Visualizing and Quantifying Myocardial Oxygenation Changes with Statistically Optimal Colormaps

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Introduction: Blood-oxygen-level dependent (BOLD) MRI may be used for detecting myocardial oxygenation (MO) changes secondary to coronary artery stenosis. Under pharmacological stress, areas of the myocardium supplied by a stenotic coronary artery are hypointense relative to healthy regions. Visualizing these changes requires manual windowing. In this paper a method for automatic visualization and quantification of myocardial signal changes reflecting the regional variations in oxygenation is presented, using images obtained from a canine study under controlled conditions. The objective of this study is to overcome the rather subjective step of windowing by establishing an optimal colormap that permits visualization of statistical changes in signal intensities between healthy and pathological cases. In addition, graph theory is used to derive a quantitative metric indicative of changes in myocardial oxygenation. The purpose of this effort is to facilitate the evaluation of myocardial BOLD images by automating the detection of regional abnormalities in MO under pharmacological stress in the presence of coronary artery stenosis.

Methods: Data Acquisition: Breath-held and ECG-gated short-axis cardiac phase-resolved 2D SSFP-based myocardial BOLD images were acquired in two dogs under pharmacological stress with and without left-circumflex coronary artery stenosis in a Siemens 1.5T scanner. Scan parameters: voxel size=1.2x1.2x6mm^3; flip angle=90^o; TR/TE=5.7/2.9ms; 20 cardiac phases. Image Processing Algorithms: To have the greatest myocardial surface available for analysis, only the end systolic images of the two image series (adenosine without stenosis (AD) and adenosine with severe stenosis (SS)) were identified. An ROI was chosen around the heart and a segmentation algorithm (1) was utilized to isolate and segment the myocardium. The myocardial AD intensities were collected and a location-scaled Student's t-distribution was fitted by maximum likelihood estimation (MLE) of its parameters (mean (μ), variance (σ), and degrees-of-freedom). The t-distribution exhibits robustness against outliers, which may result from inaccurate myocardial segmentation. An optimal pixel colormap was created by assigning red hues to signal values below the threshold $\rho = \mu - \sigma$ and yellow hues to larger values. The color-coded myocardial segments for both images were laid over the grayscale original images. We defined the continuity metric Q_M as the area of the largest 4-neighborhood connected component (2) of pixels below ρ (ie., the largest number of continuous red colored pixels) divided by the total number of pixels in the myocardium. The relative ratio of hypointense contiguous pixels between AD and SS, Q_M (AD) / Q_M (SS), is also calculated. All operations were performed in MATLAB.

Results: End-systolic AD and SS images from the two dog studies are shown in Fig. 1 with, and without, windowing. The empirical distributions for (AD and SS) of the myocardial signal intensities and the fitted t-distributions are shown in Fig. 2. The color overlays and the optimized color colormars are shown in Fig. 3. The ratio Q_M (AD) / Q_M (SS) for each study is: 0.19/0.07~2.53 and 0.16/0.03~5.

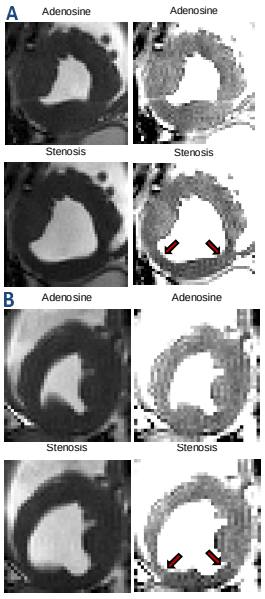

Fig. 1 End-systolic adenosine images without (AD) and with LCX stenosis (SS) from the two controlled canine studies are shown in panels (**A**) and (**B**), respectively. The top row shows the AD and SS images without any windowing. The bottom row shows the same images but windowed the same to increase the regional myocardial contrast corresponding to oxygenation changes. Red arrows on the windowed SS images illustrate the limits of the affected myocardial segments corresponding to the LCX artery.

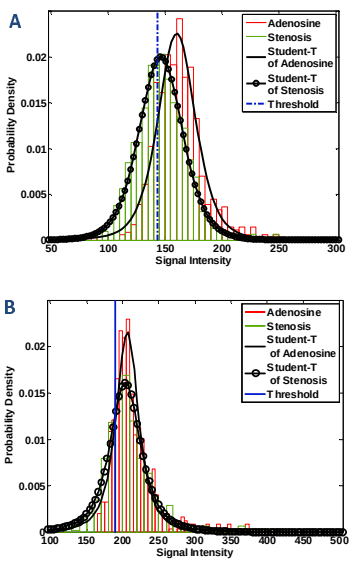

Fig. 2 Probability density plots for the two canine studies (A) and (B) are shown. For each case, the empirical densities of the myocardial signals under AD and SS, are plotted in red, and green bars, respectively. Overlaid are the Student's t- densities for each signal. Finally, the threshold ρ is shown in blue at 143.3 for study A, 189.7 for study B, respectively.

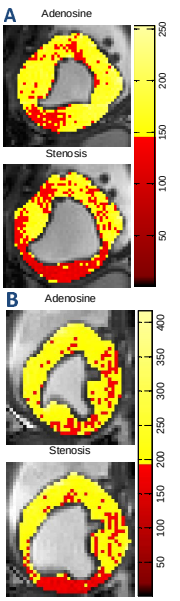

Fig. 3 Color coded end-systolic adenosine images without (AD) and with LCX stenosis (SS) from the two controlled canine studies are shown in panels (A) and (B), respectively. Only the myocardium was color coded. The corresponding optimized colormaps are also shown. The yellow hues are for pixel values larger than ρ, shown in blue in Fig. 2. This method allows the observer to rapidly assess the presence of disease, as well as, potentially identify the section of the coronary tree that is stenotic on the basis of BOLD MRI.

Discussion and Conclusion: As Fig. 1 demonstrates, without proper windowing the appreciation of MO differences is cumbersome. It takes several minutes for a reader to window the images. Moreover, windowing is subjective and has large intra- and inter-observer variability. Fig. 2 illustrates that Student's t-distribution closely approximates the intensity distribution of the myocardium. The motivation for choosing ρ as the midpoint for the colormap is to highlight intensities below this value, which are expected to have low probability of occurrence in a healthy case. It is expected that regions supplied by stenotic arteries will be hypointense, and will thus shift the intensity distribution towards the left. Hence, in cases where stenosis is present, the occurrences of intensities lower than ρ are greater, and therefore the amount of red-colored pixels are greater. Note that the contiguous red-colored region corresponds to the left-circumflex territory (Fig. 3). In fact, we have found a substantial elevation in the Q_M of SS relative to the Q_M of AD for both cases. There are also mild signal changes in the AD images as well, that may be due to imaging artifacts, normal physiology changes, and/or presence of an inadvertent stenosis. Nevertheless, the presented method allows the observer to rapidly assess the presence of disease, as well as, potentially identify the section of the coronary tree that is stenotic on the basis of BOLD MRI. Although more studies are needed, this method is an initial step in the development of improved visualization and characterization based on quantitative methods for cardiac BOLD MRI.

References: (1) Tsaftaris, et al. *ICIP* (2008); (2) Haralick & Shapiro *Computer and Robot Vision* (1992)