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● *Original Contribution*

EFFECT OF VESSEL CURVATURE ON DOPPLER DERIVED VELOCITY PROFILES AND FLUID FLOW

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Abstract—Side-branches and curvatures in the arterial tree yield deviations from the axial oriented velocity. Velocity or volume flow estimates based on the assumption that flow is axially oriented are of limited value at these sites. This article evaluates information obtainable by using a multigate Doppler ultrasound (US) instrument used with curved phantoms, which resemble the human coronary arteries. The comparison of experimental velocity data with data provided by an accurate computational fluid dynamics (CFD) method shows differences in the range of 4 to 11% for four curvatures with different radii. Multigate data are also used to estimate the volume flow in the curved segments at different experimental conditions. An error lower than 15% is obtained, to be compared with a 24% error obtained by assuming a parabolic velocity profile. In particular, it is shown that the residual error is not related to the small deviation of the velocity vectors from the axial direction due to the presence of secondary velocity components, which are found to be of magnitude less than 10% with respect to the axial velocity component. (E-mail: r.krams@erasmusmc.nl) © 2005 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Doppler, Velocity profiles, CFD, Secondary velocity.**

INTRODUCTION

Atherosclerosis has a distinctive distribution pattern, *i.e.*, near curvatures or side-branches, which cannot be explained by the current risk factors (Brand et al. 1989; Honda et al. 2001; Krams et al. 1997). Several laboratories have provided evidence that deviations of the normal velocity field occur at these sites (Brand et al. 1989, Friedman et al. 1986; Gnasso et al. 1997; Honda et al. 2001; Ku et al. 1985; Shaaban and Duerinckx 2000; Wentzel et al. 2001b; Zarins et al. 1983).

Kinetics of fluid elements in curved segments is quite complex, due to the secondary velocity components induced by centrifugal forces (Chang and Tarbell 1988; Dash et al. 1999; Kang and Tarbell 1983; Mann and Tarbell 1990; Perktold et al. 1991; Sabbah et al. 1986; Weston and Tarbell 1997). As the secondary components are large in the symmetry plane of the curved segment and as these components are directed outward, the maximum velocity shifts to the outer curvature (Chang and Tarbell 1988; Mann and Tarbell 1990; Perktold et al. 1991; Weston and Tarbell 1997). The possible presence of atherosclerotic plaques yields further deviations from the ideal parabolic velocity distribution (Wentzel et al. 2001a; Wentzel et al. 2001b; Wentzel et al. 2000).

Several methods have been developed for measuring velocity patterns near atherosclerotic plaques, including MRI-, echo- and Doppler-derived fluid flow. (Friedman et al. 1986; Gnasso et al. 1997). MRI-based methods are non invasive but offer a rather low resolution (Glor et al. 2003; Long et al. 2003; Thomas et al. 2003; Wu et al. 2004). Fluid flow measurements based upon correlation of subsequent IVUS images needs a catheter to be located inside the artery, thereby affecting the velocity profile and the shear stress pattern (Chandran et al. 1996; Cheng et al. 2003; Krams et al. 1999b; Liu et al. 2001). Doppler-based techniques (Evans et al., 2000) are particularly promising. The earlier intra vascular Doppler methods measure maximum velocity over a cross-section and calculate flow and shear stress after assuming a parabolic velocity profile (Doucette et al. 1992). However, as stated above, such assumption is not realistic and neither this method nor other methods measuring velocity in a single point (single-gate Doppler) provide con-

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sistent fluid flow estimates (Doucette et al. 1992). Another limitation common to all Doppler approaches is that, to convert the measured frequencies to velocities, the beam-to-flow angle can only be estimated on the basis of geometrical considerations, by assuming that, at any measurement point, the velocity vector is oriented along the local vessel axis. The unavoidable presence of (transversely oriented) secondary velocity components in curved vessel segments makes such an assumption a further possible source of measurement error.

