Quantitative IVUS Blood Flow using an Array Catheter

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Abstract

In recent years, a new method to measure transverse blood flow, based on the decorrelation of the Radio Frequency (RF) signals has been introduced. In this paper, we studied the decorrelation characteristics of transverse blood flow using an intravascular ultrasound (IVUS) array catheter by means of computer modeling. Blood was modeled first as randomly located point scatterers and second as aggregates moving across the ultrasound beam. Next, spread of flow and flow gradient were simulated. IVUS flow measurements were used to study the influence of the ring-down size on flow measurements. Coronary Flow Reserve (CFR) was computed from this data and from a calibrated Transonic flowmeter. The decorrelation pattern for point scatterers, for aggregates and for non-homogeneous flow is in agreement with theoretical predictions from sound field calculations. Underestimation of flow occurs by the ring-down obscuring but good agreement between IVUS and flowmeter CFR was found.

1. Introduction

IVUS RF-data processing [1] has significantly increased the possibility to obtain morphological and functional information from arteries [2]. Recent research showed the possibility to measure blood velocity and quantify the volume flow based on decorrelation method with a rotating single-element IVUS catheter [3]. The measurements were performed from cross-sectional IVUS RF signals. This rotating single-element catheter has an extra component of decorrelation, the angular displacement of the ultrasound beam [3]. The use of array technology in IVUS [4] applications removes this limitation in the measurements of blood flow.

In this paper, the decorrelation properties of an array catheter, as well as other decorrelation properties that could affect the flow measurements are studied. We simulated transverse blood flow by moving a scattering medium transversally across the acoustical beam. The scattering medium was defined as a collection of randomly positioned scatterers in a three-dimensional space. First, point scatterers were used as single red blood cell (RBC). Second, strings of point scatterers with different lengths and at random angles simulated aggregates of RBCs [5, 6]. Next, the effect of spread of flow and linear flow gradient on the decorrelation pattern was studied. In all cases, the decorrelation pattern was assessed for the near field (≈1 mm). CFR was measured from experimental data; using a computer program, the influence of the catheter position and the ring-down size on the blood flow measurements was also studied.

2. Methods

2.1. IVUS transducer

We simulated an IVUS array catheter with 64 elements mounted on the circular surface of the catheter tip with a diameter of 1.2 mm; which operates at a central frequency of 20 MHz and the -20 dB bandwidth is 7.5 MHz. In flow imaging mode, four elements are electronically tied together as a single element for transmission and reception to produce the acoustical beam [7].

2.2. Computer modeling

2.2.1. The simulation program

The mathematical development to simulate ultrasound signals is based on pressure field calculations using the impulse response method. This simulation program was developed and validated separately [8].

2.2.2. Blood flow simulation

The scatterer density was chosen to meet the Rayleigh criterion [5]. To simulate blood flow, the scattering medium was moved transversally across the acoustical beam. At each displacement, the backscattered RF signals

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from the scatterers within the -20 dB beam width are summed and saved as one RF signal.

2.3. Temporal correlation method

The temporal correlation was used to examine the variations between RF signals when a scattering medium is transversally moved across the acoustical beam. The correlation coefficient $\rho_{i,j}$ between two RF signals, $s_i(n)$ and $s_j(n)$, received from positions of the scattering medium corresponding to d=i and d=j is:

$$\rho_{i,j} = \frac{\sum_{n=1}^{N}\left(s_i(n)-\bar{s}_i(n)\right).\left(s_j(n)-\bar{s}_j(n)\right)}{\sqrt{\sum_{n=1}^{N}\left(s_i(n)-\bar{s}_i(n)\right)^2.\sum_{n=1}^{N}\left(s_j(n)-\bar{s}_j(n)\right)^2}},$$

where the subscript i=1,2…D and j=1,2…D being D the number of displacements. For the RF signals, N is the length in time and $\bar{s}$ is the mean value. The $\rho_{i,j}$ are the correlation coefficients for the signal pair, s_i and s_{i+m}, which are spaced $m=(j-i)$ steps and $m=0,1\ldots D-1$. Next, the average correlation coefficients in the signal set for a space of m steps between signals is calculated and ρ_m describes the decorrelation pattern as a function of transverse displacements.

2.4. Decorrelation from point scatterers and aggregates of RBCs

The decorrelation pattern from the RF signals when the scattering medium is transversally moved across the ultrasound beam was assessed. The aggregates were formed by strings of point scatterers of various lengths (0.75, 1.25 and 1.75λ) and at random angles ranging from -45° to +45° with respect to the catheter axis. For these simulations, all scatterers were moving at the same speed (plug flow). The step size was $\Delta x \approx 0.02$ mm.

