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Technical note

Fixed volume particle trace emission for the analysis of left atrial blood flow using 4D Flow MRI

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ABSTRACT

4D Flow MRI has been used to quantify normal and deranged left ventricular blood flow characteristics on the basis of functionally distinct flow components. However, the application of this technique to the atria is challenging due to the presence of continuous inflow. This continuous inflow necessitates plane-based emission of particle traces from the inlet veins, leading to particles that represents different amounts of blood, and related quantification errors. The purpose of this study was to develop a novel fixed-volume approach for particle tracing and employ this method to develop quantitative analysis of 4D blood flow characteristics in the left atrium. 4D Flow MRI data were acquired during free-breathing using a navigator-gated gradient-echo sequence in three volunteers at 1.5 T. Fixed-volume particle traces emitted from the pulmonary veins were used to visualize left atrial blood flow and to quantitatively separate the flow into two functionally distinct flow components: Direct flow = particle traces that enter and leave the atrium in one heartbeat, Retained flow = particle traces that enter the atrium and remains there for one cardiac cycle. Flow visualization based on fixed-volume traces revealed that, beginning in early ventricular systole, flow enters the atrium and engages with residual blood volume to form a vortex. In early diastole during early ventricular filling, the organized vortical flow is extinguished, followed by formation of a second transient atrial vortex. Finally, in late diastole during atrial contraction, a second acceleration of blood into the ventricle is seen. The direct and retained left atrial flow components were between 44 and 57% and 43–56% of the stroke volume, respectively. In conclusion, fixed-volume particle tracing permits separation of left atrial blood flow into different components based on the transit of blood through the atrium.

1. Introduction

Blood flow patterns have been postulated to influence the efficiency of pump function through energy preserving redirection of blood through the heart [1]. Three-dimensional cine phase-contrast MRI with three-directional velocity encoding (4D Flow MRI) permits detailed investigations of complex cardiovascular blood flow [2]. Blood flow can be visualized in a straight-forward and intuitive manner and visualized flow paths can be quantitatively analyzed to reveal information about the kinetic energy, speed, travel distance, etc., of different functional components of blood flow. One way of achieving such information for blood blow in the ventricles of the heart is to emit virtual blood particles backwards and forwards in time from a uniform volumetric grid in the LV or RV at the time of end-diastole and trace these particles to end systole [3,4]. In this "volumetric and single time-point emission" approach, each virtual blood particle represents the same amount of blood. Analysis of the resulting pathlines permits quantification of the volume and kinetic energy of distinct sub-components of ventricular blood flow with minimal user interaction [3].

The "volumetric" approach to particle emission used in the ventricles relies on the presence of a time-point during which there is no flux in or out of the ventricle (isovolumetric contraction). Unfortunately, the "volumetric" particle emission approach is insufficient in cardiovascular structures with continuous inflow, such as

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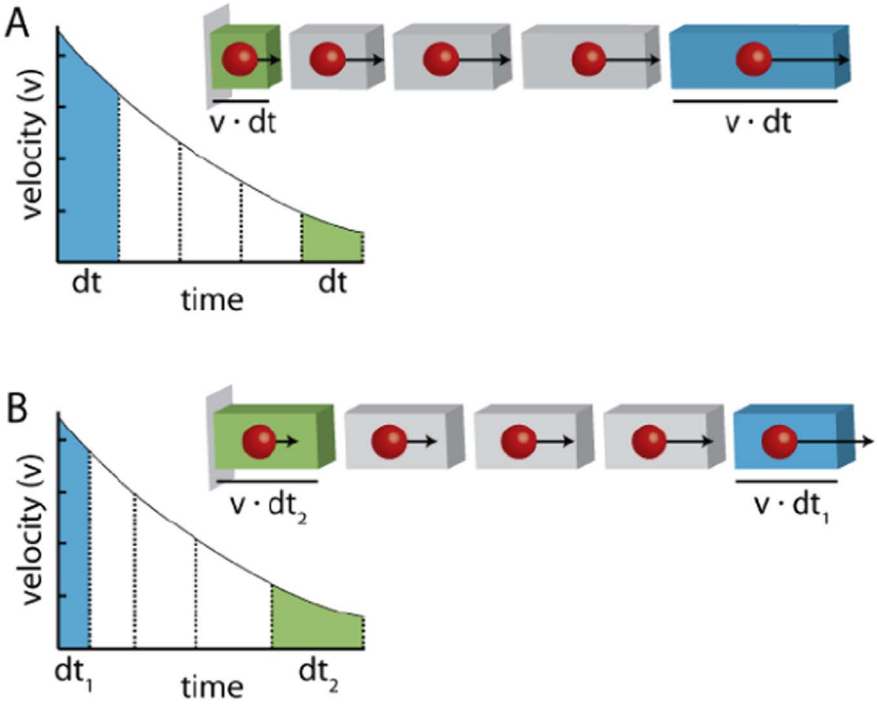

