

# Three-Dimensional Reconstruction of Blood Flow Within the Left Ventricle: Comparison of Normal, Dilated Cardiomyopathy and Reduced Ejection Fraction

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## Abstract

*We have developed a method for creating a three-dimensional reconstruction of blood flow within the left ventricular chamber from a set of two-dimensional color flow echocardiographic cine loops. The resulting reconstructions allow a physician to view blood flow in multiple dimensions permitting an immediate perception of the dynamic shape, size and direction of the flow structures and patterns in their true nature, without the need for the physician to mentally construct three-dimensional views from a limited number of two-dimensional color flow loops. In addition to their value in qualitative assessment, these three-dimensional reconstructions offer the promise of a more complete quantitative clinical assessment of blood flow based on statistical values derived from these three-dimensional models of flow—as opposed to extrapolated from two-dimensional data as is done clinically today. The ability to measure left ventricular flow rates and volume is quite important because changes in flow rates and volume may prove critical for analysis of patients with heart failure. These measurements are also keys to understanding the ventricular function. We also have defined an approach for creating a three-dimensional reconstruction of left ventricular blood flow over time—in effect, a four-dimensional model of left ventricular blood flow. We have shown that in the absence of significant velocity aliasing defects the models obtained by this technique conform to the conservation of flow. Finally, we note that this study can be used to differentiate between normal, dilated cardiomyopathy, and reduced ejection fraction, although it offers limited insight into the specific causes of these disorders.*

## 1. Introduction

Many studies have been designed to correlate mitral flow velocity patterns and measure variables with

hemodynamic findings in patients with various cardiac diseases [1]. The authors conclude that despite the complex nature of factors affecting ventricular finding, clinically useful information regarding left ventricular diastolic pressures and function is associated with distinct mitral flow velocity patterns. They hypothesized that this occurs because certain factors influencing these patterns predominate under different circumstances. The mitral flow velocity recordings appears to have clinical potential that deserves further investigation in assessing left ventricular diastolic properties in patients with heart disease. Some studies examine changes in absolute flow velocities and the distribution of flow velocities between early and late diastole seen at various location within the left ventricle[2][3]. The minor change in sample depth are associated with significant changes in recorded transmitral flow. The velocity near the mitral leaflet is higher than at the annulus plane.

The accurate assessment of left ventricular flow pattern and its volume is of great interest to the cardiologist. Many three-dimensional reconstruction techniques have been developed [4][5][6][7]. The reconstruction are intended to study ventricular flow pattern and its volume. Knowledge of left ventricular flow pattern and volume, particular at various points in the cardiac cycle, is important in assessing the performance of the disease heart.

The present study introduces a three-dimensional reconstruction of blood flow within the left ventricular chamber with comparison of normal, dilated cardiomyopathy and reduced ejection fraction. This reconstruction is based on a synchronized set of two-dimensional color flow echocardiograms. The resulting reconstruction of three-dimensional flow characteristics is amenable to analysis using techniques drawn from fluid dynamics and promises more completes qualitative and quantitative clinical assessment of left ventricular blood flow patterns.

## 2.1. Data to data

Echocardiographic images were obtained using a Hewlett-Packard Sonos 5500 ultrasound machine (Hewlett-Packard, Andover, MA) with a Omniplane transducer. Two-dimensional color flow echocardiographic cine-loops are acquired from the apical left ventricular chamber view with the examiner positioning the transducer over the cardiac apex with the central ray of the scan plane directed parallel to the long axis of the left ventricle. The transducer is automatically rotated between loops and sets of loops are made that yield a 360-degree view of left ventricular blood flow [Figure 1].

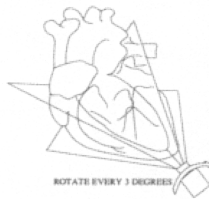


Figure 1. How to acquire the images for visualization of blood flow within the left ventricle

## 2.2. Slice construction

We begin by establishing a frame of reference along the long axis of the left ventricle. This task is performed manually by selecting points that correspond to the left ventricular apex and the center of the mitral valve annulus on a single frame in any of the cine-loops. A set of sampling lines is then automatically positioned perpendicular to the line formed by these points. The sampling lines are equally-spaced starting at a point below the left ventricular apex. The resulting reference framework is shown in Figure 2.

