Partial Voxel Segmentation of the Left Ventricle: Interpolating Blood Content of Voxels

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INTRODUCTION: Current ventricular segmentation algorithms do not linearly interpolate the blood content of voxels that are composed of both blood and myocardium [1-5]. This may lead to substantial volume measurement error in cine SSFP because the voxel dimensions are large (8 mm thick), and papillary, trabeculae, and boundary endocardium are complicated structures. High accuracy measurements are crucial for diagnosing patients, especially those with low ejection fractions.

We have developed a semiautomatic segmentation algorithm that measures blood volume from cardiac cine SSFP images by estimating the partial blood content within each voxel of the left ventricle. Signal equations based on the pulse sequence and tissue characteristics are used to estimate the content of blood within voxels. Region-growing and thresholding algorithms discover the voxels that compose the left ventricle. User input consists of a single mouse click within the ventricle.

ALGORITHM: Our Partial Voxel Segmentation (PVS) algorithm runs in two steps: 1) voxels of full blood content are sampled by region-growth expanding in 2D or 3D from a user-specified point within the ventricle. The constraint for region-growth is that a voxel's neighbor must be $\geq 97\%$ of its own signal intensity. In-plane neighbors are 8 connected, and transversal neighbors are 2 connected. The sampled voxels are classified as full blood volumes, and their mean (μ) and standard deviation (σ) are calculated. Blood signal is then estimated as $S_b = (\mu - \sigma)$. Myocardium signal is estimated as $S_m = (\mu + \sigma)/(b/m)$, where (b/m) is the blood to myocardium signal ratio calculated from SSFP signal equations that are dependent on T1,T2, TR, M_0 (proton density), and α (flip angle): $M_{SS} = M_0((E_2(1-E_1)\sin\alpha)^{1/2}/(1-(E_1-E_2)\cos\alpha - E_1E_2))$ where $E_{1,2} = e^{-TR/T1,2}$ [6]. Standard deviation is used in our equations to account for 84% of variations in signal intensity, assuming variation follows a normal distribution.

2) Region-growth continues with two constraints: For each new voxel v_i having signal S_i, the condition ($S_i \geq S_m$) must be true, and the sum of neighborhood blood content must be $\geq 3\%$ of a voxel. Partial blood content (PBC_i) of v_i is linearly interpolated by fitting S_i between the previously estimated myocardial and blood intensities: $PBC_i = (S_i - S_m)/(S_b - S_m)$.

MATERIALS AND METHODS: In 11 patients scanned with short-axis 2D whole-heart cine SSFP, we performed visual inspections of the PVS algorithm segmentation and compared EF ratios and volume measurements to expert manual segmentation. We also verified the accuracy of the PVS algorithm's volume measurements by 3-dimensionally segmenting a complexly shaped plastic phantom filled to two different water volumes, then comparing the results to ground truth and expert manual segmentation.

RESULTS: Results from patient studies are summarized in Table 1. PVS systolic and diastolic volume measurements were consistently smaller than manual (25.6% and 23.2% on average, respectively). EF ratio did not vary significantly (3.3% on average). Phantom experiments of 1000mL and 800mL are summarized in Table 2. Algorithm measurements were consistently minimal underestimates (99% and 98.25% average accuracy). Manual measurements were consistently significant overestimates (90% and 73% average accuracy).

DISCUSSION: The PVS algorithm is highly accurate in phantom testing and robust in vivo for segmenting ventricles. Errors observed in manual segmentation of the phantom are a result of overestimating partial voxels as full voxels at the top and bottom slices, as well as the complex compartment. The difference between the PVS algorithm and manual segmentation in vivo is significant, in terms of volume measurement; however, EF ratio did not vary significantly. One possible explanation is that manual segmentation consistently overestimates proportionately to the volume. We cannot conclude from this study which of the methods is more accurate since true volume is unknown. Possible sources of volume measurement error in 2D cine SSFP include slice misregistration, slice gaps, and partial voxel effects. While the PVS algorithm tends to deal well with partial voxel effects in the phantom experiments, slice misregistration and slice gaps do not occur in phantom data. In order for proper validation of segmentation, high-resolution 3D data acquisition is required.

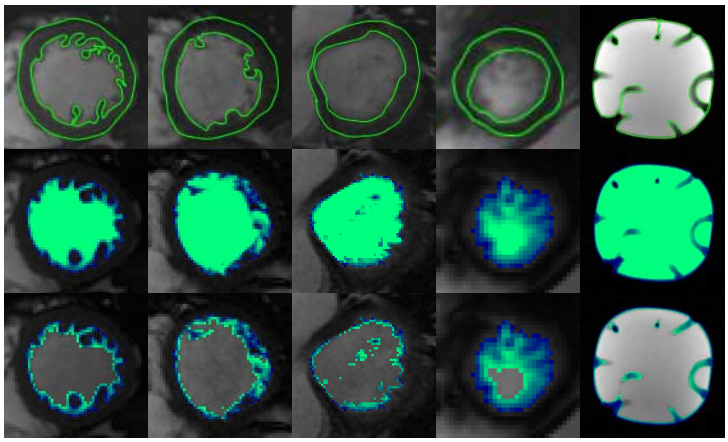

Figure 1: Rows *from top to bottom:* Manual segmentation, Partial Voxel Segmentation, PVS detected partial voxels. Blue to green denotes blood/water contents from least to most. *Columns 1-3:* PVS is able to recognize high levels of ventricle detail. In *Column 3,* thin cords connecting papillary muscles below the slice to valves above the slice are readily detected by PVS (shown as dots of partial voxels inside ventricle cavity). *Column 4:* Partial voxel effects in apical slices are abundant. *Column 5:* A single slice from the segmentation phantom.

	SV	DV	EF
PVS	55 ± 47	120 ± 53	59 ± 14
Manual	72 ± 53	153 ± 56	57 ± 14
p	.000205	.00001	0.15
Diff. %	25.6 ± 3.3	23.2 ± 2.9	3.3 ± 1.7

Table 1: Statistical results from 11 patients. Last row shows average and standard deviation relative differences, in terms of % manual.

Water Level	Manual Accuracy	PVS Accuracy	# of PV	Avg. PV Content
1000mL	90%	99%	31%	51%
800mL	73%	98%	34%	29%

Table 2: Phantom study summary: water level, manual accuracy, PVS accuracy, number of partial voxels (% of total voxels), and average water content per partial voxel. Smaller average PV content caused greater manual overestimations.

References: [1] Mühlenbruch et al. ER (2006) 16:1117-1123 [2] Schlosser et al. AJR (2005) 184:765-773 [3] van der Geest et al. JCMR (2004) 6:609-617 [4] Kaus et al. MIA (2004) 8:245-254 [5] Lynch et al. CBM (2006) 36:389-407 [6] Scheffler, Lehnhardt. Eur Radiol (2003) 13:2409-2418