and 10, there appeared to be a migration of the retrograde stream from the inside to the outside of the upper arch.

Retrograde movements usually coincided with regions of relatively high nonaxial velocity (see Figs 2, 3, and 6), indicating oblique, backward flowing vectors. Flow entering the ascending aorta. Velocity mapping in an oblique plane cutting through the two coronary cusp sinuses above the aortic valve (in the additional subject, Fig 5) showed secondary recirculating flows in the sinuses toward end systole.

In a slightly different oblique plane, aligned with the ascending aorta as well as left ventricular outflow (in subject 1, Fig 6), velocity mapping demonstrated the onset of both helical and retrograde flows in the proximal ascending aorta. Relatively low levels of through-plane velocity in the left ventricular outflow tract suggest that rotation developing in ascending aorta is not, in this case at least, a continuation of nonaxial movements already present at the ventricular outflow level.

Incidental findings. The principal velocity mapping plane, aligned with the upper arch, also passed through the right pulmonary artery and left atrium in all subjects. In the right pulmonary artery, in-plane velocity maps demonstrated right-handed helical flow in late systole. In the left atrium, through-plane velocity maps showed evidence of a coherent blood movements during atrial filling, with ant clockwise rotation of the blood mass, as viewed from the front of the heart.

In Vitro Flow Studies

The images in Fig 8 have been selected to illustrate the principal in vitro results.

Continuous flow in the flat arch. This led to bilaterally symmetric patterns of secondary flow, with only minimal flow (less than 0.1 m/s) recorded through the central plane (Fig 8a). Where the main forward stream tended to separate from the inside of the arch, the space was filled by oblique, inward flowing streams sweeping round the walls from each side, without retrograde movement.

We found that the symmetry of flow was easily broken. Slight departure of the arch curvature from a single plane resulted in asymmetric patterns.

Continuous flow in the twisted arch. This showed strong, exclusively right-handed helical rotation in the upper arch, with nonaxial velocities through the arch plane up to 0.4 m/s (Fig 8b). A dark/light/dark banding is seen where inflow curves into the arch plane. This indicates paired helices, with the right-handed helix coming to dominance as soon as the tube curves into the arch itself.

Pulsatile flow in the flat arch. This demonstrated the progression from axial to secondary flows through the course of systole (Fig 8c). During early systolic acceleration, as in the aorta, axial velocity profiles showed marked skewing, with highest velocities close to the inner wall. As these high axial velocities migrated outward, nonaxial secondary flows curved into the separation zone from each side, leading, by end systole, to secondary movements that resulted in well-developed paired helices and a strongly developed retrograde stream back along the inner curvature (marked “R”).

Pulsatile flow in the twisted arch. This also demonstrated development from axial to secondary flows (Fig 8d). In this case, secondary flows began as paired, counterrotating helices with streams moving obliquely into the inner wall region from each side. But, as flow from the twisted ascending limb began to arrive in the upper arch, the right-handed helix came to dominate. At end systole, a retrograde stream was identifiable along the inner curvature of the distal arch. Mapping of axial velocities through a plane transecting the top of the arch showed that the retrograde stream, less strongly developed than in the flat arch, was itself deflected by the helical, rotational movement. This accounts for the absence of retrograde flow in the upper arch region of the vector map located in the central arch plane.
Discussion

The development of intra-aortic flow patterns can be appreciated through study and comparison of images in the figures, which have had to be selected from the very large number of cine frames acquired. But static illustration is a limitation as some flow findings are more readily appreciated when the data are viewed in cine mode. The schematic drawings of Fig 7 are intended as a guide to recognition of typical flow features.

