Advanced Vector Flow Imaging in vascular evaluation

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A new technique for non-invasive evaluation of flow dynamics in human vessels may allow earlier detection of abnormal vascular conditions.

INTRODUCTION
Hemodynamics play an important role in the pathogenesis of atherosclerosis. Thus, vessel walls that are exposed to a steady blood flow and with a higher level of wall shear stress (WSS) remain essentially disease-free. In contrast, areas of blood vessels that are affected by disturbed or turbulent flow, which in turn results in a low level of shear stress, become prone to atherosclerosis [1]. Disturbed flow usually occurs in vessel dilatation, branching regions or in case of adverse pressure gradient and significant flow decelerations [2]. Consequently, the ability to analyze WSS hemodynamically and to measure it accurately is an essential basis for the assessment of the atherosclerotic risk in the general population.

Color Doppler imaging (CD) and Spectral Doppler or Pulsed Wave analysis (PW) can provide a real-time direct imaging visualization of flow and the measurement of blood velocities, respectively. The methods have been used to characterise patterns of flow velocity [3,4,5] and correlate them with variations in WSS [1]. However, such conventional Doppler modalities measure only one-dimensional blood velocity components, namely those parallel to the direction of the UltraSound (US) beam. The techniques are therefore dependent on angle and vessel geometry which can cause variability in the results [4,5].

Moreover, line-by-line US transmission provides a limited CD frame rate of about 20 to 30 Hz, thus permitting only low temporal resolution. This characteristic reduces the possibility of the detection and display of the dynamics of any transient phenomena. PW has a higher temporal resolution than CD and provides a complete spectrum of velocities, but it displays information generated in only a small sample volume.

The accuracy of PW depends on the precise estimation of the angle between the ultrasound beam and the flow in the vessel. This angle is difficult to estimate correctly particularly when streamlines differ from the vessel course, even when using CD as a guide. The assumption that the flow velocity vectors are axial at bifurcations and curves and in the presence of plaques has been shown to be incorrect [3]. Moreover, because of their pulsatile nature, flow components frequently vary temporally over a cardiac cycle.

All these limitations explain why, in routine clinical practice, a precise quantification of disturbed flow, which by definition is multi-directional, is not achievable with conventional ultrasound systems.

To overcome these limitations, a new method of multi-dimensional estimation of flow velocity vectors, known as Vector Flow Imaging (VFI), has been developed [6]. This proposed vector Doppler method is based on the estimation of at least two of the three components (namely the x, y, and z-axis) which, in physics describe a velocity vector. In practice, VFI is carried out by measurements taken in two or more independent directions using multiple US transmitters and receivers [7]. The independent velocity so estimated can then be used to reconstruct the true flow vector and the velocity magnitude at each site [7].

The main advantages of VFI are the independence of the method on beam-flow angle and the ability to assess multi-directional blood flow, thus displaying the real flow characteristics.

VECTOR FLOW IMAGING
Various VFI methods, based on several different measurement principles have been proposed, but only a few have been implemented in commercial systems. Whatever the principles of measurement, the methods can be categorized into two groups. The first category, based on conventional line-by-line acquisition, evaluates the flow pattern complexity in real-time at a relatively low frame rate, whereas the second group, being based on plane-waves and parallel receiving, achieves a higher frame rate during a short period of acquisition, thus allowing a better depiction of the complex flows [8,9].

In plane wave imaging (PWI), a series of single
unfocused beams, oriented in different directions over a wide area of the field of view, are transmitted and allow parallel retrospective beamforming upon reception [10]. The number and angulations of the transmitted plane waves and the retrospective beamforming, performed from multiple angles, affect the spatiotemporal resolution of PWI [11].

Several PWI-based VFI methods have been developed, but only one of them, using a new vector computation algorithm known as vector projectile imaging (VPI), generates a significantly high frame rate of 416 Hz.

VPI derives the true velocity vectors (i.e., each velocity component) at any location from the multidirectional transmission and reception of plane waves. Tested in vitro on an anthropomorphic phantom simulating carotid bifurcation, VPI has been shown to enable adequate tracking of spatiotemporal flow variations [12].

HIGH FRAME RATE VECTOR FLOW

High frame rate VFI, known as V Flow, and currently commercially available only on Mindray’s Resona 7 system, represents one implementation of the VPI method and generates a frame rate of 400-600 Hz, thus allowing a detailed characterisation of flow patterns and simultaneous high-resolution B-mode images by interleaving focused waves with multi-directional Doppler transmission [13].

