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THREE-DIMENSIONAL BLOOD FLOW DYNAMICS: SPIRAL/HELICAL LAMINAR FLOW

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Introduction

Recent work in cardiac and peripheral vascular blood flow has shown evidence for an elegant complexity to flow within the heart and in the large to medium arteries. Blood flow is normally described as laminar in that the blood travels smoothly or in regular paths. The velocity, pressure, and other flow properties at each point in the fluid remain constant, all parallel to each other. Our understanding has revolved around a two-dimensional representation of flow within three-dimensional (3-D) blood vessels. However, MRI and color Doppler flow imaging techniques have demonstrated that there is a spiral/helical/rotational property to laminar blood flow. (In this article, this blood flow profile will be termed spiral laminar flow though all are equally valid terms.) The column of blood turns on a central axis as it passes along the major arteries (Figure 1).

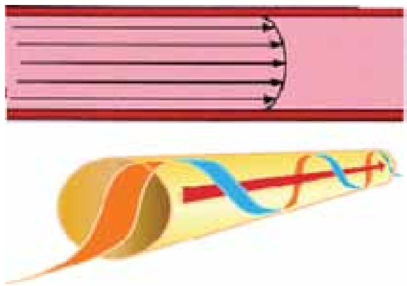

Figure 1. Two-dimensional versus three-dimensional representation of laminar flow in a tube.

Heart

The heart is a remarkable structure that displays a twisting/wringing motion during emptying and early filling, in part due to counter-wound helical muscle fibers. Much of this underlying principle has been known for 500 years, the helical nature of myocardial fibers being described by Lower in the second half of the 17th century. More recently, Buckberg focused on linking cardiac helical anatomy with cardiac function based on work by Torrent-Guasp concerning the 3-D nature of left ventricular myocardial structure.[1, 2] This is encompassed in the concept of the "helical" pump or heart. The heart appears to operate as a spiral-compressive pump with the wall following a spiral descent rather than a direct linear move to the center (Figure 2).[3] The spiral trabecular configuration of the internal surface of the left ventricle demonstrated by Gorodkov may also have a role.[4] This twisting motion during contraction is believed to result in more efficient cardiac emptying, with blood ejected from the left ventricle having a rotational element. It can be argued that having a rotational element to flow has the additional advantage of imposing a laminar order rather than the natural "settling out" of turbulence. Eliminating turbulent flow may also be important with respect to cardiac work since turbulent flow is more resistant to pumping, requiring more energy to move the fluid and therefore more work for the heart. The concept of the 'helical heart' therefore could be anticipated to have advantages in terms of efficient emptying and efficient energy use.

Interestingly, Leonardo da Vinci appears to have come to a similar conclusion with respect to spiral cardiac emptying as he sketched what very much appears to be spiral flow being generated within the left ventricle of the heart in the 16th century.

Aorta

Modern imaging techniques have shown spiral

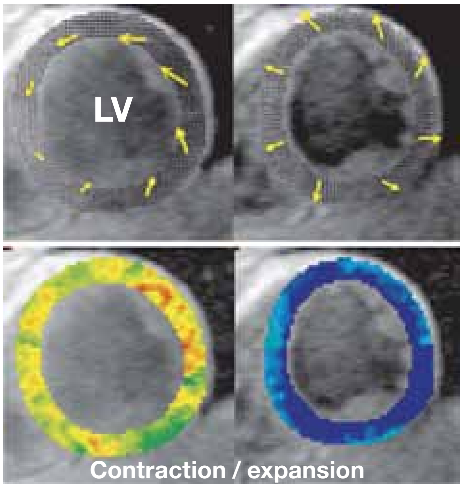

Figure 2. MRI images of left ventricular myocardial motion and interpretation. From: Jung B, Markl M, Föll D, Hennig J. Investigating myocardial motion by MRI using tissue phase mapping. Eur J Cardiothorac Surg. 2006;29 Suppl 1:S150-7.

laminar flow within the ascending, arch, descending thoracic and abdominal aorta.[5-11] A clockwise rotation has been demonstrated during systole, although a counter-clockwise rotation has been shown in diastole in the descending aorta.[12]

