Surgical navigation and planning with minimum radiation in orthopaedic interventions

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Introduction: In orthopedic interventions, it is critical to reduce radiation for high sensitive candidates such as young females with pelvic osteotomy or youth people with bone tumor by using minimum radiography. According to the statistics from American Academy of Neurological and Orthopaedic Surgeons, though bone cancer is not as common as other types of cancers, it has higher occurrence rate in children and youth, which tremendously devastates the entire life quality of patients. Hence, it’s of great importance to develop minimally invasive interventions with minimal radiation exposure. Planning could be done using the patient pre-operative CT images. However, such CT images are not always available since taking CT scan is not suitable for all patients due to its high radiation exposure. For the case of bone tumor ablations, we can address two key challenges in the computer-assisted interventions: 1) how to establish the spatial transformation of patient’s tumor with respect to a global map of the patient using minimum amount of radiation such as a couple of intra-operative X-ray images or partial CT scan away from critical organ; 2) optimal treatment planning for large tumors.

Material and Methods: We addressed the aforementioned challenges through statistical atlas constructions [1], atlas to 2D radiography registration approaches for estimating patient-specific models with minimal radiations (that is, just using a sparse set of fluoroscopy shots and preoperative statistical atlas), and multiple-objective optimization for planning the treatments. Statistical atlas can be employed to construct the global reference map. The atlas then can be registered to a pair of intra-operative fluoroscopy images for constructing a patient-specific model. In this way, we can reduce the radiation exposure to the patients such as pregnant and infants. Thus the proposed statistical atlas based surgical planning system consists of three key modules (see Figure): 1) statistical atlas construction, 2) deformable 3D-2D registration for simultaneous pose estimation and patient-specific model construction, and 3) optimal treatment planning.

High-resolution CT images of 19 normal adult cadaveric femurs were acquired. Each slice is 512x512 pixels with pixel size of 0.703 mm and thickness of 0.625mm. The ground-truth model of each cadaveric femur was obtained by manually segmenting its CT using Analyze (AnalyzDirect Inc., Kansas, USA). Then, the “leave-one-out” evaluations were carried out using these CT reconstructions of 19 cadaveric femurs. A simulated tumor of 24 mm diameter was generated and
registered to the patient specific model. An ablation probe of 20 mm diameter is used for radiofrequency ablation, assuming the ablation electrode can kill a spherical space with multiple tines.

To characterize shape variations, a statistical shape atlas is constructed using Point Distribution Model (PDM) [2], according to the procedures in the principle component analysis (PCA) of shapes. Consequently, a mean shape, modes of shape variation and shape variation are obtained. A valid shape instance can be constructed by a linear combination of the mean shape and the first K dominant modes [3] [4].

Instead of using the same-patient pre-operative CT images, a patient-specific model is built from a couple of X-ray images and a preoperative statistical atlas via deformable 3D-2D registrations [5]. We developed a new approach to optimize the registration and model construction simultaneously [5] in order to address the challenging coupled problems: the registration needs an accurate model while the accurate modeling requires an accurate pose.

Then the tumor treatment optimization module derived optimal probe insertion trajectories as well as optimal placement locations of ablation electrode. The optimization need to satisfy the constraints of fulfilling complete tumor coverage, starting from specified entry points, avoiding critical no-fly zone, and minimizing the number of ablations and skin punctures.

**Results:** The construction error of the patient-specific model measured with surface-to-surface distance is about 0.84 mm, and the resulted tumor ablation plans can achieve 100% over the large tumor region using 4 to 6 ablations. The experiments validated the benefits of the proposed method: 1) no patient CT scan or only partial CT scan is required, which reduces the radiation exposure to the patient as well as to the physicians; 2) the patient-specific model and its spatial transformation to a pair of intra-operative X-ray images are optimized simultaneously rather than sequentially, which increases the accuracies of the model and registration; and 3) the treatment planning module yields optimal overlapping ablation plans based on the constructed patient-specific anatomical model and tumor model.

**Discussion:** The article shows the feasibility of the proposed method for atlas-based, image-guided orthopaedic interventions using minimal radiograph and optimal planning. The proposed system can be extended to other potential applications and one example is for periacetabular osteotomy, particularly for young females which is of great importance to minimize radiation dose during surgical planning and navigation.

**References**


