Cardiac BOLD Imaging with Cine 2D-Balanced SSFP

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Introduction Detecting changes in oxygen content in tissues can aid in understanding pathological processes. In the MR environment, changes in blood oxygen saturation are accompanied by local magnetic field variations sampled by the spins, allowing for acquisition of oxygen-weighted images [1-2]. This observation has been exploited in identifying myocardial oxygen deficits that originate from coronary occlusions [3]. However, long scan times, poor oxygen sensitivity, and/or poor image quality have been the obstacles for clinical implementation of the techniques for cardiac imaging [3-5]. More recent developments in new MRI methods, particularly steady-state acquisition strategies, provide opportunities for obtaining temporally resolved high quality images [6]. Recently, there have also been reports that 2D balanced steady-state free precession (SSFP) imaging is capable of detecting microcirculatory blood-oxygen-level dependent (BOLD) signal changes [7]. In this work, we investigate (1) the potential for balanced 2D SSFP imaging to detect myocardial oxygen deficits originating from coronary stenosis in an animal model and (2) whether such BOLD contrast may be obtained within the framework of cine imaging.

Methods Four, 15-25kg, mongrel dogs underwent left thoracotomies at the eighth intercostal space. Aortic, right and left atrial catheters were inserted, secured, and routed for intravenous and intra-arterial injections, respectively. In all animals, a portion of the proximal left circumflex (LCX) coronary artery was isolated, and an occluder was secured around the LCX. A 3-4 mm Doppler flow probe was secured distal to the occluder to estimate blood flow velocities within the LCX. Prior to imaging, animals were sedated, intubated, and placed on a ventilator. Following manual tuning and shimming over the whole heart, short axis baseline SSFP cine BOLD images, clearly delineating anterior and posterior papillary muscles, were obtained within one breath hold (19 - 25 s). Following this, pre-occlusion BOLD images were obtained in the presence of constant adenosine infusion (0.14 mg/min) into the right atrial catheter. Following this, two additional scans were acquired at different LCX stenosis levels (mild occlusion = 46 % +/- 4.2 and severe occlusion = 88% +/- 4.0) in the presence of constant adenosine infusion. Occlusion levels were assessed based on Doppler flow velocities. A total of 7 MR studies were performed in 4 dogs with at least 48 hours of rest between studies. Heart rate remained approximately constant in all adenosine studies. All studies were performed on a Siemens Sonata 1.5T scanner (Erlangen, Germany). The scan parameters were: field of view = 130 mm x 260 mm, segments per cardiac phase = 5 – 7, 10-12 phases/heart beat, imaging matrix = 144 x 192, slice thickness = 6 mm, T_E/T_R = 3.1/6.3 ms, flip angle = 90°, readout bandwidth = 241 Hz/pixel, RF pulses were phase cycled, number of averages = 3. Note that consistent with previous findings (7), a longer T_R than what is typically used in conventional cine SSFP imaging (3 - 4 ms) in order to detect BOLD contrast and the same cardiac slice was continuously excited to maintain steady state. Each study was terminated with a first-pass perfusion exam at the severe stenosis state. From the signals measured at the anterior and posterior papillary muscles (PM) at the cardiac phase with the greatest systolic thickening, BOLD contrast was computed as:

$$\text{SSFP BOLD Contrast} = 100\% \times (S_{adeno} - S_{var}) / S_{adeno}, \quad \text{(Eq. 1)},$$

where S_{adeno} and S_{var} are myocardial signal magnitudes at pre-occlusion condition with adenosine and at other experimental conditions (pre-adenosine, mild and severe occlusions), respectively.

Results Fig. 1 shows the typical short-axis MR images obtained at the baseline (A), pre-occlusion with adenosine (B), severe stenosis (C), and first-pass perfusion at severe stenosis. Fig. 1 shows evidence of regional oxygen-sensitive contrast with change in occlusion. There is also good qualitative agreement between the flow-deficit region identified by the first-pass perfusion method (Fig. 1D) and the 2D SSFP BOLD image (Fig. 1C). Fig. 2 shows the average contrast values calculated according to Eq. 1. A paired t-test shows that there is a statistically significant increase in BOLD contrast with increasing severity of LCX occlusion ($p<0.005$). Based on Fig. 2, it is also evident that the LCX occlusion only affects the local region surrounding the LCX since no statistically significant contrast changes can be seen with regions supplied by left anterior descending artery. BOLD contrast was also absent in other regions not supplied by the LCX. The cine 2D-balanced SSFP images also showed the presence of BOLD contrast in other cardiac phases and wall motion abnormalities within a single scan when the LCX occlusion was severe.

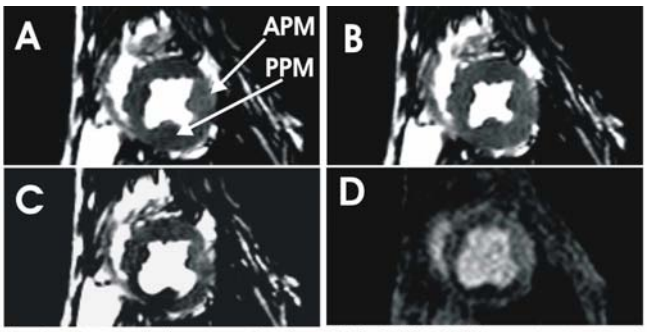

Fig. 1 Short axis images showing 2D-b-SSFP BOLD contrast at pre-adenosine baseline (A), pre-occlusion with adenosine (B), and severe stenosis (C). Image D represents the associated first pass perfusion image obtained at severe stenosis state at the same image position as images A - C. Note the discriminating signal loss in the posterior papillary muscle (PPM) region (supplied by the LCX) during stenosis. Also note that the signal in the anterior papillary muscle (APM) region (supplied by the LAD) remains unaffected at the severe stenosis state.

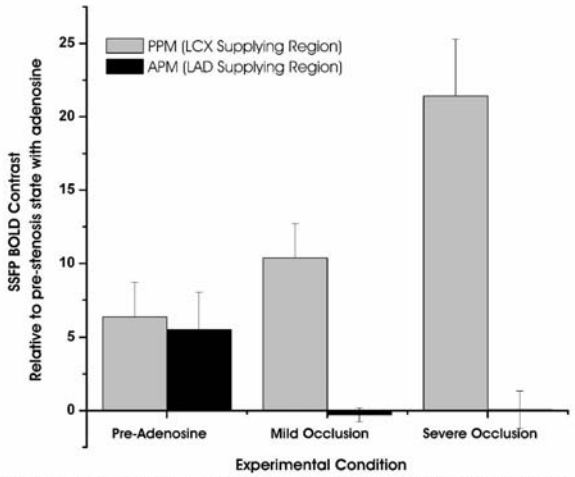

Fig. 2 2D-b-SSFP Cardiac BOLD Contrast relative to adenosine baseline at pre-adenosine, mild and severe occlusion expermental states. Contrast values were computed at anterior (LAD supplying region) and posterior papillary muscles (LCX supplying region) of the canine myocardium. Note that there is statistically significant BOLD contrast increases with increasing occlusion level in the PPM, while no such differences are obsered at the APM (paired t-Test with $p < 0.005$).

Discussion & Conclusion In this work we have demonstrated that high quality, temporally resolved, cine 2D-balanced SSFP imaging has the potential to detect myocardial oxygen deficits due to acute coronary stenosis. Since 2D balanced-SSFP imaging combines the capabilities of volumetric measurements and detection of wall motion abnormalities of cine MRI with BOLD MRI, it is anticipated that this technique may be useful in the diagnosis of ischemic heart disease.

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