Three-Dimensional Deformable Image Registration For Pleural Photodynamic Therapy

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Abstract

Pleural photodynamic therapy (PDT) following surgical resection is a critical treatment for malignant pleural mesothelioma, where accurate light delivery directly impacts treatment efficacy and patient outcomes. A fundamental challenge in PDT dosimetry is the significant deformation of pleural cavity geometry during surgery, which creates substantial discrepancies between pre-operative CT imaging and intraoperative navigation system measurements. This study addresses this challenge by developing an advanced three-dimensional deformable image registration framework using COMSOL Multiphysics 6.3 to accurately map navigation-acquired pleural cavity volumes (Figure 1) onto CT-derived anatomical structures (Figure 2).

Our methodology represents a significant advancement from previous 2D approaches [1,2], implementing a two-stage deformation process that leverages COMSOL's enhanced Moving Mesh physics coupled with Structural Mechanics modeling. The first stage employs an extended dynamic iterative boundary matching algorithm, originally developed for 2D applications, now expanded to full 3D coordinates (Figure 3b). This algorithm calculates displacement vectors between corresponding points in the navigation reference volume and CT target geometries, establishing initial spatial correspondence through COMSOL with Matlab and Moving Mesh interface, which replaces the previously used ALE model for improved computational efficiency and stability. COMSOL's advanced mesh handling capabilities enable seamless integration of complex anatomical geometries while maintaining numerical stability throughout the deformation process [3]. The second stage introduces physics-based refinement using COMSOL's Structural Mechanics module, incorporating realistic tissue biomechanical properties including Young's modulus, Poisson's ratio, and density values for tissues [4,5]. This finite element method approach ensures that deformations respect physiological constraints while achieving optimal geometric registration [6,7]. The CT-derived organ volumes serve as fixed target geometry, while navigation system contours undergo controlled deformation to match the pre-surgical anatomical configuration. COMSOL's multiphysics environment allows seamless coupling between geometric deformation and mechanical analysis, providing a unified computational framework that eliminates the need for external data transfer between different software packages. The implementation utilizes COMSOL's advanced tetrahedral meshing algorithms to generate high-quality finite element discretizations of complex anatomical structures. The software's built-in optimization routines and convergence criteria ensure robust numerical performance across varying patient geometries and deformation magnitudes. COMSOL's parallel computing capabilities further enhance computational efficiency, enabling real-time analysis potential for clinical applications.

Results demonstrate substantial improvements in registration accuracy compared to previous methods, with transformation errors reduced to sub-centimeter precision across multiple patient datasets (Figure 4). The integrated Moving Mesh and Structural Mechanics approach successfully preserves anatomical structure integrity during deformation while accommodating the significant volume changes that occur during pleural surgery. The von Mises stress distribution (Figure 3c) and final displacement field (Figure 3d) demonstrate the physical realism of the deformation process. The method enables precise mapping of light fluence distributions to critical organs-at-risk, including heart and liver surfaces, providing essential dosimetric information previously unavailable through conventional detector-based measurements. This enhanced 3D deformable registration framework offers transformative capabilities for pleural PDT treatment planning and real-time dosimetry guidance, potentially improving treatment uniformity and reducing complications in mesothelioma patients. The robust COMSOL-based implementation provides a foundation for future clinical translation and integration into existing PDT treatment workflows.

Reference

[1] B. Liu, J. Li, T.C. Zhu, Deformable image registration for pleural Photodynamic Therapy, COMSOL Conference Proceedings, Boston (2013).
[2] R. Penjweini et al., Deformable medical image registration of pleural cavity for photodynamic therapy by using finite-element based method, Proc. SPIE, 9701, 970106 (2016).
[3] Y. Cai et al., Dynamic meshing for deformable image registration, Computer-Aided Design, 67-68, 87-106 (2015).
[4] K.K. Brock, Accuracy of finite element model-based multi-organ deformable image registration, Medical Physics, 32, 1647-1659 (2005).
[5] H. Zhong et al., A finite element method to correct deformable image registration errors in low-contrast regions, Physics in Medicine & Biology, 57, 3499-3515 (2012).
[6] S.K. Kyriacou, C. Davatzikos, A biomechanical model of soft tissue deformation, with applications to non-rigid registration of brain images with tumor pathology, Medical Image Computing and Computer-Assisted Intervention, 531-538 (1998).

