Caas MR Solutions

Whitepaper

Flow pattern quantification

Introduction

Blood flow patterns have been used to describe the differences between healthy and pathological flow. Quantification of blood flow patterns is needed to create cut-off values and inform clinical decision making. This whitepaper highlights flow pattern quantification methods, such as 2D flow displacement, flow reversal ratio, and rotational angle. It also discusses the potential clinical relevance of these methods.

Background flow patterns

Physiologically, blood flow in a healthy, straight vessel is laminar, meaning the blood moves in parallel layers, all traveling in the same direction. In such a flow, velocity is highest at the center of the vessel and gradually decreases toward the vessel wall (Figure 1).

Flow disturbances can occur for various reasons, such as stenotic lesions or the presence of a bicuspid aortic valve. Using visualization techniques, these disturbances can be observed in the resulting flow patterns (Figure 3).

While visual identification of flow disturbances is an important first step, quantitative assessment is essential for accurate analysis and clinical decision-making.

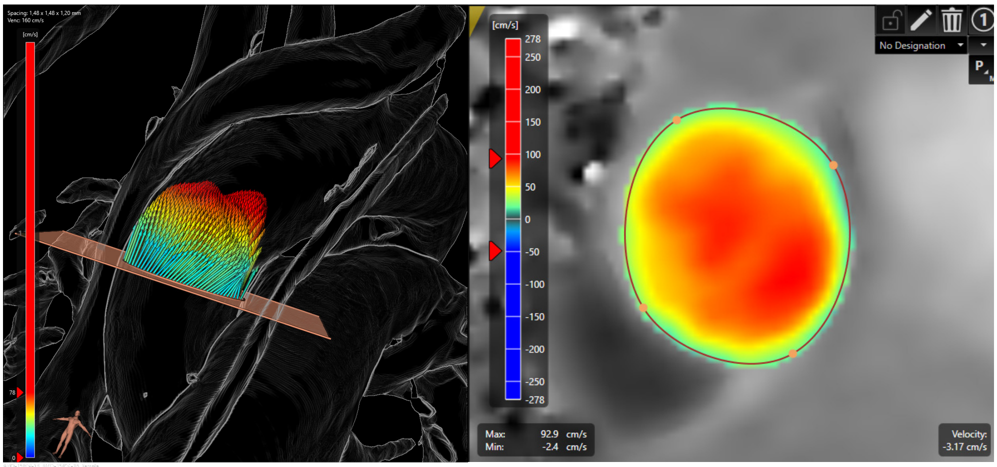

Figure 1: Laminar flow visualised by 3D vectors (left image) and in a 2D cross-section of the vessel (right image). Higher speeds are indicated by red and lower speeds by yellow, green and blue.

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2D Flow Displacement

Physiological flow is laminar, and higher velocities are located at the center of the vessel. In cases like bicuspid aortic valve disease or aortic dilation, the blood flow can become eccentric (off-centered). 2D flow displacement is a way to quantify this eccentricity. 2D flow displacement is defined as the distance between the geometric centre of the vessel and the center of blood flow, the flow-weighted centroid (Figure 2). The flow-weighted centroid represents the average location of blood flow within the vessel, weighted by velocity, meaning it lies closer to areas where blood is flowing faster. A larger displacement indicates more eccentric flow, which can signal abnormal hemodynamics.

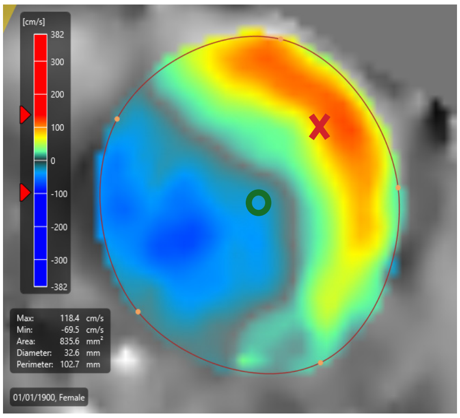

Figure 2: Eccentric flow with visualisation of the geometric center (green circle) and the flow-weighted centroid (red cross).

Flow displacement and increasing ascending aorta diameter

An increase in ascending aorta (AA) diameter is clinically significant as it reflects structural remodeling that may predispose to aneurysm formation or dissection. Flow displacement has been linked to progressive dilation of the AA in patients with a normally functioning aortic valve [1]. A study by Korpela et al., the AA diameter was measured at the sinus of Valsalva and at the mid-ascending aorta at baseline and after one year of follow-up. Patients who exhibited AA growth (n = 6) had a higher baseline flow displacement (7.5%) compared to those with stable AA dimensions (n = 24, 5.0%). Although the reproducibility of the dichotomized flow displacement threshold was only moderate, these findings suggest that increased flow displacement may predict future aortic enlargement. Consistent results were reported by Kauhanen et al., who also found that higher flow displacement was associated with a dilated ascending aorta [2].

These findings support the potential of flow displacement as an early hemodynamic marker for identifying patients at risk of progressive ascending aortic dilation, highlighting its value in risk stratification and monitoring.

Flow reversal ratio (Vorticity)

Vorticity in blood flow is a measure of how much the blood is swirling or rotating as it moves through vessels or the heart. Flow reversal ratio is a measure of how much of the blood in a vessel flows backward (retrograde) compared to the total flow (Figure 3).