As there is spiral flow within the ascending aorta, the nonplanar arch of the aorta appears not to be the prime initiator of this flow profile. It is likely, however, that it reinforces and propagates this 3-D flow pattern through wall motion, compliance, and the tapering nature of the aorta.[13]

The spiral flow axis line is at the center line of the aorta. This is thought to play a significant part in maintaining the blood flow direction passing through the curved aortic arch, keeping the most effective ejection as well as in dispersing the shear stress in the aortic wall.[14]

Lee J. Frazin, 20 years ago, concluded that spiral flow may affect organ perfusion and that the rotational element of flow should be taken into account when studying flow within the aorta.[7] Recent numerical analyses of the impact of spiral flow within the aorta have concluded that the flow profile may indeed have physiological significance in the aorta. It is predicted to play a positive role in the transport of oxygen by enhancing oxygen flux to the arterial wall. It reduces the luminal surface LDL concentration in the aortic arch and probably plays a role in suppressing severe polarization of LDL at the origins of the three branches on the arch, therefore protecting them from atherogenesis.[15, 16] A study examining the effect of spiral flow on the uptake of LDL on a straight segment of rabbit aorta arrived at a very similar conclusion: that spiral flow in the arterial system plays a beneficial role in protecting the arterial wall from atherogenesis.[17]

Passing into the abdominal aorta, a further numerical study of spiral flow within the aorta showed a beneficial effect on the nature of flow within the iliac vessels. There were no regions of flow separation and decreased differences in the shear stress between the inner and outer walls in the iliac arteries. Spiral flow appears to impart a stabilizing effect on flow patterns in the downstream branches of the aorta.[18]

Peripheral Arterial

In 1991, parallel work related to blood flow in arteries led to the suggestion that the normal physiological blood flow pattern may in fact be spiral laminar flow.[19] The 3-D nature of blood flow was demonstrated in more peripheral and superficial arteries using color-flow Doppler. A true transverse plane, color Doppler interrogation of blood vessels at low velocity settings shows a characteristic appearance — the "red/blue split" (Figure 3).[20] This has been shown to represent spiral laminar flow with its axis at the centre of the artery, which has been termed "spiral laminar flow." It is important to emphasize that the flow profile is not only rotating but also laminar for the characteristic profile to exist. Using this methodology, this distinctive appearance and therefore flow profile has been reported in relatively superficial vessels such as the femoral and carotid arteries.[21] Magnetic resonance angiography (MRA) can be used in a similar way to interrogate the carotids, revealing the same 3-D flow profile.[22]

The peripheral arterial tree beyond the aortic arch also has significant elements of nonplanar construction that may play a role in the occurrence of spiral laminar flow.[23] It is also interesting to note that the arrangement of the muscle and elastin fibers of the arteries have been shown to be in helical arrangement.[24] Whether this is a coincidence or has a more direct relationship with the nature of flow in the vessel is as yet unknown.

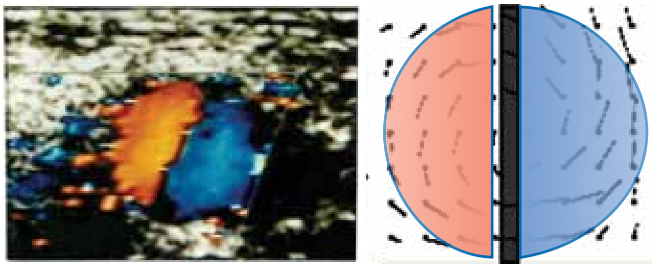

Figure 3. Arterial color Doppler of a transverse view of the common femoral artery and a graphic representation.

As a consequence of the above work, it is now possible to bring left ventricular anatomy and function together with blood flow within large-to-medium arteries as a coherent beneficial flow system. Cardiac architecture causes the left ventricle to "wring/squeeze" the heart empty, acting as a kind of spiral-compressive pump. This ejects the blood flow from the left ventricle through a nondiseased aortic valve with a spiral laminar flow profile. This flow pattern has been shown to be preserved as it passes around the arch of the aorta and into the descending/abdominal aorta, which may in part be due to the nonplanar nature of the aortic arch. Finally, spiral laminar flow has been identified within more distal direct line vessels (femoral arteries) and branch vessels (carotid arteries). Spiral flow may also have beneficial effects on cardiac work and tissue oxygenation and in the protection of the arterial wall from atherogenesis.

