Functional Chiral Asymmetry in Descending Thoracic Aorta

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To determine whether rotational blood flow or chiral asymmetry exists in the human descending thoracic aorta, we established the ability of color Doppler ultrasound to detect rotational flow in a tornado tube model of a vortex descending fluid column. In a model of the human aortic arch with a pulse duplicator, color Doppler was then used to demonstrate that rotational flow occurs first in the transverse arch and then in the proximal descending thoracic aorta. With the use of color Doppler esophageal echocardiography, 53 patients (age range, 25–78 years; mean age, 56.4 years) were prospectively examined for rotational flow in the descending thoracic aorta. At 10 cm superior to retro–left ventricular position, 22 of 38 patients (58%) revealed rotational flow with obvious diastolic counterclockwise rotation but less obvious systolic clockwise rotation. At 5 cm superior to retro–left ventricular position, 29 of 46 patients (63%) revealed rotational flow with a tendency toward systolic clockwise and diastolic counterclockwise rotation. At the retro–left ventricular position, 47 of 53 patients (89%) revealed rotational flow, usually of a clockwise direction, occurring in systole. Our data suggest that aortic flow is not purely pulsatile and axial but has a rotational component. Rotational flow begins in the aortic arch and is carried through to the descending thoracic aorta, where flow is chirally asymmetric with systolic clockwise and diastolic counterclockwise components. These data demonstrate an aortic rotational flow component that may have physiological implications for organ perfusion. (Circulation 1990;82:1985–1994)

Because most objects in nature are not symmetrical, handedness, or chirality, exists. Although humans demonstrate structural chirality (e.g., the heart is to the left of center and the liver is to the right), the existence of functional chirality and its relation to blood flow have not been elucidated.

The parabolic nature of blood flow in the descending thoracic aorta characterized by a higher velocity in the center of the aorta during peak systole has long been recognized and recently confirmed by videodensitometric methods and magnetic resonance imaging. In the aortic arch, blood flow has been shown to be more complex, and research by Yearwood and Chandran in a model of the human aortic arch has demonstrated multiple vortices. Other studies in animals and humans have indicated the presence of turbulence (i.e., random velocities in more than one direction) in the ascending aorta, and additional studies have reported a rotational component without defined direction in the arch and proximal descending thoracic aorta.

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The advent of esophageal echocardiography and its subsequent improvements has allowed the qualitative and noninvasive assessment of rotational blood flow in the human descending thoracic aorta and determination of its asymmetrical nature by the use of color Doppler techniques. The esophageal probe’s proximity to the descending thoracic aorta and its ability to reveal transverse cross sections of the aorta enabled the investigation of rotational blood flow.

The purpose of the present study was to use color Doppler and esophageal echocardiography to determine the existence and origin of rotational blood flow in an in vitro model of the human aortic arch and the
existence of rotational blood flow in the descending thoracic aorta and to establish functional chiral asymmetry if present.

Methods

In Vitro Models

Rotational flow model. As a simple in vitro model of rotational flow, the tornado tube (Figure 1, upper left) was chosen. The tornado tube consists of two 1-l cylindrical bottles joined at the neck by a stiff, threaded plastic collar. The lumen between the two threaded ends of the collar is narrower (9 mm) than the opening of the bottles (22 mm), allowing for slow drainage. One bottle is filled with water, and the bottles are connected by the collar. The apparatus is inverted with the filled bottle superior. The liquid is agitated and drains into the lower bottle, creating a vortex as seen in tornados (Figure 1, upper right). Starch is added to the water to create echo-reflective particles.

