3D X-Ray imaging of bone tissue from micro to nano scale and associated inverse problems

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Imaging bone tissue from the organ to the cellular level is a major goal in bone research to understand, diagnose and predict bone fragility associated to bone disease such as osteoporosis. In this presentation, we show that X-ray CT is particularly well adapted to image bone in 3D up to the nanometer scale. After recalling the principles of 3D CT, we describe advances in bone CT imaging and the needs in associated inverse problems.

Clinical X-ray CT is daily used to image skeletal tissue at the organ scale with a spatial resolution of about 0.5mm. However such systems do not permit to image bone micro-architecture made of a complex network of thin trabeculae (thickness about 150 µm). Imaging trabecular bone has been a driving application in the development of X-ray micro-Computerized Tomography (CT) *ex-vivo*. New High Resolution peripheral Quantitative CT (HR pQCT) systems provide images at voxel size around 100 µm, permitting the investigation of bone micro-structure *in vivo* [1]. Synchrotron X-ray CT, in addition to an accurate analysis of bone microarchitecture, provides quantitative information about the degree of mineralization of bone [2]. Finally, exploiting X-ray phase contrast has permit to reach 3D imaging of bone samples up to 50nm by using the magnified phase nano CT setup developed at the ESRF [3].

Basic CT reconstruction relies on the inversion of the Radon Transform, which is conventionally done using the Filtered Back Projection algorithm. Recently compressive sensing (CS) methods have raised increasing interest in CT imaging [4]. These algorithms are generally based on the minimization of a functional including a prior term promoting some form of sparsity. While many progresses have been made in the development of methods and algorithms, their practical uses in applications still requires developments. We describe current works and perspective in this field concerning bone imaging.

A first study concerns the use of sparsity promoting methods to improve the spatial resolution from *in vivo* HR pQCT images of bone microstructure, which still remains limited for the quantification of bone micro architecture. A scheme based on Total Variation (TV) was proposed for the joint super-resolution and segmentation of bone micro architecture. An algorithm based on the Alternating Direction Method of Multipliers (ADMM) was developed. Figure 1 illustrates the improvement in the structure connectivity that can be achieved with this method.

A second study is devoted to the tomographic reconstruction of bone micro architecture from a limited number of projections in order to achieve low dose imaging. A reconstruction scheme taking into account the binary constraint based on TV regularization was developed. Simulations based on noisy projections shows that it permits a dramatic reduction of the number of projections (Figure 2).

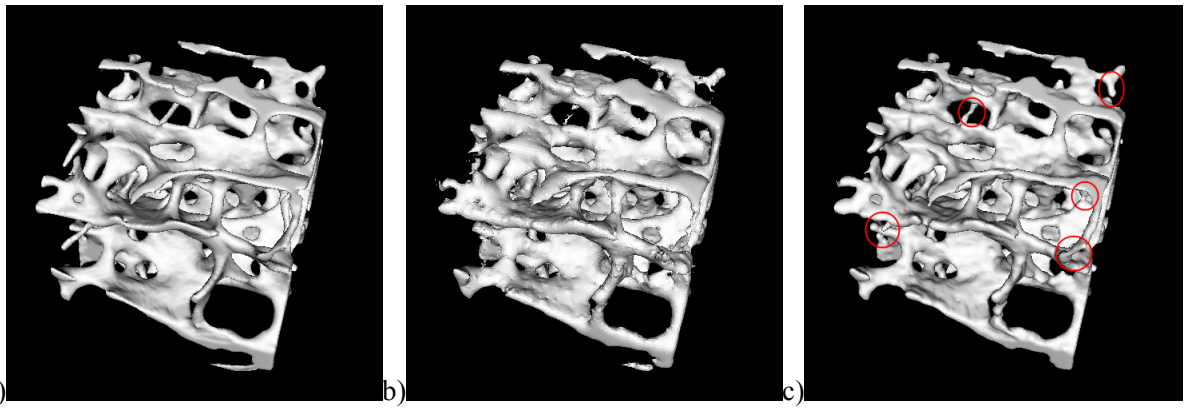

Figure 1 : Illustration of joint segmentation/super resolution applied to a 3D bone micro image : a) original image, voxel size 20µm, b) low resolution image including undersampling by a factor 2 and additive Gaussian noise (σ=0.1), c) restored 3D binary image. The red circles show that the method has allowed the restoration of the connectivity that was lost after undersampling

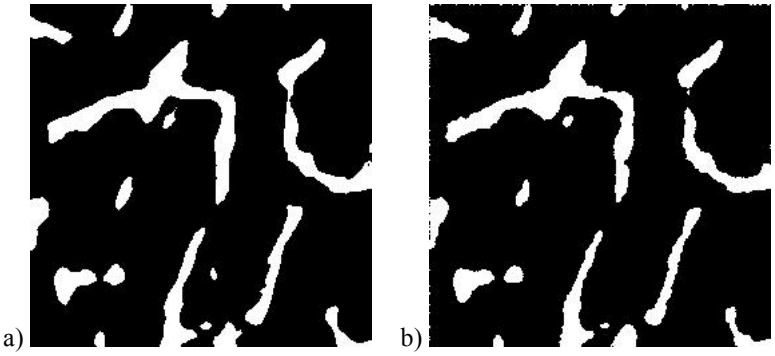

Figure 2 : Illustration of CT reconstruction of bone micro architecture from a limited number of projections : a) original 256x256 image reconstructed from 400 projections, b) TV reconstruction with binary constraints from only 50 noisy projections

Finally, we present current work in nano phase CT for bone tissue imaging. The underlying inverse problem including a phase retrieval step prior to CT reconstruction will be described. Currently these two problems are generally solved independently [5]. Work is in progress for the joint phase retrieval/CT reconstruction, which could allow the inclusion of priors in the object domain.

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