●A Dedicated Cone-Beam CT System for Musculoskeletal Extremities Imaging

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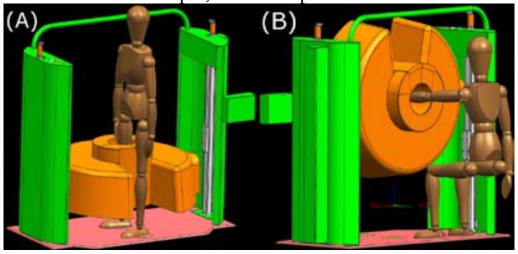
INTRODUCTION:

X-ray CT and MRI provide important, complementary diagnostic modalities for imaging of musculoskeletal (MSK) extremities – the former offering high spatial resolution and the latter exquisite soft-tissue visibility. While each offers a powerful diagnostic tool with numerous strengths, a variety of limitations can be identified, including: (i) difficulty in examining weight-bearing extremities (e.g., impingements that manifest only in loaded or tensioned extremities); (ii) limitations in the presence of prosthetic implants (e.g., total knee replacement), where metal artifacts can hamper the visualization of implant loosening and bone disintegration; (iii) the potential for large cumulative radiation dose in longitudinal studies (e.g., analysis of fracture healing or response to therapy); and (iv) cost, space, and workflow associated with whole-body scanners used for extremities imaging. Addressing these challenges could benefit diagnosis, planning, and therapy evaluation in applications such as trauma, cancer, and inflammatory disease (e.g., arthritis).

A dedicated imaging system is under development to address these limitations and provide complementary or alternative functionality to CT and MRI. The system is based upon x-ray cone-beam CT using a high-performance flat-panel detector, a paradigm that has demonstrated success in applications ranging from breast and maxillofacial imaging to image-guided interventions. Flat-panel detectors allow for compact CT systems with considerable flexibility in the geometry of the scanner and the capability to combine digital radiography and real-time fluoroscopy with 3D imaging. This paper summarizes scanner design and reports quantitative and qualitative studies of imaging performance.

METHODS:

Figure 1 illustrates the design of the extremities scanner, currently under construction. The gantry allows scanning in both the standing configuration (Fig. 1A) for imaging of weight-bearing lower extremities, and in the sitting configuration (Fig. 1B) for imaging of upper extremities (with the capability to apply tension) and unloaded lower extremities. The gantry is self-shielded, simplifying x-ray safety site requirements. The patient enters the bore through a sliding door on the side of the gantry. A flat-panel detector and fixed-anode source are mounted on a sickle-arm (Fig. 1C) to provide a side opening. The inner bore is ~20 cm and incorporates accessories for patient immobilization (e.g., inflatable air bladder). The flat-panel detector (Varian 3030+) provides a 1536x1536 pixel matrix (0.194 mm pixels) and uses a custom 10:1 antiscatter grid. The x-ray focal spot size is 0.5 mm; the source can deliver x-ray techniques up to 125 kVp, 7 mA (~0.8 kW). A custom bow-tie filter improves image uniformity, reduces x-ray scatter, and reduces peripheral x-ray dose. A single rotation captures a ~(20x20x20) cm^3 volume with isotropic, sub-mm spatial resolution.



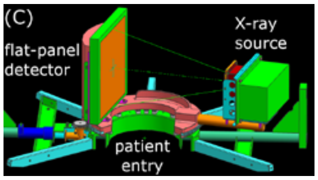


Fig. 1: The scanner illustrated in (A) standing and (B) sitting configurations. (C) Within the gantry are a flat-panel detector and fixed anode x-ray source for cone-beam CT.

Image quality was assessed in quantitative studies of spatial resolution, noise, and dose as well as qualitative studies in fresh cadaver specimens (hand, elbow, foot, and knee). Initial studies used a test-bench prototype with geometry equivalent to the scanner. Using a 90 kVp x-ray beam (+0.2 mm Cu added filtration), 987 projections were collected over 360°, giving a total effective dose of ~0.06 mSv, which compares favorably (a factor of 2-5 lower) to that reported for diagnostic CT. Preliminary studies were at half-resolution (0.388 mm pixels), with reconstructions computed using 3D filtered backprojection at 0.25 mm voxel size.

RESULTS:

Quantitative x-ray technique optimization provided soft-tissue visibility within the power limits of the scanner (< 1 kW) at low radiation dose (~1/3 the dose of a conventional CT knee exam [1]). The antiscatter grid and bowtie filter demonstrated improved image quality at reduced dose to the patient. Example images of cadaveric extremities are shown in Fig. 2. High isotropic spatial resolution is apparent in the visualization of fine trabecular details. The delineation of fat, muscle, and tendons is comparable to a conventional CT scanner. Further improvement in resolution and contrast-to-noise ratio is expected through refinement of the grid and bowtie filter on the scanner as well as improved reconstruction and artifact correction techniques tailored to extremities imaging.

Fig. 2: Example reconstructions of a cadaveric hand (top) and knee (bottom) obtained in a test-bench emulating the extremities scanner. (a) Axial section in bone window through the carpal tunnel shows osseous trabecular detail at the level of the hamate hook. (b) Coronal section in soft tissue window through the palmar apsect of the hand shows the normal course of the flexor tendons. (c) Axial section in bone window shows osseous trabecular detail at the level of the patellofemoral joint. (d) Coronal section in soft tissue window through the mid tibiofemoral joints shows the periarticular muscles and medial collateral ligament.

DISCUSSION:

Initial results demonstrate that the proposed cone-beam CT scanner will provide low dose, high resolution imaging of the extremities with soft-tissue contrast approaching that of conventional CT. The system complements existing imaging modalities and offers additional capabilities in imaging of weight-bearing extremities. It also offers potential advantages in cost and workflow relative to whole-body scanners, including the ability to perform digital radiography and dynamic real-time fluoroscopy on the same scanner. In addition, the task-specific design facilitates the development of dedicated image acquisition and reconstruction techniques to optimize image quality. These include dual-energy imaging (e.g., for improved soft-tissue visualization and analysis of inflammatory disease) and functional 3D/4D motion studies. Similarly, advanced reconstruction techniques are under development, including statistical reconstruction approaches and improved scatter and metal artifact correction. The prototype scanner is currently under construction and will be deployed next year in pilot studies targeting orthopedic imaging of the knee (including weight-bearing exams and total knee replacement) and the hand (including monitoring of fracture healing and arthritis therapy response).

REFERENCES:

[1] *Biswas et al.* “Radiation Exposure from Musculoskeletal CT Scans,” *J. Bone Joint Surg. Am. 91: 1882-1889 (2009).*