[7] J. Zhang et al., Physical Constraint Finite Element Model for Medical Image Registration, PLOS ONE, 10, e0140567 (2015).

Figures used in the abstract

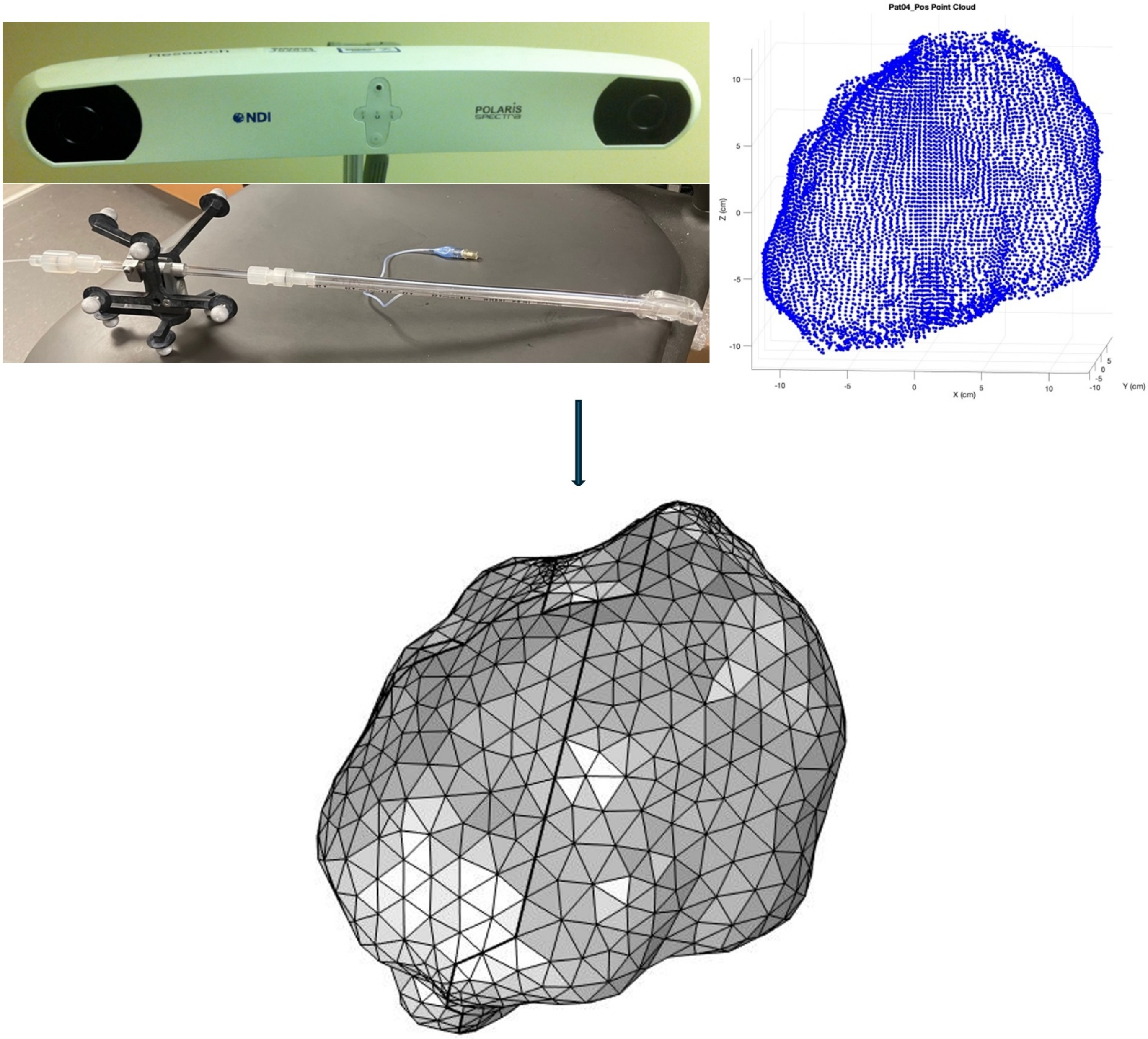

Figure 1 : Data acquisition workflow for pleural PDT deformable registration. Top left: NDI infrared camera system and treatment wand with reflective markers . Top right: Point cloud data (blue scatter points). Bottom: Reconstructed 3D mesh volume in COMSOL