2.5. Decorrelation from non-homogeneous flow

We simulated spread of transverse flow as point scatterers moving at random (normally distributed) velocities and linear transverse flow gradient where the point scatterers' velocities were defined as a linear function of depth considered only within the time window length. Thus, the scatterers nearest to the transducer are assumed to have the slowest velocity. In both cases, the mean step was $\Delta x \approx 0.02$ mm and the step size ranged from $\Delta x \approx 0.01$ mm to 0.03 mm.

2.6. Effect of ring-down on the flow measurements

Through a computer program, we studied the effect of the ring-down size and catheter eccentricity on the obscuring of the vessel lumen. The ring-down sizes were assumed to be 0.3 and 0.6 mm in depth; which are representative of the limits in ring-down size from an IVUS array catheter. The vessel lumen was considered circular with radius ranging from 3.0 to 5.0 mm. The eccentricity of the catheter, in %, is defined as the distance between the center of the lumen to the center of the IVUS catheter divided by the radius of the lumen.

2.7. Coronary flow reserve (CFR)

CFR in patients is measured as the ratio of the hyperemic flow measured during e.g. an infusion of adenosine over the baseline flow. This parameter evaluates the physiological significance of a coronary stenosis [9]. From in vitro measurements, with flows ranging from 0 to more than 250 cc/min, we have arbitrarily computed the baseline flow for each catheter position and tube combinations as half the average of all the non-zero measured flows. The *in vitro* coronary flow reserve for each recording was then computed as the measured flow over this defined baseline flow.

3. Results

Figure 1 shows an agreement between the mean decorrelation pattern for point scatterers and the autoconvolution of the acoustical beam. Figure 2 shows the mean decorrelation patterns for strings of 0.75, 1.25 and 1.75λ in length and at random angles in close agreement with the one from point scatterers. Only plug flow was considered in Figure 1 and 2. The mean decorrelation patterns for spread of flow (Fig. 3a) and for flow gradient (Fig. 3b) are shown in agreement with the one for plug flow. Figure 4 shows the percentage of the lumen area obscured by ring-down as a function of tube diameter for five different tube diameters (3.0, 3.5, 4.0, 4.5 and 5.0 mm) and for two ring-down sizes (0.3 and 0.6 mm in depth). Figure 5 presents the CFR based on flow measurements. The IVUS flow corrected with the measured offset shows a good agreement between the IVUS derived and the Transonic CFR.

4. Discussion

An analysis of the decorrelation properties of the ultrasound beam during transverse flow was performed. From RF signals, the mean decorrelation pattern shows a

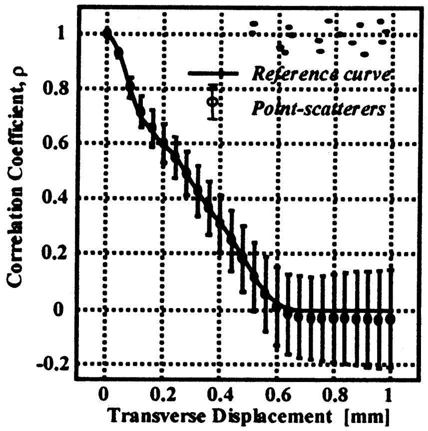

Figure 1: Mean RF decorrelation pattern from point scatterers (error-bars) as a function of transverse displacements; a comparison with the autoconvolution of the acoustical beam (solid line).

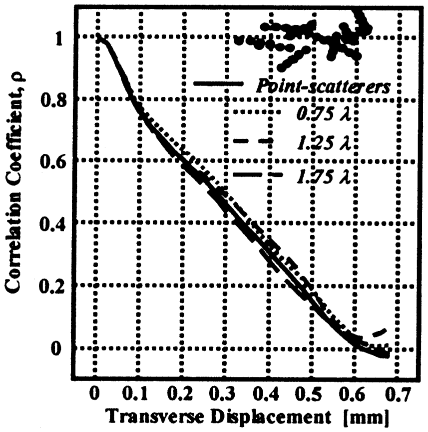

Figure 2: Mean decorrelation pattern from point scatterers (solid line) compared with the one from aggregates of various lengths (0.75, 1.25 and 1.75λ) and random angles (from -45° to +45°).