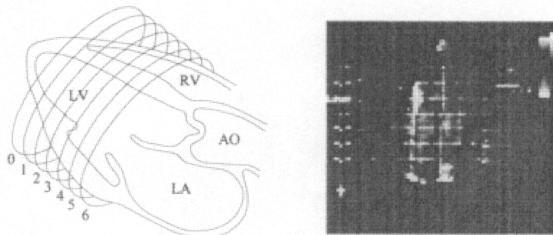


Figure 2. Showing the relationship between line Number and location in the left ventricle

This framework is then automatically mapped to every frame in all of the cine-loops. [Figure 3]

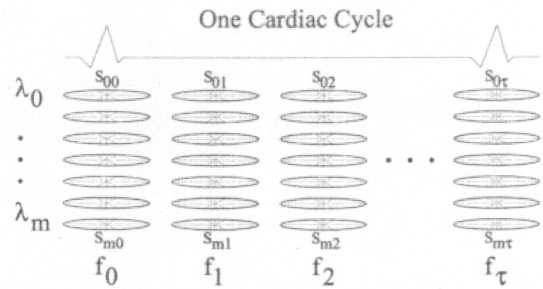


Figure 3. Putting all slices together from frame  $f_0$  to frame  $f_\tau$  in one cardiac cycle

## 3. Results

### 3.1. Qualitative results

Figure 4, 5 and 6 show slice sets produced from normal, dilated cardiomyopathy and reduced ejection fraction.

