PhD title : Simulation and processing of multi-energy data for spectral X-ray computed tomography : application to cardiac imaging

Scientific context :

Heart disease remains one of the most serious health problems in the world. According to the World Health Organization (WHO) estimates in 2011, 17.3 million people around the globe died from this disease in 2008; this represents about 1/3 of all deaths globally. According again to the WHO, the number of fatalities caused by cardiac diseases is projected to increase to over 20 million per year by 2020 and to over 24 million per year by 2030 [Nichols *et al.*, 2012]. Because of their proliferation and high mortality rate, heart diseases become the most costly group of pathologies: they accounted for 16% of total health expenditures in 2008 [Roger, 2011]. Therefore, from both health care and economic perspectives, it is very important to develop techniques that allow better understanding of cardiac structures and functions prior to heart failure.

Despite decades of intensive cardiovascular researches in basic and clinical sciences, two most fundamental aspects underlying the function of the human heart are still unknown: a) three-dimensional (3D) fiber architecture of cardiac muscle (or myocardium), and b) 3D spatial distribution of ions (or ion concentration) throughout the myocardium. The myocardial function is fundamentally related to its specific fiber architecture. For instance, the propagation of electrical activity is faster along the direction of the fibers and slower across the sheet plane [Jouk, 2007], and at the cellular level, the contraction occurs along the long axis direction of the myocytes bundles and leads to transmural thickening and apex-base shortening after rearrangements through interactions with the collagen extracellular matrix. Moreover, fibers throughout the ventricles could be a substrate for arrhythmias, including ventricular tachycardia and fibrillation, and sudden cardiac death [Collin *et al.*, 2006]. The myocardial function is also fundamentally related to the presence of ions in the myocardium since they ensure the communication of physiological signals with and between myocytes. For example, the heartbeat and cardiac force are directly regulated by the cardiac action potential, which depends on the coordinated actions of ion exchanges. Also, the activation of the heart is critically mediated by ion channels that connect adjacent myocytes [Langer 1997]. Nowadays, no relationships have been established between the ion distribution and the fiber architecture. With the recently appeared diffusion tensor imaging (DTI), we begin to get some insights into 3D fiber architecture properties of the myocardium. However, the 3D distribution in space of ions in the myocardium is totally unknown until now. The only reason for this situation is that there is currently no means to access such information.

Objective of the PhD study :

The PhD thesis aims to investigate a novel imaging modality, spectral X-ray Computed Tomography (CT) combined with the use of specific contrast agents in order to find new approaches to the diagnosis, monitoring and treatment of heart diseases.

Spectral X-ray computed tomography (CT) [Schlomka et al. 2008], simply called spectral CT in what follows, appears as a new and promising technique for accessing the 3D spatial distribution of ions vital for heart function. Compared to conventional CT systems which are not able to provide valuable information about the chemical composition of tissues because their scintillator detectors integrate energy information over the whole spectrum, spectral CT presents the particularity of acquiring a huge quantity of projection data during one single CT scan through using photon-counting energy-resolving detectors, from which material-dependent attenuation can be exploited using appropriate data processing algorithms and many (instead of one single as in the conventional CT case) possible images or volumes can be reconstructed using reconstruction algorithms. More importantly, combined with the use of contrast agents such as iodine and gadolinium, spectral CT opens up a lot of new possibilities for a wide range of (medical or industrial) applications.

However, the development of spectral CT raises new problems and issues. When using N energy

bins in spectral CT instead of one single energy in conventional CT, the number of photons captured by detector will be divided by N, which leads to a decrease of signal-to-noise ratio (SNR) by a factor of $\sqrt{N}$. This constitutes a real bottleneck for reconstructing good quality CT images. Meanwhile, the N datasets corresponding to N energy bins pose the problem of how to process and exploit them for ion identification and separation.
The proposed approach for this PhD study consists of :

- designing new spectral CT acquisition strategy through simulating and quantifying the influence of noise and sparse information on image quality,
- developing appropriate processing algorithms for multi-energy data including denoising, chemical element decomposition, and data combination or fusion,
- evaluating the proposed approaches via experiments on phantoms and animals,
- quantifying 3D spatial ion distribution.

By this approach, we expect to achieve the first attempt in the world to obtain the 3D spatial distribution of ions in the myocardium.

Scientific programme :

1) Appropriate acquisition strategies through simulation of spectral CT imaging
To achieve appropriate multi-energy acquisitions useful for ion identification and separation, we will use simulation. Realistic simulation of conventional CT imaging is always a persistent problem. This is even truer for the simulation of spectral CT imaging. To address this problem, different physical situations will be simulated including the influence of noise, in order to evaluate the detectability of different chemical elements in combination with contrast agents such as gadolinium, and optimize the whole CT chain (energy threshold position, spectral response function model, X-ray tube spectrum, photon flux and counting, etc.). The work will be based on a simulation tool ("Virtual X-ray Imaging"[Duvauchelle2000]) developed at the LVA laboratory.

2) Suitable processing of multi-energy data
With the use of photon counting detectors, high energy resolution (about 1 keV) and high spatial resolution (about 0.2 mm), both raw projection data and reconstructed CT images are highly noisy. To avoid paying the penalty of increased image noise or increased patient dose, we will investigate denoising techniques which make use of not only data in the same energy bin but also in other energy bins.

3) Experiments
Experiments will be performed first on an experimental bench developed by the INSA-LVA laboratory where a spectral CT scan can be acquired voxel by voxel. On another hand, a unique experimental spectral CT scanner (the first machine of this type in the world) will be installed at INSA-Lyon by Philips in the frame of the France Life Imaging platform. That will allow for, in particular, appropriate energy scale calibration of the imaging system and its response function characterization.

4) Quantification of different ions simultaneously present in a single voxel and their 3D spatial distribution in the myocardium.
This topic has not yet been addressed in the literature, but it is strongly related to the new issue of “multi-energy data” and the use of specific contrast agents (extension of K-edge imaging to several spectral bands [Roessl 2007]). We intend to tackle it by studying the strategies of processing, combining and reconstructing multi-energy projection data and reconstructed CT images, including chemical element (e.g. ions vital for the myocardium) decomposition methods. No work or knowledge is today available about 3D spatial distribution of ions in the myocardium. As it is a novel type of data, there is no gold-standard we can use to assess the

reconstruction or combination of multi-energy CT images, the pre-processing and/or combination of multi-energy projection data, and the post-processing and/or combination of the reconstructed multi-energy images. To get rid of these difficulties, we will intensively use the results from simulation, experiments on physical phantoms, and medical expertise of clinical doctors involved in the project.

Supervision :
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Collaboration
Cardio Hospital of Lyon (Pr Philippe Douek, CREATIS and Loïc Boussel)

Candidate profile and competences developed during the PhD
General knowledge in applied physics, applied mathematics and computing competences are required. During the PhD, the candidate will be strongly expertised in a novel imaging technique (spectral CT), interesting for a further carrier in the domain of medical imaging or industrial NDT.

References

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