Aortic arch model. A human-casted model of the aortic arch developed by Yearwood and Chandran and Chandran et al (Figure 2 and Figure 3, top) was used to evaluate rotational flow. This model consists of an acrylic aortic flow chamber incorporated into a mock circulatory system of water adjusted to produce a 5-l/min cardiac output at physiological pressures. Flow was pulsatile, and a pericardial aortic valve was used to simulate a normal aortic valve. The great vessels extend from the aortic arch and absorb 20% of the cardiac output. Physiological saline was used as the blood analogue fluid in the flow system. The average radius of the descending aorta was 1.15 cm, and the radius of curvature of the aortic arch (R) was

FIGURE 1. Upper left: Photograph of tornado tube model consisting of two 1-l bottles joined by a threaded collar. Tube is inverted and agitated to create a vortex. Upper right: Photograph of tornado tube vortex created by inverting bottles and applying gentle agitation. Bottom: Color Doppler ultrasound analog of vortex or rotational flow in a descending fluid column. From perspective of looking down into vortex, hemicircles represent counterclockwise rotation. Red indicates rotation toward and blue indicates rotation away from transducer.

FIGURE 2. Schematic of arch model developed by Yearwood and Chandran with ascending, transverse, and descending portions and branches.
For a mean flow rate ($Q$) of 4 l/min into the descending aorta, the average velocity ($v = \frac{Q}{\pi a^2}$) is 32 cm/sec, where $a$ is area. The mean Reynolds number ($Re$), is 7,801, and the Dean number ($D$) is 4,280. $Re$ and $D$ are defined by the relations

$$Re = \frac{2pva}{\mu}$$

and

$$D = Re \sqrt{\frac{a}{R}}$$

where the density ($p$) is 1.06 g/ml, and $\mu$ is 0.01. Poise is the viscosity coefficient of the blood analogue fluid. Starch was used as the echogenic medium.

Protocols

**Rotational flow model protocol.** The initial phase of this study consisted of establishing the ability of color flow Doppler technology to reveal rotational flow in a descending fluid column. After creation of the tornado tube vortex, the color Doppler transducer was applied against the upper bottle, allowing for transverse cross-sectional views.

**Aortic arch model protocol.** To investigate the origins of rotational flow through the use of color Doppler, the model of the human aortic arch (Figure 2 and Figure 3, top) was used. The arch was tilted so as to simulate a patient lying on his or her left side. Imaging and Doppler studies were obtained at 1, 2, 3, 4 (Figure 3, bottom left), and 5 cm superior to the aortic valve and just proximal to the innominate branch. Imaging and Doppler studies were obtained in the transverse arch between the innominate and left carotid arteries (Figure 3, bottom center) and in the descending thoracic aorta at 1, 2, and 3 cm (Figure 3, bottom right) inferior to a line extending from the inner wall of the transverse arch. Subse-
quently, imaging and Doppler studies were performed in the transverse arch and the descending thoracic aorta with no branch vessel occlusion, various branch vessel occlusions, or all four branch vessel occlusions. Systole and diastole were identified using the pressure waveform data.

Patient population and protocol. All patients undergoing routine esophageal echocardiography in the Northwestern University laboratory during a 5-month period were considered candidates for investigation of rotational flow. Fifty-three patients were studied (30 men and 23 women; age range, 25–78 years; mean age, 56.4 years). The indication for esophageal echocardiography was evaluation of native mitral or aortic valves (13 patients), prosthetic valves (14 patients), endocarditis of native valves (seven patients), intracavitary thrombi (nine patients), interatrial shunts (six patients), mediastinal mass (one patient), aortic dissection (two patients), and coarctation of aorta (one patient).

Informed consent was obtained from all patients. Before esophageal probe insertion, glycopyrrrolate 0.1 mg i.v., aerosol of benzocaine, and 2% viscous lidocaine were administered to reduce salivary secretions and provide topical anesthesia. Midazolam hydrochloride injection was given to anxious patients. After premedication, patients were oriented in a left decubitus position, and the angled tip of the esophageal probe was passed through a bite guard into the mouth and through the esophageal orifice to the retroventricular position (approximately 40 cm from the patient’s incisors). Fifty-three patients were studied in the semirecumbent position with left lateral rotation. The one remaining patient was studied in the sitting position only. Five patients were studied while sitting as well as in the semirecumbent positions. The electrocardiogram was continuously monitored.