Clinical Correlation

When assessing the significance of spiral laminar flow, it is important to show a causal relationship with the development of arterial disease. There is very little work in this area and it is more circumstantial than definitive.

The loss of spiral blood flow has been associated with the presence, severity and progression of atheromatous disease.[25, 26] However, it should be stressed that this is an association and not proof of a causal relationship. A long-term mapping of flow patterns against disease and its progression is required, and this has not been performed as yet.

Flow Analysis and Vascular Stents and Grafts

Hemodynamic forces are a key localizing factor in arterial endothelial dysfunction and, as a result, arterial pathology.[27] Low shear stress appears to be one of the key components of this flow/vessel wall interaction.[28] In 1993, Zarins et al. demonstrated that intimal thickening and atherosclerosis develop in regions of relatively low shear stress and variation from axially aligned unidirectional flow.[29] Stonebridge and Brophy hypothesized that spiral flow could exert a beneficial effect on the mechanisms of endothelial damage and repair.[19] A study by Caro et al. supported this hypothesis and demonstrated that spiral flow may lead to relative uniformity of wall shear and inhibition of flow stagnation, separation and instability.[30]

Spiral flow has also been shown to preserve laminar flow through stenoses ("laminar stability"), markedly reducing turbulent kinetic energy (Figure 4). It also reduces laterally directed forces impacting on the vessel wall. Spiral laminar flow generates a thin, less-dense (probably acelluar) outer shell, which may act as a "fluid bearing" for the denser inner core, again assisting in reducing rotational decay.[31, 32]

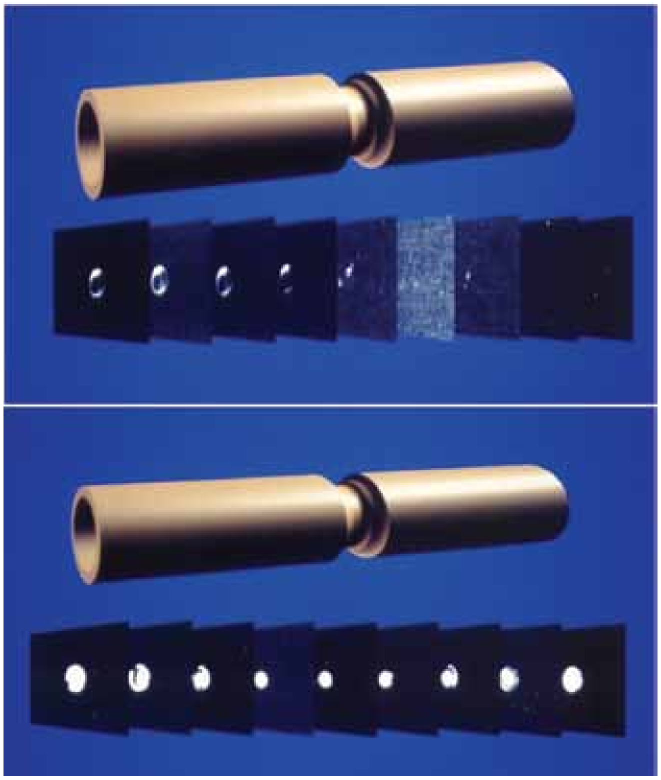

Figure 4. Laminar stability — nonspiral (upper) and spiral (lower) MRI image of flow through a stenosis showing loss of image with nonspiral flow and preservation of image with spiral flow.[31]