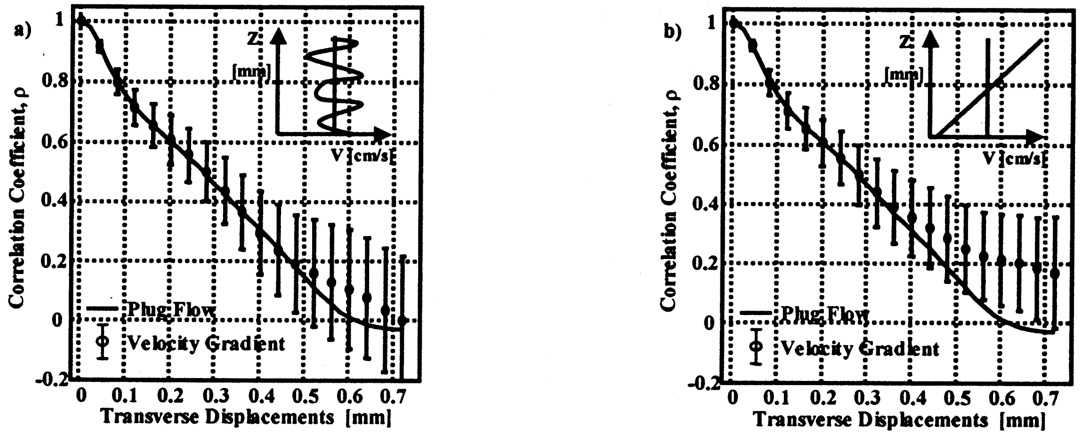

Figure 3: Mean RF decorrelation pattern for spread of flow (a, error bars) and for linear flow gradient (b, error bars), a comparison with the decorrelation pattern for plug blood-flow (solid line).

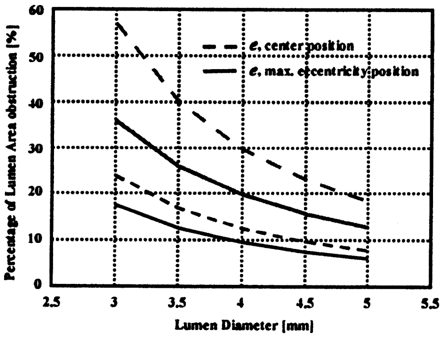

Figure 4: Percentage of obscured area due to catheter eccentricity for different tube diameters when the eccentricity ranged from 0 (center of the lumen) to 60 %. Catheter radius of 0.6 mm with a ring-down size of 0.3 (thin black lines) and 0.6 (thick gray lines) mm in depth.

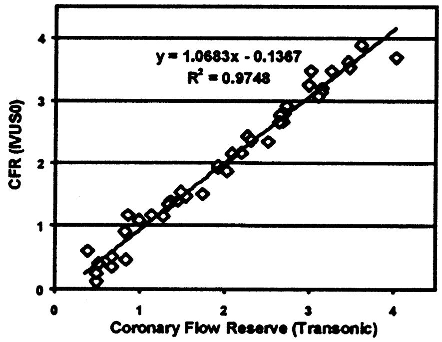

Figure 5: Comparison between the measured coronary flow reserve (CFR) derived from the IVUS flow decorrelation method and the true CFR computed on the measured Transonic flows.

monotonic decay as a function of transverse flow. The agreements shown in Figure 1 and 2 are of great of importance; the decorrelation properties of the ultrasound beam can be assessed just by the autoconvolution of the acoustical beam.

The analysis of the decorrelation patterns for non-homogeneous flow, show a good agreement with the one for plug flow (Fig. 3a and b). The only deviation was for lateral displacements below 0.4 mm (Fig. 3b). For velocity calculations, decorrelation values above 0.5 are used, so this has no influence on our flow estimation method. Blood flow gradient always exists because flow velocities are non-uniformly distributed over the vessel cross-section and the ultrasound sampling volume has certain dimension.

The ring-down, formed by the interaction of the ultrasound beam and the packing material, obscures part of the lumen where blood is flowing, producing an under estimation of the flow if the system is not compensated for it. When the amplitude of the RF signals is saturated, no change due to flow can be detected by the decorrelation-based method. The ring-down is shown to obscure up to 45 % of the lumen (Fig. 4). Therefore, a maximum eccentricity of the catheter is important during *in vivo* recordings.

Absolute coronary blood flow would be the optimal parameter for intracoronary physiological studies. However, a useful clinical index at the end of an intervention such as a stent implantation is the CFR [10]. The results of our study suggest that the CFR could be estimated in patients with an IVUS catheter (Fig. 5). A limitation will be that the catheter must occupy a relatively stable position in the coronary lumen, ideally, at the most eccentric location, which can be achieved.

5. Conclusions

A computer program to simulate the acoustical beam and transverse blood flow for an intravascular array transducer catheter was developed. The decorrelation-based method showed to not be influenced by the presence of aggregates -at random lengths and angles- as well as by non-homogeneous flow conditions -random spread of flow or linear flow gradient-. We have characterized experimentally some of the limitations of the IVUS quantitative blood flow assessment. The ring-down artifact clearly showed to affect the flow measurements. Despite the deleterion effect of the ring-down artifact, a practical solution was proposed for the calculation of coronary flow reserve. In conclusion, the decorrelation-based method to derive quantitative volume blood flow and coronary flow reserve using IVUS RF signals are very encouraging.

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