After completion of routine esophageal echocardiographic evaluation, the descending thoracic aorta was investigated at the retro–left ventricular level, at 5 cm superior to the retro–left ventricular level, and at 10 cm superior to the retro–left ventricular level. Because humans, particularly comparing men with women, have different body sizes and aorta lengths, the retro–left ventricular level was chosen as the baseline level of investigation instead of a specific distance from the dental incisors. All 53 patients were studied at the retro–left ventricular level. Forty-five of these patients were studied 5 cm superior to the retro–left ventricular level, and 38 patients were studied 10 cm superior to the retro–left ventricular level. Images were visualized and recorded with the anterior wall of the descending aorta closest to the transducer and the right side of the aorta at the right side of the echocardiographic image. To avoid errors due to tangential imaging, the aortic image was maintained as circular as possible.

Image Acquisition

Two echocardiographic units were used for imaging. For the Northwestern protocols, the Hewlett-Packard Model 500 phased-array echocardiographic system (Hewlett-Packard, Andover, Mass.) was used with a 2.5-MHz standard transducer for the rotational flow model and a 5.0-MHz esophageal transducer for the patient population. An IREX 880 phased-array echocardiographic system with a 3.5-MHz transducer was used for the arch model studies at the University of Iowa.

Rotational flow was of low-to-moderate velocity in patients (10–30 cm/sec), and alias would occur at low-velocity color Doppler settings. In the models and patients, velocity settings were established at greater than the point of alias. In no patient was rotational flow velocity more than 60 cm/sec—the color Doppler Nyquist limit in both echocardiographic machines. The transducers were hand-held in all studies. Due to the thickness of the acrylic plastic in the arch model, a standoff was not required. All images for the three protocols were recorded onto videotape for subsequent playback and analysis.

Statistics

Data were analyzed using χ² analysis. The incidence of rotational flow versus axial flow was tested against an expectation of 100% axial flow and an equal odds expectation axial to rotational flow. The incidence of clockwise versus counterclockwise flow in systole and diastole was tested against an equal odds expectation.

Results

Rotational Flow Model

Figure 1 (bottom) illustrates an obtained image revealing particulate matter rotating in a clockwise or counterclockwise direction (dependent on the initial direction of agitation) and confirmed the ability of color flow Doppler to qualitatively detect rotational flow. With the transducer perpendicularly placed against the tornado tube, with the left side of the image representing the right half of the bottle, and from the perspective of looking along the direction of flow, counterclockwise rotational flow had the appearance of red/blue hemicircles with red representing flow toward the transducer and blue representing flow away from the transducer.

Aortic Arch Model

Following the observations in the rotational flow model, flow was considered to be axial if there was a uniform red or blue blush (depending on the transducer angulation) or to be mixed if there was a uniform speckled pattern. Multiple vortices were considered to be present when simultaneous multiple red and blue segments other than in a hemicircle distribution were found. Multiple vortices were the consequence of secondary rotations but were not sufficiently organized to manifest full rotation with hemicircles. Hemicircle distribution as seen in the tornado tube model indicated rotational flow.
Figure 3 illustrates flow patterns obtained in the aortic arch model.

**Ascending aorta.** All levels studied revealed multiple vortices (multiple red/blue segments) with no hemicircle distribution indicating the absence of pure rotational flow (Figure 3, bottom left).

**Transverse arch.** With the transducer placed between the innominate and left carotid artery and with all branch vessels open, mixed vortices were generally present (speckled pattern), with a tendency toward systolic rotational flow. With the innominate artery or left carotid artery occluded, mixed vortices were also present. When all four branches were occluded, there was hemicircle rotational flow during systole and diastole with rotation appearing clockwise in the direction of blood flow (Figure 3, bottom center).

**Descending thoracic aorta.** All levels studied revealed an axial systolic flow pattern. From the perspective of an observer looking down the descending thoracic aorta, there was development of counterclockwise rotational flow in diastole (Figure 3, bottom right). The diastolic counterclockwise vortex appeared to be accentuated by occlusion of all four great vessel branches.