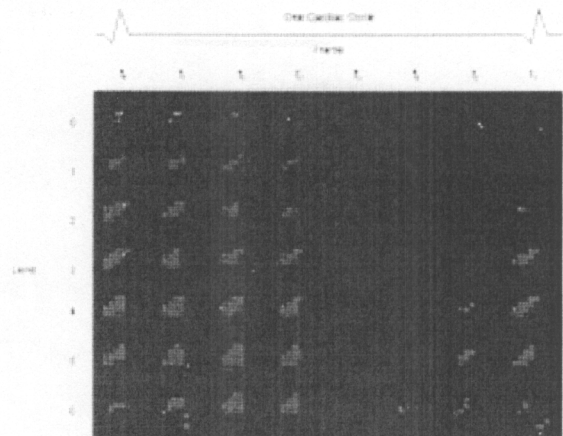


Figure 4. Normal heart transition slices

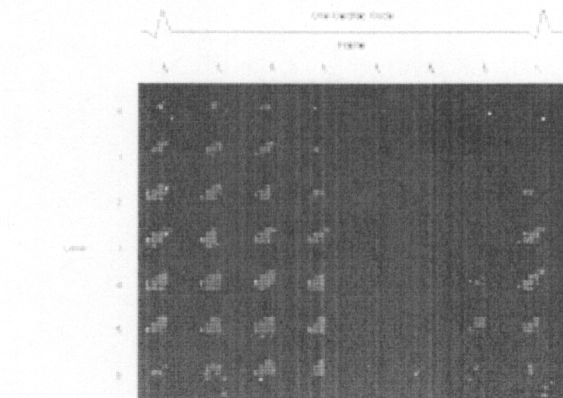


Figure 5. Dilated cardiomyopathy heart transition slices

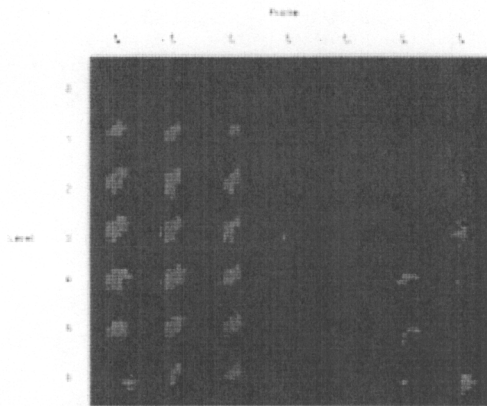


Figure 6. Reduced ejection fraction heart transition slices

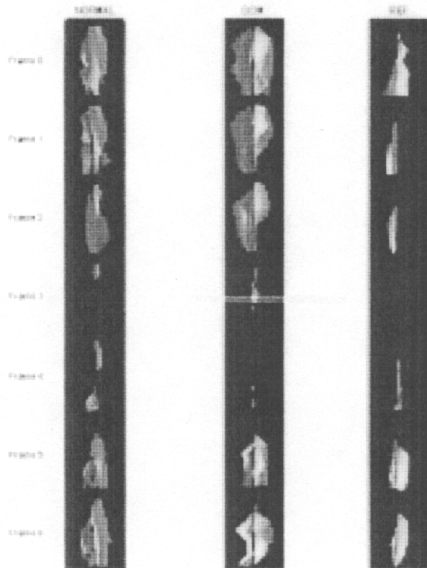


Figure 7. Three-dimensional volume visualization comparison between normal, dilated cardiomyopathy and reduced ejection fraction

In Figure 4, one can see the characteristics of normal left ventricle ejection and filling. Filling starts with frame  $f_5$  and continues through frame  $f_7$ . Ejection takes place during frames  $f_0$  through  $f_4$ . This order is the product of the fact that the data acquisition is gated to the peak of the ECG R-wave (start of ejection).

In Figure 5, The area and volume of flow in the dilated cardiomyopathy heart, by contrast, is much larger than in the normal heart—reflecting the fact that the heart itself is larger. Although the overall flow patterns are similar to the normal heart, the flow rates are more constant between levels.

In the reduced ejection fraction heart, the magnitude of flow is markedly decreased compared with the normal heart. This can be seen quite clearly in Figure 6. These patterns are even more evident in the three-dimensional volume visualizations shown in Figure 7.

## 3.2. Quantitative results

### 3.2.1 Volumetric flow rates

We investigated the accuracy of our three-dimensional reconstruction by comparing accumulative inflow volume with the accumulative outflow volume. Since the blood flowing into the left ventricle must eventually flow out of the left ventricle, these volumes should be the same. This assumes that the blood remaining in the left ventricle each cycle is the same, a reasonable assumption.

Table 1 shows the inflow and outflow volumes across patient's left ventricle by level as well as the total inflow and outflow for each patient. The resulting ratio of total inflow to total outflow range from 0.76 to 1.07 with a mean of 0.897 and a standard deviation of 0.105. This establishes that our reconstruction appears accurate with respect to gross flow volume. Note that it does not address the accuracy of the distribution of flow between levels over time.

Table 1. Flow rate calculated at various levels

Subject			Normal			DCM		REF			
	1	2	3	4	5	1	2	3	1	2	
Inflow	Level 0	106.45	8.13	31.64	61.32	5.18	34.17	36.38	31.97	60.90	6.38
	Level 1	202.71	42.46	64.96	120.58	45.66	81.60	71.29	118.73	130.34	25.25
	Level 2	270.46	89.70	104.76	170.63	146.20	113.60	103.09	205.40	169.39	65.14
	Level 3	332.82	141.82	272.94	227.47	202.44	105.45	87.96	227.31	161.97	109.20
	Level 4	417.99	225.89	384.16	305.49	342.46	101.18	78.85	222.35	141.76	128.35
	Level 5	455.24	273.92	438.10	335.73	440.93	102.07	62.47	204.43	91.75	144.78
Outflow	Level 6	395.56	189.79	362.12	299.38	322.32	107.47	43.77	225.41	68.25	163.51
	Level 0	79.89	4.33	13.63	51.48	1.45	12.99	25.90	16.08	6.96	2.43
	Level 1	172.20	42.73	44.99	133.35	48.73	48.01	48.88	102.93	27.31	17.15
	Level 2	256.16	109.76	121.44	217.76	147.85	91.66	91.43	220.70	69.47	50.26
	Level 3	366.20	201.66	265.71	329.14	258.65	92.53	102.49	284.04	181.46	114.95
	Level 4	449.25	217.12	398.53	369.23	423.14	90.11	98.94	325.47	223.69	200.71
Level 5	504.52	296.34	523.96	376.15	496.92	103.59	88.43	314.05	173.33	245.32	
Level 6	441.82	233.97	620.59	414.71	348.82	165.01	40.79	231.40	95.00	218.25	
Sum of Inflow	2172.23	971.71	1658.68	1520.61	1503.19	645.53	483.71	1235.60	624.35	642.61	
Sum of outflow	2270.04	1105.81	1987.25	1891.82	1725.66	603.90	528.86	1494.67	777.24	949.07	
Ratio	0.96	0.88	0.83	0.80	0.87	1.07	0.91	0.83	1.06	0.76	