The velocity maps show evidence of coherent patterns of flow, with general conformity to vessel contours, and development from axial to secondary patterns of flow through the course of systole. These results are, in a sense, self-validating. Methodologic errors or artifacts could not be expected to give such orderly...
patterns. Artifacts caused by background noise and non-velocity-related phase shifts occurred in peripheral parts of images, but they did not significantly degrade data from regions of blood flow, which gave reliable levels of magnetic resonance signal. The accuracy of magnetic resonance phase shift velocity measurements is now well established, and as long as sources of error are minimized\textsuperscript{23,24} velocity in medium to large blood vessels can be measured with at least 90% accuracy.\textsuperscript{3,4}

We limited the main study to 10 healthy subjects, and this meant that sample images from all could be presented together, without exclusions (Fig 1). Mapping of velocity components in and through the arc plane allowed comparison of flows in different arch regions, including the principal inner curvature where we had expected that flow separation and the origins of retrograde flow might be observed. The velocity maps demonstrated right-handed helical flow in the upper arch in mid to late systole. We believe that this is the only reasonable interpretation of the combinations of axial and nonaxial velocity patterns recorded, especially as studies in transaortic planes (Figs 3 and 4) corroborated findings in the arch plane.

Helical patterns in the descending aorta showed variability, and adequate assessment of the prevalence of different variants would require a larger series. Frazier et al\textsuperscript{16} did study larger numbers, but using the more limited technique of color Doppler ultrasound, capable only of recording flow directed to and from the intraesophageal transducer. Our findings in the upper part of the descending arch are generally in accordance with theirs. We agree with them that there is variability between subjects, and, on the basis of our observations, we suggest that differences in eventual rotational direction are related to the degree of flow separation in the distal arch, dependent, in turn, on the acuteness of distal arch curvature and the presence of a duc tus diverti culum. Separation of streamlines that are themselves moving helically appears to give rise to quite a complex recirculating movement in the separation zone, with reversal of rotation as well as axial direction (compare Figs 2, 3, and 7b).

Causal connections between flow separation and the bulge of the ductus diverticulum may work both ways. Diameter increase immediately beyond a bend can be expected to predispose to flow separation, and, conversely, it may be that the distributions of wall shear stresses and pressure fluctuations associated with unstable, separated flow contribute to the molding of contours in the distal arch region.

\textbf{In Vitro Model}

\textit{Helical flow.} The in vitro studies confirmed our view that twisted curvature might lead to dominance of a single helix. Continuous flow gave rise to a right-handed helical flow field in the upper curvature of the "anatomically" twisted arch, and during pulsatile flow, a right-handed helix came to dominate during systole. The flat arch, on the other hand, contained bilaterally symmetric patterns.

Deviation from flow symmetry resulted when overall pipe symmetry was broken by lateral displacement of the inflow. Right-handed helical flow dominated when the tube itself traced part of a right-handed helical path. This principle also applies to the curve of the pulmonary trunk leading into the right pulmonary artery, where right-handed helical flow was observed.

\textit{Retrograde flow.} Pulsatility of flow in both the flat and the twisted arch led to retrograde movement along the inner curvature, but this was more strongly apparent in the flat arch. The weakness of recorded retrograde flow in the upper part of the twisted arch can be explained by the more uniform distribution of forward momentum where helical flow is established. Furthermore, helical movement leads to lateral displacement of any retrograde stream to one side of the arch plane.

\textit{Limitations and strengths of the model.} The plastic tube that we used had no significant compliance, it had no branches, and was of uniform diameter. In these respects it did not simulate the aortic arch, but the advantage was that we could explore the effects of vessel curvature and pulsatility without the influence of additional variables. The corrugations were very small in relation to pipe diameter, and although it is likely that very small vortices were formed and trapped in the corrugations during flow experiments, we do not believe that these significantly influenced larger-scale secondary flow patterns.

Changes of parameters such as flow rate, pulsatility, and curvature might have given different results, but what we aimed for was a system with appropriate relative dimensions and a peak Reynolds number falling within the range of those in the aorta between rest and exercise. (Peak in vitro velocity of 0.5 m/s was half that in the resting aorta, but the vessel diameter was about 50% greater, and the viscosity of the solution used was about 35% of that of blood; this implies that peak Reynolds number rose to about twice that in the resting aorta.)