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**Patient Study**

Rotational flow was identified as simultaneous appearance of red and blue hemicircles. From the perspective of an observer looking down the descending thoracic aorta (along the direction of blood flow), blue hemicircles on the right side of the echocardiographic image (patient's right) and red hemicircles on the left side of the image (patient's left) indicated clockwise rotation. Blue hemicircles on the left side of the echocardiographic image and red hemicircles on the right side indicated counterclockwise rotation. Figure 4 illustrates a typical example of rotational flow in a clockwise direction. Table 1 lists rotational flow characteristics in the population studied. All patients in the study were hemodynamically stable; in the cohort of patients studied, the type of heart disease did not appear to influence the presence or direction of rotation.

Thirty-eight patients were studied at 10 cm superior to the retro–left ventricular level (Table 1). Twenty-two patients (58%) revealed rotational flow. Six patients (27%) manifested clockwise rotation, and 15 patients (68%) manifested counterclockwise rotation.
TABLE 1. Rotational Flow and Position in Descending Thoracic Aorta

<table>
<thead>
<tr>
<th>Position</th>
<th>Clockwise rotation (n)</th>
<th>Counter clockwise rotation (n)</th>
<th>No rotation (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Patients (n)</td>
<td>Systole only</td>
<td>Diastole only</td>
</tr>
<tr>
<td>Retro-LV+10 cm*</td>
<td>38</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Retro-LV+5 cm†</td>
<td>45</td>
<td>11†</td>
<td>0</td>
</tr>
<tr>
<td>Retro-LV‡</td>
<td>53</td>
<td>33‡</td>
<td>3</td>
</tr>
</tbody>
</table>

LV, left ventricular.
*One patient with systolic clockwise and diastolic counterclockwise rotation.
†Three patients with systolic clockwise and diastolic counterclockwise rotation.
‡Two patients with systolic clockwise and diastolic counterclockwise rotation.
§Systolic versus diastolic rotation, p<0.01.
¶Systolic versus diastolic rotation, p<0.05.
#Systolic versus diastolic rotation, p<0.01.
**Systolic versus diastolic rotation, p<0.01.

rotation. Of the six patients with clockwise rotation, four (67%) revealed rotational flow in systole, one patient (16%) in diastole, and one patient (16%) in systole and diastole. Of the 15 patients with counterclockwise rotational flow, 14 patients (93%, p<0.01) manifested diastolic rotation, and one patient (7%) manifested systolic rotation. One patient revealed systolic clockwise and diastolic counterclockwise rotation. Of the 16 patients with no rotation, multiple vortices were seen in 15 (94%), in systole, diastole, or both.

Forty-five patients were studied at 5 cm superior to the retro–left ventricular level. Twenty-nine (64%) revealed rotational flow. Sixteen (55%) manifested clockwise rotation, and 13 (45%) manifested counterclockwise rotation. Of the 16 patients with clockwise rotational flow, 11 patients (79%, p<0.05) revealed rotational flow in systole only; in three patients (21%), it was also noted in systole and diastole. Of the 11 patients, counterclockwise rotation was noted in systole in three (27%), in diastole in seven (64%, p<0.01), and in both portions of the cardiac cycle in two (18%). An additional two patients revealed systolic clockwise and diastolic counterclockwise rotation. Of 17 patients (37%) with no rotation at 5 cm superior to retro–left ventricular level, seven (21%) revealed multiple vortices, and the other patterns were linear or speckled.

Forty-seven of the 53 patients (89%) studied at the retro–left ventricular level manifested rotational flow in the descending thoracic aorta. Of the 47 patients with rotational flow studied at the retro–left ventricular level, 41 (87%) manifested clockwise rotation, and three (7%) manifested counterclockwise rotation (two in systole and one in diastole). Of these 41 patients with clockwise rotational flow, 33 (80%, p<0.01) revealed rotational flow in systole only, three in diastole only, and five in systole and diastole. An additional three patients revealed systolic clockwise and diastolic counterclockwise rotation. Of the six patients with no rotational flow at the retro–left ventricular level, two revealed multiple vortices in either systole or diastole, and the other patients had linear or speckled patterns.