With V Flow, the flow within a selected region of interest (ROI) is analyzed by the system at a pulse repetition frequency (PRF) of 15 kHz and an extremely high frame rate for 1.5 seconds, thereby allowing the examination of at least one cardiac cycle. V Flow measures the speed and direction of all blood cells flowing through every point of the ROI in a short space of time. The data are reprocessed automatically by the system, generating a sequence of 900 images displayed at a frame rate of 25 Hz. The flow is represented by several colored arrows showing the different velocity, magnitude, and direction at every point of the vessel. Green arrows represent low velocities, yellow and orange arrows medium velocities, and red arrows depict high velocities. The longer the arrows, the faster the flow. The color and size of the arrows thus allow visual quantification of the flow behavior. The high acquisition frame rate results in a detailed visualization of the flow, with even otherwise uncaptured transitory events, which can occur during a cardiac cycle, being able to be assessed. The approach also allows the distinction of the different flow components and their extension and duration [11].

The flow characteristics can be evaluated visually, frame by frame, to assess the flow pattern (e.g., laminar and helical flow, recirculation, counter eddy, vortex, and turbulence) by considering the vectors’ directions and lengths. Such detailed analysis is particularly helpful whenever the hemodynamics become extremely complicated, as in vessel bifurcations or when plaques develop [Figure 1].

For numerical quantitative flow evaluation, a package of...
easily applicable tools and measurement parameters have been developed. These comprise: multiple user-defined vector velocity curves, which show the variation of flow velocities in subsequent cardiac cycles; the automatic detection of the maximum velocity vector point, combined with the circular variance for the angles of vectors in a specific selected area, thus allowing the characterization of non-laminar flow; measurements of volume flow and wall shear stress (WSS) at different locations, which are useful for the study of the hemodynamics of complex flow [Figure 2].

CLINICAL APPLICATIONS OF VFI
A comprehensive assessment of blood flow should be the ultimate goal of every ultrasound evaluation, which means that the hemodynamic characteristics of the flow should be displayed. Because local hemodynamic variations have a strong influence on the WSS and are a major factor in the development of atherogenesis, the practical clinical applications of V Flow relate to each change in vessel direction or bifurcations and changes in the vessel wall itself (e.g. plaque and vessel diameter), which greatly affect the profile of the blood streams.

Due to its anatomical position and strategic clinical role the carotid bifurcation has been the vessel most thoroughly investigated in detail by VFI, ever since the early development phase of the technology. In such studies, VFI has been able to identify a vortex in the carotid sinus during the deceleration phase after peak systole, no matter which estimation method was used [14,15,16,17]. In addition, thanks to the combination of higher spatial and temporal resolution, V Flow has been shown to be able to clearly outline flow behaviour in vessel enlargement and kinking, together with variations in the

Figure 2. Top Left and Top Right. B-mode longitudinal and transverse views show a low-to-moderate degree stenosis at the entrance of the ICA, quantified as 44.2% in diameter and 53.1% of the area.

Bottom Left. CD shows increased velocities in the ICA (*), coded in blue as a consequence of the aliasing artefact. Spectral Doppler rules out an increased velocity (PSV 97.7 cm/s) and highlights flow disturbances through the spectral broadening and bidirectional flow.

Bottom Right. The VFI frame, extracted at the systolic peak, shows a narrow high-velocity streamline (long red vectors) shifting toward the anterior wall of the ICA (arrowhead) at the stenosis level (*). Distally to the stenosis (arrow), the separation of the layers develops a slow fluid movement upstream (short green vectors). The automatic detection of the point of maximum velocity vector in the selected ROI allows the recognition of an instant PVS of 131 cm/s, higher than the PW finding, thus grading the stenosis as moderate (50-60% – NASCET). The high WSS value (max 9.4, mean 1.9 Pa) at the stenosis level (blue dot #3) is related to the impact caused by the plaque on the hemodynamics.
shape of the carotid bifurcation [17]. In such conditions, some measurement parameters, such as the circular variation of the vector angles in a selected region of interest allow the instant characterisation of any flow disturbances and thus provide a deeper understanding of possible effects on plaque formation, so enabling a stratification of the patient’s risk [Figure 3].

Analysis of the relationship between disturbed flow patterns and atherosclerosis has shown that V Flow has the potential to improve the understanding of turbulence [17]. The possibility, via the V Flow method, to estimate WSS at a precise location among different flow patterns, as well as in vessel stenosis, can be an important adjunct in the assessment of overall clinical value.

Another emerging clinical application of V Flow is the evaluation of arteriovenous fistulae (AVF) used hemodialysis [18].

This current brief review has mainly focused on the current clinical applications of the high frame rate of VFI, but it should be noted that the vector Doppler technique can also be applied in other vascular areas, such as in femoral arteries [19], as well as in the cardiology field [20].

CONCLUSION
VFI technology provides an intuitive representation of flow in all directions, independent of the vessel geometry. V Flow has been shown to be able to visualize complex flow patterns, thus providing new information on flow behaviour and allowing for a quantitative evaluation of turbulence. The benefits of the high frame rate in VFI are even more evident when the technology is used for WSS measurement, an important parameter associated with vascular function and atheroma growth.