The results we obtained demonstrate that twisted curvature and pulsatility of flow in the curve lead to helical and retrograde flow, respectively, but we cannot comment on the possible influence of other factors such as the presence of branch vessels, wall compliance, and wave reflection in the peripheral vascular bed. And we cannot exclude the possibility that rotational momentum originating in the left ventricle is carried forward into the aorta, although our one study that recorded nonaxial velocities in the left ventricular outflow tract (Fig 6) showed that these were small compared with the nonaxial velocities arising in the curve of the ascending aorta.

\textit{Skewed Axial Flow Profile and Retrograde Flows}

The in vitro studies helped us to recognize and understand the sequence of axial flow development in the arch, and the following discussion applies to flow in both the phantom and the aortic arch. First, in early systole, axial flow quickly develops a skewed profile, with higher velocities close to the inner curvature. This pattern has been recognized in a range of earlier aortic flow studies,\textsuperscript{12-15} and skewing has been predicted by a mathematical model of curved tube flow.\textsuperscript{13} A way to understand it is to imagine axial streamlines, or stream "tubes," in the incompressible fluid around the bend. Those round the inner curvature have a shorter length, and relatively smaller inertial mass, and so are accelerated more readily in early systole. But they also decelerate more readily in late systole, a factor that contributes to the genesis of retrograde flow.
Axial velocities in a bend have a centrifugal tendency, local momentum always being tangential to the fluid’s curved path. This, combined with relatively low velocities of the boundary layer adjacent to the walls, leads to migration of peak axial flow away from the inner curvature and movement of relatively low velocity secondary flows toward the low-pressure inner wall region. The resulting low momentum of fluid close to the inner wall compared with the high forward momentum of outer streams explains the onset of retrograde flow along the inner wall as net flow is interrupted at end systole.

At no point in the cardiac cycle does flow in the arch have the flat velocity profile of “plug” flow. This is significant because it implies that attempts to deduce cardiac output from local velocity and cross-sectional area measurements may be subject to error, with overestimation likely if high-velocity regions are sampled.

Secondary flows in the aortic sinus. The trapped vortical flows developing during systole in the sinuses the aortic valve cusps (Fig 5) may be regarded as a special case of flow separation and local retrograde flows, more closely related to flows through other cardiac and venous valves than to the secondary flows of the aortic arch. We include the illustration to record their presence and to distinguish them from the retrograde streams of the aortic arch. In the early 16th century, Leonardo da Vinci, apparently on the basis of his own anatomic and flow studies, sketched aortic sinus flow patterns with remarkable accuracy, and their fluid dynamic significance has been investigated.

The stability of helical flow. Flow separation, which occurs readily in a pulsatile, curved system, predisposes to turbulence (flow through cardiovascular valves, with cusp tissue averting collision between forward and recirculating streams, may represent an exception to this rule). A significant aspect of helical flow in the upper arch may be that it minimizes flow separation and turbulence. In a fully developed helical flow, fluid moves obliquely into the potential separation zone from one side only, and carries on round without separation from the inner wall. Momentum is tangential to the curved path, and the helical path makes it possible for the vectors of fluid momentum to not pull away from the inner curvature at any point. This may delay flow separation and minimize turbulence.

In all of our studies, velocity data were averaged over many heartbeats. This means that the chaotic velocity fluctuations of any turbulent regions were not recorded, although regular cyclic variations were captured by cardiac gating. The fact that secondary flow patterns remained clearly recognizable under these conditions indicates that coherent streams were present. But the additional presence of chaotic velocity fluctuations cannot be excluded.