Five patients with no rotational flow at the retro–left ventricular position and two patients with no rotational flow at 5 cm superior to the retro–left ventricular position were also studied while they were sitting. All patients subsequently manifested rotational flow in the sitting position (Table 1).

Figure 5 demonstrates systolic clockwise motion of a large mobile intimal density in a patient with an atherosclerotic aorta. The mobile intimal density moves with the pattern of rotational flow.

Discussion

We demonstrated that the use of the tornado tube with color flow Doppler ultrasound can identify rotational flow in a descending fluid column. In an aortic arch model, color Doppler ultrasound revealed flow patterns similar to those found in the tornado tube in both the transverse and descending portions, indicating the origins of rotational flow.

Finally, in the patient model, with the use of esophageal color Doppler flow data, we demonstrated the presence of rotational flow in at least part of the descending thoracic aorta in the majority of patients. Multigated color segments allowed an integrated view of the net effect of all involved vortices. To date, it has not been possible to establish an integrated view of these vortices in humans, their extent in the descending thoracic aorta, their frequency of occurrence, or their direction of rotation. With color Doppler, we demonstrated that rotational flow has a characteristic pattern and may be a significant component of flow dynamics.

Of the patients studied with the probe placed at the retro–left ventricular level, a small minority failed to reveal the full rotational flow pattern of colored hemicircles. Moreover, in the great majority of patients, the rotation was clockwise (looking down the aorta perspective) and usually occurred in systole; in some patients, clockwise rotational flow occurred in both systole and diastole. Few patients exhibited systolic counterclockwise rotation at this position.

There was less consistency of rotational flow pattern closer to the aortic arch. Of the patients studied 5 cm superior to the retro–left ventricular level,
approximately one third did not reveal rotational flow. Of the remaining patients with rotational flow, approximately one half revealed clockwise and one half revealed counterclockwise rotational flow. Clockwise rotational flow usually occurred in systole. The presence of counterclockwise rotation was more evident in diastole. Multiple vortices during systole or diastole were also evident at this level closer to the aortic arch.

At a level even closer to the aortic arch, 10 cm superior to the retro–left ventricular level, less clockwise rotational flow was demonstrated; diastolic counterclockwise rotational flow was seen in two thirds of the patients; and there was additional evidence of multiple vortices being present in systole, diastole, or both. The presence of multiple vortices at this level, along with the presence of diastolic counterclockwise rotational flow, may reflect the proximity of this position to the final bend in the aortic arch. Multiple vortices are probably the result of secondary flows but are not sufficiently organized to manifest a full rotation.

For clarification, Figure 6 demonstrates a schematic representation of the findings in the aortic arch model and patient population. Panel A demonstrates rotational flow in the transverse aortic arch with a forward-flowing helix in systole and diastole as found in the arch model. The three-dimensional schematics show clockwise rotation along the direction of blood flow. Panel B demonstrates rotational flow in the proximal descending thoracic aorta with a backward-flowing helix representing diastolic flow reversal as found in the arch model and most of the patients studied. The three-dimensional schematics show counterclockwise rotation in diastole, looking inferi-
shortened period of forward flow and more pronounced retrograde flow. Along the right anterior wall, there were lower maximum velocities, but the forward velocities lasted for a longer period of time, sometimes encompassing diastole. Segadal and Matre felt that because of these differential velocity patterns, blood appeared to rotate in a clockwise direction as observed from the left anterior aspect of the ascending aorta. Yearwood and Chandran\textsuperscript{5} used the pulsatile noncompliant arch model and established with the use of still photography of resin beads the presence of vortices in transverse sections of the ascending aorta. Our studies in the ascending aorta of this aortic arch model did not reveal a hemicircular rotational pattern. The multiple vortices present may have reflected a double vortex as seen in a bent pipe or may have been due to aortic valve irregularity.

