Fuzzy logic analysis and reconstruction of bone structure from high-resolution MRI

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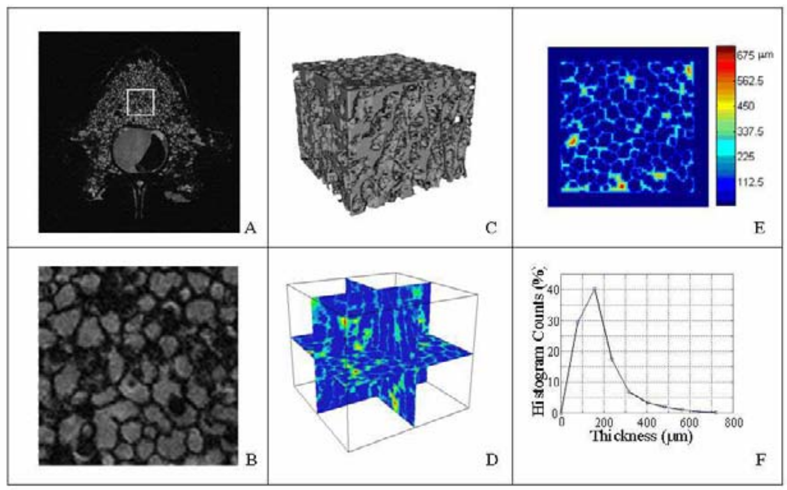
Introduction: Bone fractures as a consequence of osteoporosis are becoming a major concern for the aging population. Quality of life may be dramatically affected by the disease and its consequences. Vertebroplasty is a nonsurgical therapy to strengthen an osteoporotic bone. This is accomplished by injecting a medical cement mixture through a needle into the fractured bone. Understanding the rheology of the cement in the bone pore structure would improve the effectiveness of the treatment. Significant progress has been made in the extraction of geometrical parameters describing the complicated morphological structure of trabecular bone from MR images.[1-4] For example, the distance transform (DT) and more recently the fuzzy distance transform (FDT) methods were applied to the assessment of trabecular bone thickness.[4-6] This methodological study focuses on combining high-resolution MRI together with advanced methods of image analysis, which is a 3D FDT, for the assessment of the key geometrical features of bone. The analysis is done at the pore, meso- and vertebral scale. The broader objective of this work is to have a better understanding of geometrical changes associated with osteoporotic bones and emerging techniques to repair the fractured bone by the use of medical cements.



Materials and Methods: Several intact 3-years old sheep vertebrae, homologous to human lumbar vertebrae were used without defatting to keep the experiments as closed as possible from an *in vivo* procedure. The MR signal was thus originating from the bone marrow with the black regions representing the bone structure (Fig. A). A complete vertebra was imaged using a 3D gradient echo sequence (TR/TE: 16.4/9.35 ms; NA: 54; matrix: $(512)^3$, FOV: 41 x 41 x 32.8 mm, resolution: 80 µm x 80 µm x 60 µm) on a 7T Varian MRI scanner. With this resolution the small vertebral trabecular structure could be discriminated (Fig. B).

The fuzzy image analysis was performed in three steps. First fuzzification of the input image based on a sigmoidal function was performed. Second the FDT was applied producing a 3D map that shows the Euclidian distance between bone and marrow pixels at the scale of individual pores and trabeculae. Finally, defuzzification produced the thickness distribution along the skeleton of the bone. The average cavity size can be calculated on the basis of that distribution.

Results and Discussion: Fig. C shows a virtual biopsy (corresponding to the location shown in Fig. A) allowing the assessment of the bone morphology. Specifically, FDT associated with a color map depicting the thickness distribution (Fig. D, E) has been rendered in three planes (Fig. D). The thickness was distributed between 0 and 700 µm (Fig. E), with the most probable value at approximately 150 µm. The large majority of the trabeculae have a thickness below 300 µm (Fig. F). This study focused on combining advanced image analysis algorithms with high-resolution MRI.

To the best of our knowledge, the very high resolution images acquired from a *complete* intact vertebra had not been achieved previously.

Conclusion: This study extends the use of MRI as a tool for the assessment of the microstructure of an entire vertebra. It is non-invasive and, if combined with adequate image analysis and computations,[7] can lead to a better understanding of bone mechanical and transport properties. Our research will focus on treating osteoporotic fractures using minimally invasive methods. This problem has high relevance because of the dramatic illness increase of our increasingly aging population.

References:

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