Turbulence, above a relatively low level of intensity, is detectable on cine magnetic resonance imaging, using an echo time of 14 milliseconds, because it results in signal loss. Complete signal loss did not occur in our studies, although certain arch regions, localized in space and time, did show relative loss of signal (see Fig 2, upper row). These included the core of the helix in the upper arch and the inner edge of the separated stream in the distal arch. In the latter case, where the recirculating stream is shearing against the forward stream, local turbulence probably occurs. But in both cases velocity gradients between regions of through-plane flow, which give enhanced signal, could account for the relative signal loss. The evidence of this study suggests that turbulence remains localized, transient, and of low intensity in the aortic arch at rest, with the distal arch being a particularly susceptible region.

Flow Patterns and the Pathophysiology of Atheroma

The sites of deposition of atherosclerotic plaque are considered to be influenced by flow patterns that cause regions of altered shear stress on the aortic wall. Faingh and Perroneau reviewed studies of the distribution of atheroma and of regions of uptake of various markers in the aortic arch in animals. Their evidence suggests susceptibility of the distal arch region to atheroma.

We have had little success in attempting to trace original studies of the distribution of atheroma in the aortic arch in humans. According to Gould, there is a tendency for plaques to form on the posterior wall of the descending aorta, which he attributes to the splitting effect of the vertebral column, whereas the more mobile parts of the ascending and upper arch tend to be spared. If this distribution is indeed typical, we would propose a fluid dynamic explanation that the relative stability of helical flow in upper arch spares this region, whereas more unstable flow patterns impinging on the posterior wall of the descending aorta predispose to atherogenesis.

We have found that patterns of flow in the distal arch vary significantly between individuals. A future study of distribution of atheroma in the aortic arch, which seems to be called for, should take into account individual variations of arch geometry and flow. Magnetic resonance is well suited for this; in addition to its anatomic and flow-imaging capacities it is able to localize and characterize atheromatous plaques in arterial walls.

The Dynamic Significance of Arch Curvature and Helical Flows

The ability of helical flow to minimize turbulence in the upper arch has been discussed. That the blood moves round such a steeply curved arch in the first place has its own dynamic consequences. Rate of change of momentum is proportional to, and in the direction of, the force acting on it (Newton’s second law of motion). Within fluids, the forces associated with momentum changes manifest as pressures and pressure gradients. Flow round a steeply curved arch is associated with a raised dynamic pressure on the outside of the bend, i.e., at the top of the aortic arch, where the brachiocephalic arteries take their origin. We estimate that convective acceleration resulting from flow at 1 m/s completely changing direction in the span of the arch (a velocity change of 2 m/s in 0.15 second, the arch span being about 15 cm in length) is about 1.35 times the acceleration of free fall in gravity. This suggests dynamic pressures toward the top of the arch of the order of several centimeters of blood, or a few millimeters of mercury, enhancing flow into the brachiocephalic branches.

This applies to resting peak systole. A comparable effect may be extended in time by the late systolic helical spin of blood in the upper arch, where tangential velocities are lower, but the radius of curvature is
smaller. Calculation suggests that the late systolic acceleration due to helical spin is also of the order of gravitation acceleration. A sense that this spin of blood can work to the benefit of branch filling can be gained from study of the vector map in Fig 4.

The significance of the beneficial dynamic gradients, on the one hand, and of the avoidance of detrimental turbulence, on the other, would increase greatly during exercise, each tending to climb with the square of flow velocity. And it is worth remembering that we are considering a system that has to operate unceasingly for a lifetime.

Flow Direction Changes in the Heart

This study has demonstrated the nature of flow direction changes in the aortic arch, and some fluid dynamic implications have been discussed. We would like to close by drawing attention to the direction changes of blood movement through the heart itself.

The vertebrate heart, from its very beginnings, develops a tortuous, S-shaped form, and this basic pattern is retained through all vertebrate species, perhaps because it facilitates efficient, directional exchanges of energy between muscle and blood. The nature and dynamic significance of multidirectional intracardiac flow patterns in health, and their alterations through disease or surgery, remain relatively unexplored. Magnetic resonance velocity mapping opens new possibilities for investigation of the "morphodynamics" of blood movement through heart cavities as well as large vessels.

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