The limitations of single point measurements are partially overcome by real-time multigate instruments that have been recently developed (Tortoli et al. 2002; Tortoli et al. 1997; Tortoli et al. 1999) for measuring the actual distribution of Doppler frequencies along the US beam axis. This paper investigates the effects of vessel curvature on Doppler-derived velocity profiles and on related fluid flow estimates. CFD-derived velocity profiles are used as a reference for evaluating the accuracy of experimental velocity profiles measured with the multigate system in curved phantoms resembling the human arterial coronary system. Fluid flow estimates based on different Doppler (single-gate and multigate) techniques are then evaluated. The effect of secondary velocity components on these estimates is also discussed.

MATERIALS AND METHODS

Ultrasound system

A piezoelectric unfocused 16 MHz transducer (manufactured at the Institute of Fundamental Research, PAN, Warsaw) is excited at 16 kHz pulse repetition frequency (PRF) to generate bursts of US energy. The US beam is narrower (−6 dB) than 1 mm over a range of about 15 mm, as measured through an advanced system dedicated to US probe characterization (Esaote S.p.A., Florence, Italy). Circuits for electrical excitation of the piezoelectric element and for amplification of received echoes are included in the radio-frequency front-end. Phase-quadrature demodulation, allowing forward and reverse flows to be distinguished, provides two base-band signals.

Acquisition-processing system

The multigate processing system consists of a PCI-bus plug-in card (to be housed in a PC), where three sections can be identified. The first section performs analog conditioning of input signals provided by the US system; the second carries out acquisition by means of two analog-to-digital converters (ADCs); and the third performs data management and processing in a high speed digital signal processor (DSP) associated with SDRAM and PCI channel.

For each pulse transmitted at PRF rate, the system digitizes 64 complex samples with 14-bit resolution. The operator can change the time distance between these samples, corresponding to the spacing between the range cells, to match the analyzed range to the actual region-of-interest. Processing is performed by the TMS320C6202 (Texas Instruments Incorporated, Dallas, Texas, USA) that computes the true spectra of the Doppler signals related to the subsequent range cells in real time. The computed power spectral densities are sent to the host PC for real-time display. During real-time operation, it is possible to store all data acquired over a time interval several seconds long into a file, for possible post processing.

Software measurement tools

All real-time and postprocessing operations are under user control by means of a bundled software, named GASP (global acquisition and signal processing), which consists of an integrated shell for Windows™ (Microsoft Corp., Redmond, Washington, USA) family operating system. It includes applications for postprocessing carried out in LabVIEW™ (National Instruments Corp., Austin, Texas, USA) and a Visual C++ (Microsoft Corp., Redmond, Washington, USA) coded console for real-time data acquisition and visualization (Bambi et al. 2004).

By using the post processing modules, it is possible to evaluate different features of each acquisition. Up to 200 subsequent spectral profiles are ensemble-averaged to reduce the spectral variance (Evans et al. 2000). For each of the 64 averaged spectra, related to the 64 corresponding depths, the peak frequency is estimated through the threshold method (Marasek et al. 1994). A polynomial fit of the 64 experimental points is carried out through the LabVIEW™ "HouseHolder" function.

Frequencies have been converted to velocities according to the Doppler equation, corrected to take into consideration the intrinsic spectral broadening effect:

$$V = \frac{f_{\max}}{\frac{2}{\lambda}\left(\cos\theta + \frac{1}{2}k\ \sin\theta\right)} \tag{1}$$

where V is the flow velocity, $f_{\max}$ is the estimated peak frequency, λ is the US wavelength, θ is the Doppler angle and k is a factor depending on the transducer (Tortoli et al., 1997). For the 16 MHz transducer used in our experiments, $k \cong 0.2$.

Flow phantom

A closed-loop hydraulic circuit was used, where changing the height difference between an upper and a lower reservoir controls fluid velocity. The corresponding flow rate (ml/s) was measured through a variable area flow-meter (e50-2600, ASA SpA, Milano, Italy). The