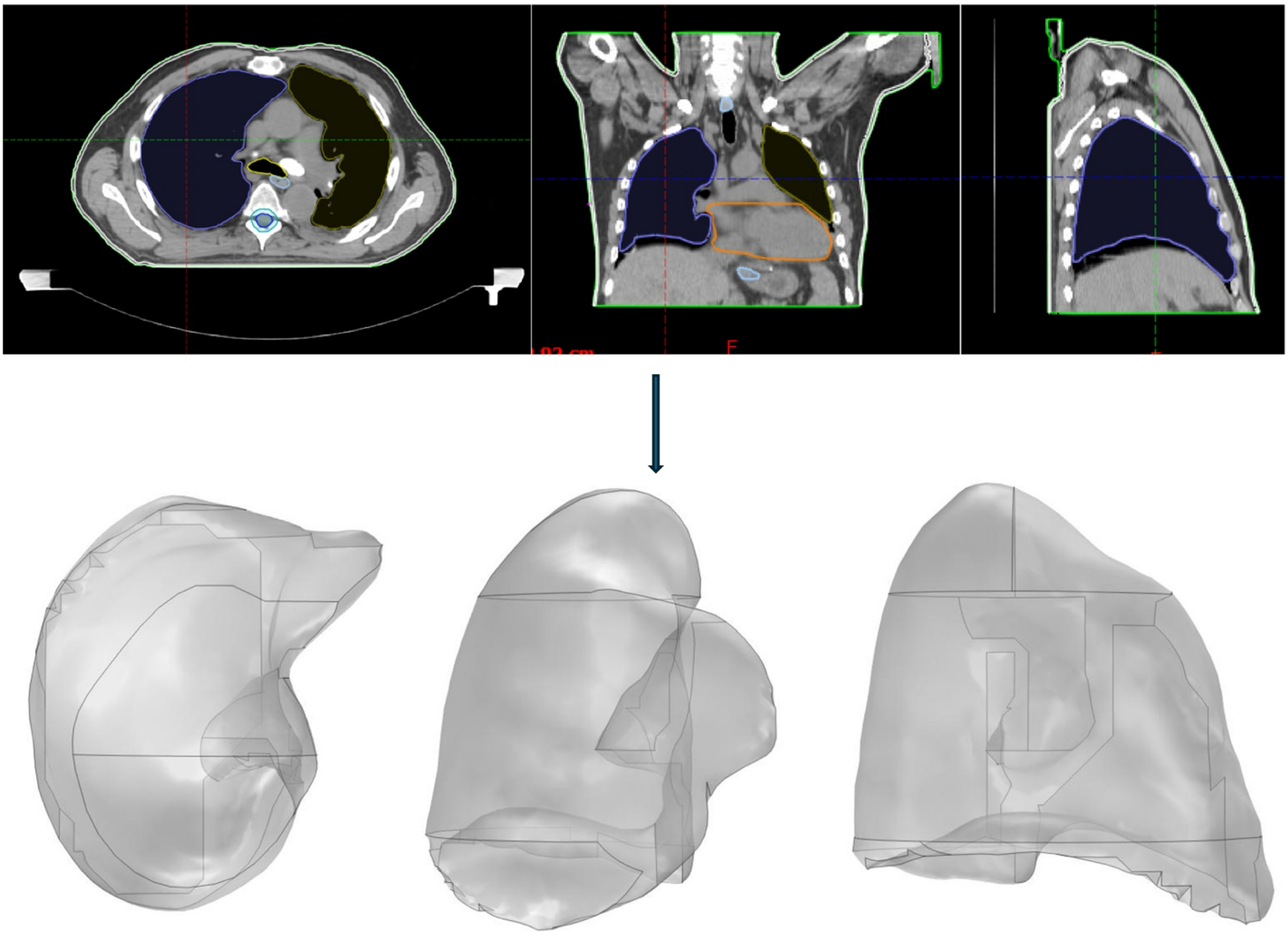

Figure 2 : CT-based anatomical structure reconstruction. Top row: Axial, coronal, and sagittal CT images showing organ segmentation with lung contours (blue). Bottom row: 3D reconstructed organ volumes obtained from CT DICOM data using ARIA software