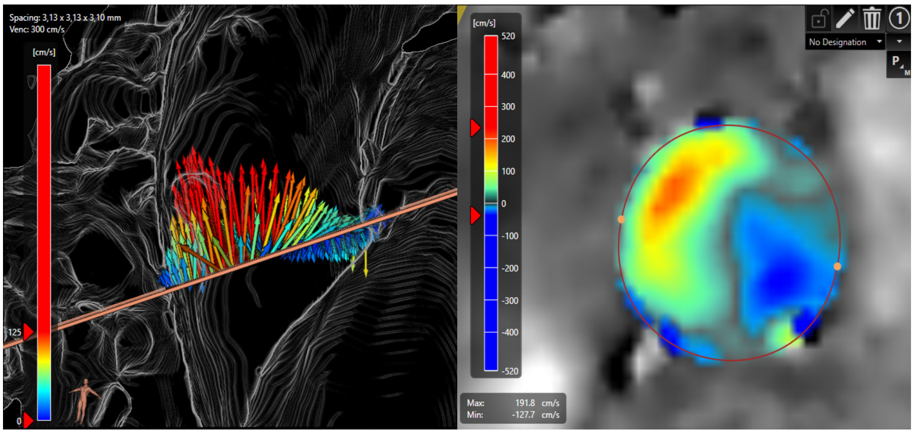

Figure 3: Visual representation of flow reversal ratio. The image on the left shows the ratio between the antegrade and retrograde vectors. The same is indicated in the 2D viewport (right image), blue is backward flow, and the remaining colors are forward flow.

Flow reversal ratio in the Bicuspid Aortic Valve

Bicuspid aortic valve disease (BAV) is the most common congenital heart disease, with a prevalence of up to 2% [3]. In patients with bicuspid aortic valve (BAV), the valve morphology and often asymmetric outflow geometry lead to disturbed haemodynamics, e.g., eccentric jets, helical and vortical flows, and are thought to contribute to the high incidence of aortopathy in this group [4]. Understanding the etiology of aortic dilation in BAV is important for risk prediction and potential intervention in the future.

The systolic flow reversal ratio, validated by Mehmood et al. [5] with a sensitivity of 82% and specificity of 100% for visual vortex presence, has demonstrated strong diagnostic performance. Its clinical relevance is highlighted by a study by Weiss et al., which found that the systolic flow reversal ratio, representing the degree of reverse flow during systole,was significantly increased (by 222%) in bicuspid aortic valve (BAV) patients compared with healthy controls [6]. Similarly, Geeraert et al. reported that reverse flow was elevated in BAV patients and that those requiring surgical intervention exhibited significantly greater reverse flow than patients not requiring intervention [7].

These findings indicate that increased systolic and overall reverse flow in BAV patients may serve as a valuable marker for aortopathy progression and help identify those with a higher need for surgical intervention.

Rotational angle (Helicity)

The rotational angle (α) is a quantitative measure of the rotational or helical behavior of blood flow within a vessel plane, derived from 4D Flow MRI data. It represents the angular displacement between the center of the vessel contour and the center of the most intense flow (velocity peak) during the cardiac cycle. Specifically, the rotational angle is defined as the angle gained between peak systole and the end of ejection, reflecting how the flow pattern twists or rotates over time (Figure 4). Rotational angle provides a localized measure of helicity, the degree of swirling motion in the flow field, and acts as a potential marker of abnormal flow behavior.

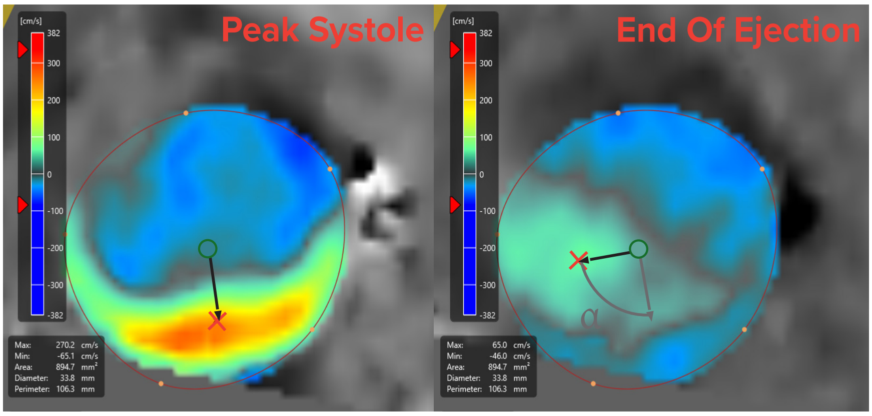

Figure 4 : The green circle indicates the center of the vessel contour, and, the red cross indicates the flow-weighted centroid. The angle (α) that is gained between peak systole and the end of ejection is the rotational angle.

Helicity in pulmonary hypertension

Chronic thromboembolic pulmonary hypertension (CTEPH) is a type of pulmonary hypertension (PH) that occurs when blood clots become stuck in the pulmonary arteries and turn into scar tissue. This blockage creates resistance and causes high pressure in the pulmonary arteries, which can lead to right-sided heart failure [8]. A study by Dong et al. showed that helical flow patterns in the pulmonary arteries reflect disease severity and patient recovery after treatment. After patients with CTEPH underwent pulmonary endarterectomy (PEA), changes in the direction and intensity of helical flow were closely linked to reductions in pulmonary pressures and improvements in right-heart function [9].

Overall, measuring helicity with 4D flow MRI could help to better understand how blood flow changes in PH and CTEPH, monitor how patients respond to surgery or medication, and perhaps even predict disease progression in the future.

References

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