### 3.2.2. Volume

Figure 8 shows the volume of blood flow in one heart cycle for a normal patient, a patient with dilated cardiomyopathy and a patient with reduced ejection fraction. Each graph begins at the start of systole (ejection) and ends at the end of diastole (filling).

In a normal heart, inflow decreases during systole. No new blood is coming into the left ventricle so the inflow is blood moving from the base toward the apex as part of the contraction and ejection process. Outflow increases initially and then also decreases, but at a less rapid rate than inflow. Since no blood is being pumped from the heart, the outflow is blood moving from the apex toward the aortic valve in proportion for the next ejection phase.

In the case of dilated cardiomyopathy, this same pattern is evident. However, there is a significant increase in the ratio of outflow to inflow during systole. In reduced ejection fraction, this pattern is retained but the volumes are significantly smaller.

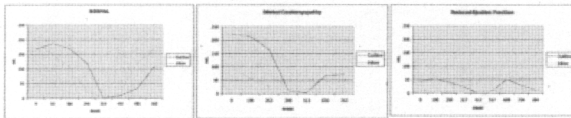


Figure 8. The volume comparison between normal, dilated cardiomyopathy and reduced ejection fraction

#### 4. Discussion

The resulting of these three-dimensional reconstructions allow a physician to view blood flow in multiple dimensions permitting an immediate perception of the dynamic shape, size and direction of the flow structures and patterns in their true nature, without the need for the physician to mentally construct three-dimensional views from a limited number of two-dimensional colorflow loops.

In addition to their value in qualitative assessment, these three-dimensional reconstructions offer the promise of a more complete quantitative clinical assessment of blood flow based on statistical values derived from these three-dimensional models of flow—as opposed to extrapolated from two-dimensional data as is done clinically today.

The ability to measure left ventricular flow rates and volume is quite important because changes in flow rates and volume may prove critical for analysis of patients with heart failure. These measurements are also keys to understanding the ventricular function.

We have defined an approach for creating a three-dimensional reconstruction of left ventricular blood flow over time—in effect, a four-dimensional model of left ventricular blood flow. We have shown that in the absence of significant velocity aliasing defects the models obtained by this technique conform to the conservation of flow. Finally, we note that this research can be used to differentiate between normal, dilated cardiomyopathy, and reduced ejection fraction, although it offers limited insight into the specific causes of these disorders.

Further work is needed to establish the accuracy of these techniques with respect to the standards of clinical practice. Future work is also needed to establish the clinical usefulness of the visualizations and statistics derived from these reconstructions. Both of these will entail conducting a larger clinical study with a wide range of patients with various disease states.

In addition to establishing the clinical utility of these techniques, future work should be directed toward expanding the range of visualizations produced by the technique and increasing the richness of the data sets derived from the resulting models. Promising areas for future research in these areas include allowing the physician to interact with the four-dimensional data set in real-time and linking this data to other data sets. Linking

volumetric analysis to pressure measurements, for example, could provide important insights into ventricular pressure-volume relations during both systole and diastole.

Finally, these techniques can be applied to other data sets. One particularly promising idea would be to create three-dimensional visualizations that include both blood flow and tissue structure (the latter being provided by the new Doppler tissue imaging techniques).

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