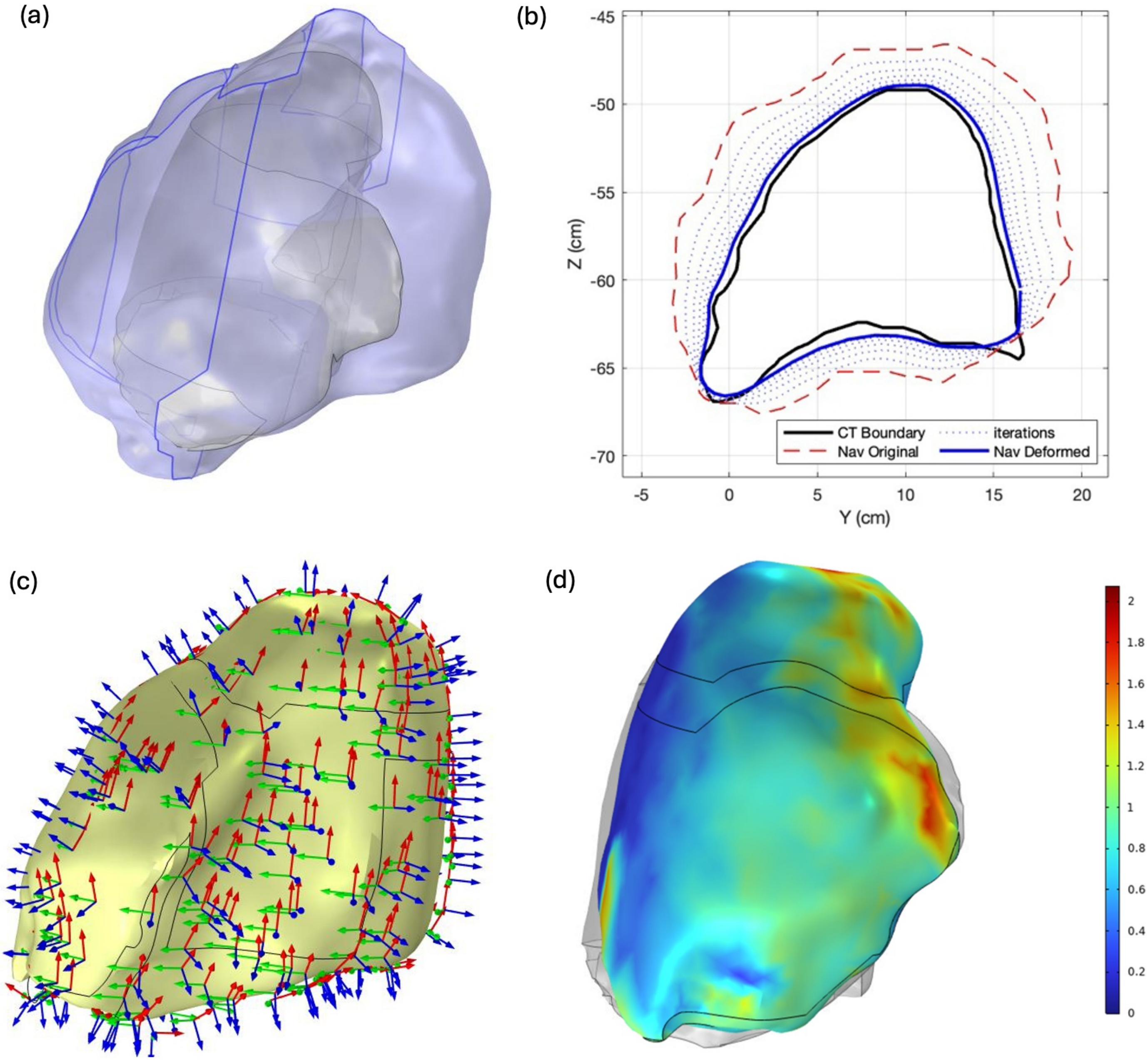

Figure 3 : Three-dimensional deformable registration process (a) Raw navigation and CT volumes (b) Dynamic iterative boundary matching (c) von Mises stress distribution (d) Final deformed navigation volume (colorful surface) overlaid with target CT volume (grey)