Fig. 1. Two different approached to plane-based particle emission. A: The traditional particle emission technique emits particles (red spheres) from each point on a plane at fixed time intervals (dt). By doing so, particles emitted during high speed flow (blue) will represent a larger blood volume than those emitted during low speed flow (green), leading to inaccurate depictions and measurements of actual volume flux. B: By changing the time step dynamically, with shorter time steps during high speed flow (blue) and longer time steps during low speed flow (green), the blood volume represented by each particle is normalized, improving the quantitative information of visualization and accuracy of volume estimates. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

blood vessels and atria. Blood flow in vessels and atria requires monitoring of particles emitted from planes throughout the cardiac cycle. Such a "plane-based" approach typically emits particles at fixed time-intervals [5,6]. As the volume of blood represented by each particle equals the area of the grid vertex multiplied by the product between the velocity of blood and the emission time-interval, "plane-based" emission results in particles that represent different amounts of blood (see Fig. 1A). When the volume of each trace is taken into account, plane-based pathlines permits quantitative analysis of parameters such as kinetic energy, as previously demonstrated for the left ventricle [5]. Nevertheless, variable particle volumes will lead to quantification errors when standard integration techniques are employed, as these typically integrate particle positions with the simplifying assumption of massless or uniform mass particles. This is a valid approach in the case of volumetric particle emission, but is incorrect when fixed time-step plane-based particle emission is used. Additionally, even if the variable volume of particles is accounted for in a quantitative analysis, varying particle volume makes visual interpretation of pathlines visualizations less straightforward as these visualizations are normally performed with stereotyped particle representations.

To overcome these important limitations in the current definition of plane-based particle traces, we propose variable time-step, or "flux-based", particle emission (see Fig. 1B) and will explore if this approach permits quantitative analysis of atrial blood flow. To that end, we sought to confirm the ability of a plane-based emission strategy to identify the left atrial blood volume as well as to develop an analysis method by which distinct subsets of left atrial flow can be quantified.

2. Materials and methods

2.1. MRI data

MRI data were acquired in three healthy volunteers (19, 21, 22 years old; 2 female) using a 1.5 T Philips Achieva scanner (Philips Healthcare, Best, the Netherlands). The study was approved by the regional Ethical Review Board and all subjects gave written informed consent before participation.

4D Flow MRI data were acquired during free-breathing using a navigator-gated gradient-echo sequence with the following parameters: VENC = 100 cm/s, flip angle = 8°, echo time = 3.7 ms, repetition time = 6.3 ms, parallel imaging (SENSE) speed-up factor = 2, k-space segmentation factor = 2, 6 mm navigator window size. The spatial resolution was 3 × 3 × 3 mm^3 and the field-of-view (FOV) was adjusted for each subject to cover the left heart with a double-oblique slab orientation. Scan time was about 10–15 min excluding the navigator efficiency, which was around 50%. Following the 3DcinePC-MRI acquisition, the flow data was reconstructed into 40 time frames. Corrections were made for concomitant gradient fields, phase-wraps, and background phase errors [7,8].

Morphological 2-, 3- and 4-chamber long-axis and the stack of short-axis images were acquired using cine balanced steady-state free-precession (bSSFP). The images were acquired in 30 time frames during end-expiratory breath holds. Slice thickness was 8 mm. Acquired and reconstructed pixel size for the short-axis images was 2.19 × 1.78 mm^2 and 1.37 × 1.37 mm^2, respectively.

Two-dimensional cine through-plane PC-CMR velocity data were acquired in a plane perpendicular to the ascending aorta just downstream from the aortic valve. Imaging parameters included velocity encoding range (VENC) = 200 cm/s, echo time (TE) = 3 ms, repetition time (TR) = 5 ms, flip angle = 15°, slice thickness = 7 mm, and pixel size = 1.6 × 1.6 mm^2. Three lines of k-space were acquired per heartbeat, resulting in a temporal resolution of 30 ms.

2.2. Segmentation of left atrium

Time-resolved left atrial anatomy was defined in the short-axis bSSFP images using freely available segmentation software (Segment, version 1.9). Briefly, the endocardial border of short-axis slices was identified by visual inspection and defined at each time step for all slices containing the left atrium (6–9 slices at end-systole for the patients included in this study). The border was confined to the body of the atrium, without extension into the pulmonary veins. The most apical slice (which varied throughout the cardiac cycle) was defined as the mitral annulus plane for later analysis. After segmentation, the left atrial volume was interpolated to 4 mm slices by proximal interpolation. Left atrial volume was computed at each time point.