TECHNICAL UNIVERSITY OF LODZ
FACULTY OF ELECTRICAL, ELECTRONIC, COMPUTER
AND CONTROL ENGINEERING
INSTITUTE OF ELECTRONICS

MSc. eng. Artur Wujcicki

Abstract of Ph.D. Thesis

Ventilation-perfusion lung imaging by filtering MR image sequence

Supervisor
Prof. D.Sc. eng. Andrzej Materka

Lodz, 2015

Lungs can be imaged using several tomographic techniques. One of them is magnetic resonance imaging (MR imaging, MRI), a technique that does not use ionizing radiation. In case of the lungs, obtaining good quality MRI is not an easy task. Lungs contain a lot of air, which makes them nearly invisible in MR image – they look like “black holes”, with visible brighter veins (but it depends on used MR sequence). Those images visualize anatomical structure of the lungs. MR images can also visualize organ functions or their biological activity. Such imaging is called fMRI – functional MRI. Lung fMRI covers perfusion imaging (flow of blood at capillary level), ventilation imaging (aeration of the lungs), and sometimes imaging of diaphragm, mediastinum or lesions movement [1].

Perfusion and ventilation lung imaging is important, as this is useful in diagnosis of lung diseases and can help precisely locate lesions inside the lungs. Using MRI, functional images can be obtained with contrast-enhanced or non-contrast-enhanced imaging methods. Contrast-enhanced methods use contrast agents that modify magnetic properties of tissues, enabling differentiation of them in the image. In case of perfusion images, contrast agent is injected intravenously [2]. Contrast-enhanced ventilation images are created during inhalation of previously prepared gas that fills the lungs. Unfortunately, intravenous injection of contrast agent may cause acute allergic reaction, which is a limitation of this method. Gases used for ventilation imaging, like ^{129}Xe or ^{3}He isotopes, are specially prepared with process called 'hyperpolarization' that strengthens the MR signal [3]. Preparing hyperpolarized tracers needs special equipment which causes that non-contrast-enhanced ventilation imaging is available in limited number of research centers. If equipment for preparing the gas is not available, it has to be delivered from the outside which increases the costs [4].

All above limitations increase role of non-contrast-enhanced functional lung imaging. In case of lung perfusion, there are available few imaging methods. The most known are TOF (Time of Flight) and ASL (Arterial Spin Labeling) [5, 6]. They use blood flow to modify MR signal which enables visualization of blood in the MR image. Unfortunately, TOF method is time-consuming [7], and ASL of the lungs produces low spatial resolution perfusion images, which are limitations [8]. For ventilation imaging, there are a few methods of non-contrast-enhanced imaging. All of them use the same physical properties of the lungs (it will be presented in more details in the next section).

Recently, a novel functional lung imaging method has been presented – FD MRI (Fourier Decomposition MRI) [9]. It computes both perfusion and ventilation images from MR image sequence. Respiration increases and decreases lung volume, which changes its proton density. Lung proton density fluctuations directly affect MR signal from the lungs according to the

respiratory rate. Those signal changes are separated using discrete filters defined in frequency domain. Energy of MR signal changes centered around respiratory frequency is visualized as a ventilation map. In FD MRI, perfusion-related MR signal is created by rapid blood flow in veins, and fluctuates according to the heart rate. Similarly to the ventilation map, perfusion map visualizes energy of blood flow-related signal changes centered around heart rate frequency. Model of perfusion signal consists of two harmonics. Relatively big heart rate frequency (typical value for healthy subjects is 60-100 heart beats/min) implies usage of fast b-SSFP (*balanced Steady-State Free Precession*) MR sequence to perform fast images acquisition. However, due to technical reasons, MR images are acquired with frequency of 3,33 Hz. This means that aliasing of second cardiac harmonic of perfusion MR signal is possible, and may create artifacts in the ventilation map.

