Purpose

Clinical implementation of adaptive treatment planning is limited by the lack of quantitative tools to assess deformable image registration errors (R-ERR). The purpose of this study was to develop a method, using finite element modeling (FEM), to estimate registration errors based on mechanical changes resulting from them.

Methods

An experimental platform to quantify the correlation between registration errors and their mechanical consequences was developed as follows: diaphragm deformation was simulated on the CT images in patients with lung cancer using a finite element method (FEM). The simulated displacement vector fields (F-DVF) were used to warp each CT image to generate a FEM image. B-Spline based (Elastix) registrations were performed from reference to FEM images to generate a registration DVF (R-DVF). The F-DVF was subtracted from R-DVF. The magnitude of the difference vector was defined as the registration error, which is a consequence of mechanically unbalanced energy (UE), computed using 'in-house-developed' FEM software. A nonlinear regression model was used based on imaging voxel data and the analysis considered clustered voxel data within images.

Results

A regression model analysis showed that UE was significantly correlated with registration error, DVF and the product of registration error and DVF respectively with $R^2=0.73$ ($R=0.854$). The association was verified independently using 40 tracked landmarks. A linear function between the means of UE values and R-DVF*R-ERR has been established. The mean registration error ($N=8$) was 0.9 mm. 85.4% of voxels fit this model within one standard deviation.

Conclusions

An encouraging relationship between UE and registration error has been found. These experimental results suggest the feasibility of UE as a valuable tool for evaluating registration errors, thus supporting 4D and adaptive radiotherapy.

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