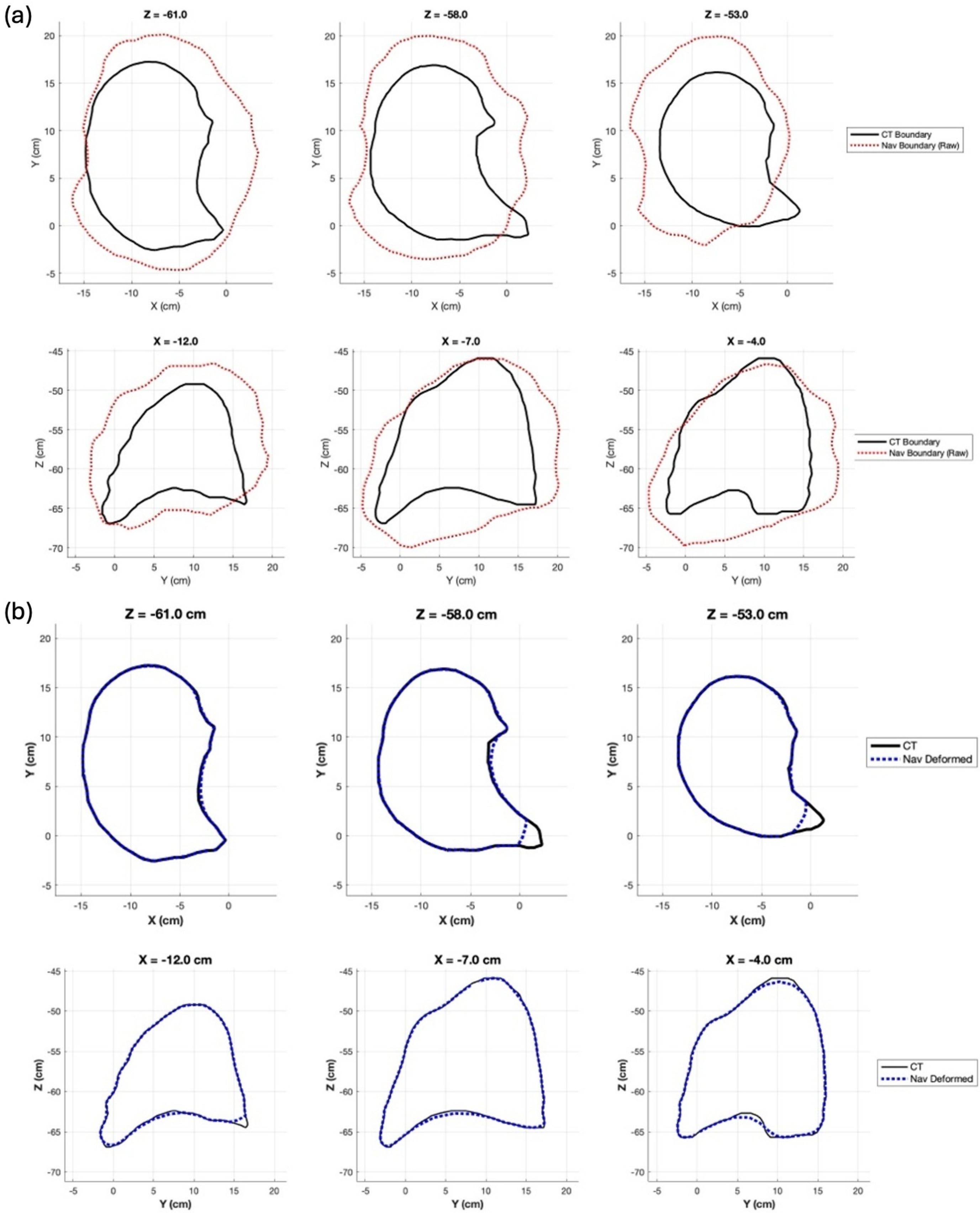

Figure 4 : (a) Cross-sectional comparison showing raw navigation volume boundary (red dotted line) versus CT target boundary (black) (b) Corresponding cross-sections showing deformed navigation volume (blue dotted dotted line) matched to CT target (black solid line)