One study investigated the magnitude of oscillating shear stress in an aortocoronary bypass computer model in the presence of spiral flow. A linear inverse relationship was found between the oscillating shear index and the helical flow index for the models. The results indicated that spiral flow damped the wall shear stress temporal gradients within the proximal graft. The authors suggested that spiral flow might play a significant role in preventing plaque deposition by moderating the mechanotransduction pathways of cells. They further concluded that the strength of the spiral flow signal could be used to risk stratify for the activation of mechanical and biological pathways leading to fibrointimal hyperplasia.[33]

A graft or stent that recreates spiral flow at the distal anastomosis/outflow might be anticipated to have some benefits. A numerical analysis based on a spiral flow inducer for endovascular stents showed that the inducer could create sufficiently strong spiral flow, effectively reducing turbulence created by the stent, so that arterial restenosis due to the stent implantation might be suppressed.[34]

The manner in which these findings can be of importance to prosthetic graft design relate to the outflow from prosthetic grafts. Many prosthetic grafts fail due to neointimal hyperplasia at the distal anastomosis, which eventually occludes outflow. One hypothesis tested by stents and grafts, which engender spiral flow, is that the endothelial cells at the distal outflow are sensitive to the flow environment. Neointimal hyperplasia may in part or whole be a normal distal anastomotic endothelial cell mechanosensory response to an abnormal flow environment (nonlaminar flow, i.e., turbulence, stagnation, oscillatory shear stress). Reducing any flow-mediated drive to neointimal hyperplasia would be anticipated to prolong graft patency.

Spiral flow has also been shown to increase the blood velocity near the vessel wall and the wall shear rate. This is thought to potentially reduce acute thrombus formation and intimal hyperplasia and thereby improve graft patency rates.[35] A second study, using a simplified model of a stent within a straight segment of an artery in which spiral flow was introduced, showed that this flow reduced the size of the disturbed flow zones, enhanced the average wall shear stress, and lowered oscillatory shear index in the stent. All of these are believed to be adverse factors in the development of arterial restenosis after stent deployment.[36] Interestingly, the minimum rotational velocity of the spiral flow required was approximately 6.5 cms/sec, which is very similar to that shown in femoral arteries of healthy volunteers.[21]

One of the major causes of early failure of small-caliber artificial vascular grafts is acute thrombus formation, in which the interaction of platelets with the grafts' thrombogenic surfaces is the initiating step. According to Sauvage, the action of shear forces can prevent thrombus from forming on the graft wall if the blood flow in the graft is higher than the thrombotic threshold velocity.[37] Unfortunately, blood flow rates in small-diameter grafts are small, usually resulting in a time average velocity of blood flow in these grafts to be below this thrombotic threshold velocity. Enhancing blood velocity near the wall of a graft by inducing spiral flow may overcome this acute thrombus problem and may be a solution to increasing the patency of small-diameter vascular grafts. A recent study showed that spiral flow generated less adhesion of platelets to the inner surface of a tube when compared with nonspiral flow. The authors concluded that intentionally introducing spiral flow in small-caliber arterial grafts has no adverse effect on platelet activation and may indeed be a solution to improving the patency of the grafts by suppressing acute thrombus formation.[38]

Whether the artificial engendering of spiral laminar flow has biological advantages has yet to be definitively answered. If endothelial cells are sensitive to juxtamural turbulence, areas of stagnation, stress gradients, and/or high oscillatory shear stress, then the stabilization of laminar flow is likely to be an advantage. The delivery of stabilized spiral laminar flow from prostheses has not been possible until recently and therefore could benefit from further research.

Conclusion

Spiral laminar flow is an elegant unified flow concept. There are a number of published features of spiral laminar flow, indicating that this flow profile may have advantages over nonspiral flow in both physiological (heart and the peripheral artery) and device-related flow (Table 1). It is possible to speculate about other potential beneficial properties but these have as yet not been tested. There is, therefore, a lot more work to be done in this field. Only more research and time will determine whether or not it is something of true significance.

Laminar stability
Reduced laterally directed forces
Reduced near-wall turbulence
Suppresses acute thrombus formation with no increase in platelet activation
Enhances oxygen flux to the arterial wall
Reduces luminal surface LDL concentration
Dampens wall stress temporal gradients
Lowers oscillatory shear stress index

Table 1. Published features of spinal laminar flow

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