Dynamic Flow Quantitation with Spatial Orientation Guided Digital Color Doppler Imaging: \textit{in vitro} Validation and Initial \textit{in vivo} Experience

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Abstract: We have developed an orientation guided digital color Doppler method for volume flow quantification in irregularly shaped flow passages. The instantaneous flow rate was calculated by the integration of area-velocity product (extracted from digital color Doppler images) with correction of the flow direction (determined from three-dimensional reconstruction using a position and orientation sensing system). The method was validated \textit{in vitro} and applied \textit{in vivo} for quantification of gastric emptying on 5 healthy volunteers. The average gastric emptying lasted 0.75 sec, and discharged 3.0 ml in volume. This new flow quantification method minimizes the angular ambiguity and geometric assumptions.

Conventional flow quantitation with pulsed-wave Doppler often relies on assumptions of geometric shape, spatial flow profile and Doppler angle. These assumptions limit its clinical applications in numerous situations. Two examples are the venous flow and gastric emptying where irregularly shaped flow passage, non-parabolic velocity profiles and ambiguous Doppler angles are expected. Color Doppler has been used widely as a qualitative and semi-quantitative method for delineating the existence and the extent of abnormal flow. However, it has not employed quantitatively for clinical study due to the difficulties of extracting the velocity information from the image. On the contrary, digital color Doppler imaging allows quantitative delineation of a cross-sectional flow field by providing noise-reduced tomographic velocity data. In addition, recent developments in a three-dimensional (3D) tracking technique have established (1,2). The technique provides the spatial location and orientation of the scan head in real-time. This method combining with digital imaging capability offers the feasibility of using color Doppler as a quantitative tool for assessment of a flow field.

We have tested this spatial orientation-guided flow quantitation method on a tube model to determine the optimized instrument settings and validate its accuracy from a calibrated static flow model. Then, we applied this method \textit{in vivo} to measure the gastric emptying.

FLOW MEASUREMENT PRINCIPLE

Figure 1 shows the flow quantitation technique in a simplified flow model of a tubular passage. The line between the centers of the flow passage at two distal cross-sections, \( r_1 \), indicates the flow direction. The flow velocity \( V_j \) at a differential area \( A_m \) in the image can be derived from the measured velocity \( V_m \) as \( V_j = V_m \cos(\theta) \), where \( \theta \) is the angle between the flow direction and the ultrasound beam (Doppler angle). The cross-sectional area that is perpendicular to the flow direction can be expressed as \( A_m \sin(\phi) \), where \( \phi \) is the spatial angle between the flow direction and the imaging plane. The flow rate for this finite area is the product of the velocity and area. The total flow rate is the integral of the entire flow field, or,

\[
\text{Flow} = \sum V_m \cos(\theta) A_m \sin(\phi).
\]

Figure 1. Illustration of the flow quantification technique with 3D guided digital color Doppler.

Figure 2. \textit{In vitro} flow quantification with 3D guided measurement versus the true flow rates.
We reconstructed the flow passage in 3D (from manually traced borders of the duodenal bulb, pylorus and distal antrum). Then, two center points (P1 and P2) were calculated from short-axis cuts at the two ends of the passage. The spatial line passing through these two centroids was assumed to be the flow direction. Thereafter, the Doppler angles and the spatial angles with respect to the flow direction were determined on consecutive image planes.

Velocity extraction was derived by converting the color pixels into a velocity value based on the color component values on the colormap. In color Doppler image, a velocity is represented by a specified color pixel, with a disparity among its R, G and B values. The velocity pixels were identified and segmented by comparing its color components for each pixel. Then, for each color pixel, its velocity value was determined by the reverse of the flow mapping algorithm. Once the velocity is determined, the flow was then calculated from the velocity-area integrals using the equation above with the angle correction.

**IN VITRO VALIDATION AND IN VIVO STUDY**

The *in vitro* experiment was conducted on a static flow model in which the flow rate has been previously calibrated by water displacement. With static flow rates ranging from 3.4 to 34.6 ml/sec, we acquired the cross-sectional color Doppler digital images at angles from 35 to 65 degrees using a HDI-3000 (Advanced Technology Laboratory, Bothel, WA) ultrasound system with a 10-5 MHz linear transducer. Fish oil (2%) was used as blood analogue fluid to enhance the acoustic back scatters. The 3D position and orientation data were acquired with a magnetic sensing system (Ascension Technology, Burlington, VT) and saved on a PC. The 3D data and the digital images were transferred to a Silicon Graphics Indigo² workstation for 3D reconstruction and data analysis.

For the ultrasound system settings, we used the velocity mode (variance of~ with no baseline shift and no angle correction. Color Gain was set so that the Doppler signal to be maximum and restrained within the lumen of the tubular passage and the highest level that no background noises were visible. Then, the velocity scale was adjusted so that the Nyquist limit was slightly above the maximum velocity (verified by pulsed-wave Doppler) in the particular flow field. Other parameters included wall filter low, priority medium, persistence off, and line density medium. These settings were saved and kept consistent for subsequent image acquisition.

Five male healthy volunteers (mean age 31) were recruited in this *in vivo* study. Subjects had fasted for 12 hours before examination. Recording of the gastric emptying episode started 10 minutes after intake of a 500 ml meal of meat soup. A rapid B-mode scan of the pylorus region was accomplished for 3D reconstruction and determining the orientation of the flow passage. Digital color Doppler images were obtained continuously covering a completed transpyloric flow episode. Images were recorded first with cineloop memory and then transferred to the computer workstation for analysis.

**RESULTS AND DISCUSSION**

Within the applicable Doppler angle range, the *in vitro* flow rates derived by 3D guided measurement slightly underestimated the reference flow rates (by average 8.3%) ranging from 3 to 35 ml/sec (r=0.98, p<0.001), with the predetermined instrument settings (Figure 2). The gastric emptying episode lasted 0.47 to 1.73 seconds (average 0.75 seconds). The emptying volume varied from 1.1 to 5.6 ml (mean 3.0 ml).

Our *in vitro* experience suggests that the Doppler angle is a major factor that determines the accuracy of flow quantification. The spatial velocity variation associated with the beam thickness affects the accuracy of measured velocities and areas, therefore, the flow rates. The 3D capability provides a quality control for imaging orientations, thereby, minimizing inappropriate Doppler angles. Lack of definitive guidance for instrument settings such as Color Gain is the major limitation of this study. Optimizing these parameters requires further quantitative investigation.

In conclusion, we have demonstrated the feasibility of extracting velocity information from the digital images. With appropriate instrument settings, spatial orientation guided digital color Doppler can be used for dynamic flow quantification with clinical comparable results (3). This new technique facilitates rapid, free-hand imaging for a variety of relatively large flow fields with minimal geometric assumptions and angular ambiguity. When direct digital velocity data output is available, this technique may provide a practical approach for many clinical situations.

**REFERENCES**