FD MRI method is able to separate ventilation and perfusion components related to only one respiratory and heart rate frequency, respectively. This limitation was resolved in WA MRI method (*Wavelet Analysis MRI*) [10], which is extension of FD MRI. WA MRI uses wavelet transform to decompose MR signal on cardiac and respiratory components. However, due to lowpass character of ventilation filter, WA MRI does not reduce impact of cardiac components on ventilation map.

FD MRI was compared with other methods that are used for ventilation/perfusion imaging – SPECT/CT lung ventilation (it uses hybrid Single Photon Emission Computed Tomography/Computed Tomography) [11], and DCE for perfusion imaging (Dynamic Contrast Enhanced – method that uses intravenous contrast agent injection for veins visualization) [12]. FD MRI has still lower quality of perfusion images than those obtained with DCE. For FD MRI, 10% of perfusion images and 30% of ventilation images have non-diagnostic quality. The root cause of artifacts in FD MRI method is non-stationarity of respiratory and cardiac cycles, because FD MRI cannot handle multiple frequencies of those cycles in functional map creation process [13].

The goal of PhD dissertation is to create perfusion and ventilation images by filtering MR image sequence, and the thesis is as follows:

It is possible to reduce perfusion information in ventilation map using discrete ventilation filter that attenuates cardiac components moved into ventilation passband due to aliasing.

To achieve the scientific goal, and to prove the thesis, author proposed and implemented subject-adaptive algorithm for computing transmittance of ventilation and perfusion filters.

Moreover, a measure to assess separation of cardiac and ventilation components in functional maps was proposed.

Proposed method of computing lung functional images is modification of the FD MRI method in terms of ventilation and perfusion filters, and computing pixel values of functional images [14]. Filters pass only spectra components related to perfusion/ventilation, most commonly occurring in "lung signals" formed pixelwise in a timeline from brightness of MR images from the sequence, for given location. To form lung signals correctly, MR images from sequences were registered to compensate lungs motion. Fluctuations of respiratory and cardiac cycles are handled using short-time Fourier transform (STFT). Computed with STFT spectra of lung signal fragments are checked for similarity to theoretical perfusion and ventilation components, respectively. Similarity check is based on comparison of signal harmonics amplitude ratio to the ratio computed for theoretical lung signal components. Outliers (spectra of lung signal fragments that are neither similar to cardiac component nor ventilation component) are neglected from processing. They are found by thresholding amplitude of first harmonic of lung signal components – signal fragments whose perfusion/ventilation components have too low amplitude are neglected. Rest of them form a histogram of frequency value of first cardiac and respiratory harmonic, respectively. Most commonly occurring frequencies in the histogram create a passband of the ventilation/perfusion filter. In the dissertation, filter that passband is formed from 90% of most commonly occurring ventilation/perfusion discrete frequencies was called a basic ventilation/perfusion filter. Similarly, functional images created with basic filters were called basic ventilation/perfusion images.

To assess how well the cardiac and ventilation components are separated, a mutual information computed between functional maps was proposed as a measure of that separation. A measure to assess separation of lung signal components has not been published so far. In author's opinion such measure is important, especially for FD MRI-like methods where aliasing of cardiac components into ventilation map is possible. It was computed that mutual information between perfusion and ventilation maps is lower when ventilation maps contain less amount of cardiac components. Results are in accordance with presented in the dissertation properties of the proposed measure.

Ventilation maps for all subjects were created with basic ventilation filters, lowpass filters (simulation of WA MRI method to show that ventilation maps created with this method may contain cardiac component due to aliasing), and with filters that pass two and one most commonly occurring ventilation components. Perfusion maps were created only with basic

perfusion filters. It was showed that narrowing the ventilation filter passband reduces cardiac information visible in ventilation maps (for subjects with observed cardiac components in ventilation maps). Passband of basic filters consists of a few (4 – 5) discrete frequencies for subjects whose respiratory and heart cycles change, and only one discrete frequency for subjects with stationary respiratory and heart cycles.

