Title: Targeted ultrasound-guided breast biopsy under dedicated positron emission mammography localization

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Structured Abstract:

Introduction: Targeting small, detectable breast lesions with high accuracy is critical for early stage diagnosis, treatment planning, and improving patient outcomes. Conventional anatomical methods to detect and localize breast lesions are limited in sensitivity and specificity, particularly in women with high breast tissue density. Positron emission mammography (PEM) is an alternative functional imaging method that combines breast-dedicated high-resolution imaging components with preeminent FDG radiotracers to detect regions of increased metabolic activity, a hallmark of cancer growth. Although PEM provides a method to optimize breast cancer detection, anatomical context and real-time needle visualization are not available. We describe a mechatronic guidance system integrating an ultrasound (US)-guided biopsy method with high-resolution PEM imaging to improve targeting for lesion sampling. This work presents the system validation and phantom study to sample simulated breast lesions detected with PEM imaging.

Methods: A mechatronic guidance system was developed to operate with an advanced PEM system and US imaging system. The system features a manually operated, counterbalanced stabilizer with the ability to access the breast between two planar PEM detector plates. The end effector is a biopsy device containing an US transducer and core-needle biopsy gun with its post-fire needle focused on a remote-center-of-motion. Custom software was developed to track, display, and guide the biopsy device and its needle. Guiding the needle to calibration fiducials on a simulated PEM detector plate registered the coordinate systems using landmark-based registration. Testing was performed with fiducials positioned within the targeting volume of a breast. Fiducial Registration Error (FRE) and Target Registration Error (TRE) were quantified to evaluate accuracy. Principal component analysis assessed for directional trends in 3D space within 95% prediction intervals. Breast phantom experiments were performed to evaluate the ability of the mechatronic system to guide, position, and biopsy simulated lesions localized with PEM imaging. Three-dimensional root-mean-square error (RMSE) in the PEM image coordinate space was quantified.

Results: Registration and testing resulted in an FRE of 0.23±0.20mm (N=8) and TRE of 0.70±0.20mm (N=72). A 3D prediction ellipsoid, centered on the mean TRE, shows the ability to target within a spherical region <2mm in diameter with 95% confidence. Phantom studies demonstrate successful targeted US-guided biopsy procedures with a 3D RMSE of 0.85±0.30mm (N=20).

Discussion: A mechatronic guidance system was developed for US-guided breast biopsy under high-resolution PEM localization. Accurate calibration and needle tracking with sub-millimeter 3D error within the targeting volume of a breast was demonstrated. Phantom studies show the capability to guide, position, and target breast lesions within a simulated PEM image.