In the transverse arch, Farthing and Peronneau,\textsuperscript{13} Clark and Schultz,\textsuperscript{14} and Seed and Wood\textsuperscript{15} also used invasive single-gate techniques and confirmed skewness of axial velocity. The resin bead photography of Yearwood and Chandran's\textsuperscript{5} arch model also revealed vortices in transverse sections of the transverse arch. Hemicircle clockwise rotational flow was seen in both systole and diastole in our analysis of the transverse portion of the arch model, confirming skewness of axial velocity. Our finding of enhanced rotation with branch vessel occlusion implies that patent branches absorb secondary vortices.

In the proximal descending thoracic aorta in dogs, the same investigators\textsuperscript{13–15} demonstrated skewness of axial backward flow in diastole, possibly accounting for multiple vortices and rotational flow. Resin bead photography of the arch model also revealed diastolic vortices.\textsuperscript{5} In the proximal descending thoracic aorta of our arch model, we found diastolic counterclockwise rotational flow, again confirming the effects of skewness of axial velocity. It is interesting to note in patients the high incidence of diastolic counterclockwise rotational flow pattern more superiorly in the descending aorta.
Similarly, we demonstrated predominantly clockwise systolic flow, indicating that the rotational component of aortic flow is nearly uniformly present as blood descends through the thoracic into the abdominal aorta.

Factors Influencing Our Results

It is unlikely that rotational flow is an artifact caused by transducer angulation imaging the aorta tangentially. Tangential imaging could create simultaneous red and blue hemicircles at the precise time when forward flow from the distal aorta and backward flow from the proximal aorta meets. However, if this artifact were present, the red and blue hemicircles would be positioned anteriorly and posteriorly rather than right and left as observed. No measures of circularity were used as inclusion criteria for the analyzed images; instead, all included images were made as circular as possible to avoid tangential imaging.

Elasticity of the aorta may have influenced our results. Although the effects of systolic expansion of the aorta were not evaluated, the high incidence of rotation of the retro–left ventricular level appears to be an independent finding. Less rotation at higher levels of the aorta may be related to elasticity or to the proximity of the final bend and branches in the arch creating multiple vortices.

Likewise, aortic plaquing may have also influenced our results because it affects distensibility and causes lumen encroachment. The presence of plaque did not seem to influence the high incidence of rotational flow at the retro–left ventricular level, as demonstrated in Figure 5. Plaques may have some minor effect with respect to individual flow components, but they do not alter major rotational forces.

Although performed in a small number of patients, the upright position may enhance the appearance of rotational flow dynamics. The type of heart disease did not appear to influence the presence or direction of rotation. However, the effects of a right-sided aortic arch, cardiac output, and autonomic activity on rotational flow as well as the inferior extent of rotation into the abdominal aorta remain to be determined.

Implications of Results

The implications of rotational flow are open to conjecture. Rotational flow in the thoracic aorta may be important phylogenetically and ontogenetically with regard to the mammalian cardiovascular system. Rotational flow may be important physiologically because the centripetal spin of blood may account for a significant amount of normal organ perfusion from branch vessels. Pathologically, there may be a relation of the shear forces caused by rotational flow to the deposition of atherosclerotic plaque and the direction and extent of aortic dissection. Therapeutically, by using left ventricular assist devices that create rotation and by using helically threaded aorta replacement grafts that enhance rotation, organ perfusion may be improved and thrombosis may be prevented.

Conclusion

We have demonstrated that rotational flow or functional chiral asymmetry appears to be established in the aortic arch and continued through to the descending thoracic aorta. In the proximal portion of the descending thoracic aorta of humans, there is the establishment of diastolic counterclockwise rotation and a high incidence of multiple vortices, possibly created by the physics of fluid dynamics in a bent pipe (double vortex) and proximal branching. In the distal portion of the descending thoracic aorta, systolic clockwise rotation is the predominant vortex with less evidence of multiple vortices. Although a consistency theory was not confirmed in vivo in the ascending aorta and transverse arch in humans, blood flow in the thoracic aorta might be typified as possessing chirality manifested as a predominantly right-handed helix in which systolic rotation would occur clockwise and diastolic rotation would occur counterclockwise in the direction of blood flow.

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References


**KEY WORDS** • echocardiography • descending thoracic aorta • rotational blood flow • chiral asymmetry • Doppler