To sum up, in the dissertation a method for computing perfusion and ventilation map was presented. The intrinsic fluctuations of respiratory and cardiac cycles are handled with STFT, which is visible in filters transmittance. It was showed, that lowpass ventilation filter (like in WA MRI method) passes to many spectra components, and thus cannot efficiently reduce cardiac information from ventilation maps. Using presented algorithm for computing filters transmittance, author created subject-adapted filters that allowed to reduce cardiac components from ventilation maps. Quantitative assessment of cardiac/respiratory components separation allows to select those filters, for which cardiac components in ventilation maps are most attenuated. Taking it into account, the scientific goal of PhD thesis was achieved, and the thesis was proved.

Proposed method was verified on data obtained from five healthy subjects. It is expected that for subjects with diseased lungs the method will give proper results. This assumption, important from medical point of view requires additional research.

References

[1] Biederer J, Heussel CP, Puderbach M, Wielpuetz MO. *Functional Magnetic Resonance Imaging of the Lung*, Seminars in Respiratory and Critical Care Medicine, vol. 35, 2014, s. 74–82.

[2] Meaney J, Boyle G, O'Keeffe S. *Contrast-enhanced magnetic resonance angiography: Current status, theoretical limitations and future potential*, Radiography, vol. 13, 2007, s. 31–44.

[3] Mills GH, Wild JM, Eberle B, Van Beek EJR, *Functional magnetic resonance imaging of the lung*, British Journal of Anaesthesia, vol. 91, 2003, s. 16–30.

[4] Bauman G, Eichinger M. *Ventilation and perfusion magnetic resonance imaging of the lung*, Polish Journal of Radiology, vol. 77, 2012, s. 37–46.

[5] JC Carr, TJ Carroll. *Magnetic Resonance Angiography: Principles and Applications*, Springer, 2012.

[6] Borogovac A, Asllani I. *Arterial Spin Labeling (ASL) fMRI: Advantages, Theoretical Constrains and Experimental Challenges in Neurosciences*, International Journal of Biomedical Imaging, vol. 2012, 2012, s. 1–13.

[7] Daftary A. *Structural and functional pulmonary magnetic resonance imaging*, Supplement to Applied Radiology, 2005, s. 57–67.

[8] Ley S, Ley-Zaporozhan J. *Pulmonary perfusion imaging using MRI: clinical application*, Insights Imaging, vol. 3, 2012, s. 61–71.

[9] Bauman G, Puderbach M, Deimling M, Jellus V, Chefd'hotel C, Dinkel J, et al. *Non-contrast-enhanced perfusion and ventilation assessment of the human lung by means of Fourier decomposition in proton MRI*, Magnetic Resonance in Medicine, vol. 62, 2009, s. 656–664.

[10] Bauman G, Dinkel J, Puderbach M, Schad LR. *Time-resolved lung perfusion- and ventilation-weighted MRI by Wavelet Analysis*, Proc. Intl. Soc. Mag. Reson. Med., vol. 18, 2010, s. 2507.

[11] Bauman G, Lützen U, Ullrich M, Gaass T, Dinkel J, Elke G, et al. *Pulmonary Functional Imaging: Qualitative Comparison of Fourier Decomposition MR Imaging with SPECT/CT in Porcine Lung*, Radiology, vol. 260, 2011, s. 551–559.

[12] Bauman G, Puderbach M, Heimann T, Kopp-Schneider A, Fritzsching E, Mall MA, et al. *Validation of Fourier decomposition MRI with dynamic contrast-enhanced MRI using visual and automated scoring of pulmonary perfusion in young cystic fibrosis patients*, European Journal of Radiology, vol. 82, 2013, s. 2371–2377.

[13] Sommer M, Bauman G, Koenigkam-Santos M, Draenkow C, Heussel CP, Kauczor HU, et al. *Non-contrast-enhanced preoperative assessment of lung perfusion in patients with non-small-cell lung cancer using Fourier decomposition magnetic resonance imaging*, European Journal of Radiology, vol. 82, 2013, s. 879–887.

[14] Wujcicki A, Corteville D, Materka A, Schad LR. *Perfusion and ventilation filters for Fourier-decomposition MR lung imaging*, Zeitschrift für Medizinische Physik, vol. 25, 2015, s. 66–76.