Reconstruction of a deformed tumor for treatment planning of interstitial photodynamic therapy: A computational feasibility study

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BACKGROUND

- Interstitial Photodynamic Therapy (I-PDT) involves the activation of a photosensitizer by a therapeutic light resulting in tumor cell destruction.
- I-PDT has been applied for the treatment of locally advanced head and neck cancer (LAHNC).
- In I-PDT, light is provided via catheter-embedded fiber optics.
- We have developed a finite element model (FEM) for computing the light propagation during I-PDT.
- CT scans of a patient with LAHNC are used to create three-dimensional (3-D) geometries for the FEM.
- While CT is used for the FEM, ultrasound is used for the guidance of fiber insertion.
- For treatment planning, the number and location of source fibers is based on the tumor size and location.
- Tumor size also dictates the simulated light dose volume histogram. However, there is not much research into the impact of tumor deformation due to fiber insertion on the light dose delivered.

MOTIVATION

Problem

CT is initially used to reconstruct digital LAHNC model for I-PDT preplanning. Treatment failure occurs at marginal region due to the mismatch between the original tumor shape used in the preplan and the actually deformed shape during operation.

Utilization of fiducial markers (FMs)

FMs are gold seeds that are implanted in or around a tumor to help pinpoint the tumor’s location in past works. In our context, relative displacement of FMs encodes information about the deformed shape, and thus can be used for capturing deformation.

Goal

From a computational perspective, predict the deformed shape of a LAHNC during I-PDT procedure from (i) initial 3D reconstruction in preplanning, and (ii) Traced FM displacements during two imaging modalities.

METHOD

Mathematical model

Standard linear finite element method is used for guiding computation. Assuming that there is no external forces on interior nodes, the nodal displacement vector x can be linearly mapped to surface nodal force vector f_s.

The constraints imposed by FMs are formulated by using a 0-1 indicator matrix D and observed FM displacement vector d.

\[ \mathbf{f}_s = \mathbf{K} \mathbf{x} \]

The above observation that LAHNCs are generally surrounded by soft tissue, force field smoothness is used for regularizing the above under-determined system. Laplacian energy on f_s is used as the mathematical formulation of this smoothness.

\[ \|f_s(x)\|_2^2 = \mu^2 \nabla^2 f_s \]

Evaluation Approach

(1) Tumor model & FMs
(2) Force field
(3) Deformation benchmark
(4) Force prediction
(5) Deformation comparison
(6) Prediction evaluation
(7) Light propagation modeling

Light propagation modeling

Our finite element model (FEM) for computing the light propagation was described previously in Oakley et al. In this approach, the three-dimensional (3-D) time-dependent diffusion equation as derived from the equation for radiative transfer was applied.

\[ \frac{1}{c_n} \left( \Phi(x,y,z,t) - F(a^2 \Phi(x,y,z,t)) \right) \]

where \(a_n = c_n - \frac{\mu^2}{\mu^2 + (1-\mu^2)\alpha} \)

\(\Phi(x,y,z,t)\) is the photon flux (Photons/m²/sec), \(a^2\) is the optical diffusion coefficient (m²/sec) of tissue n, \(\mu_0^2\) and \(\mu_s^2\) are the linear absorption and scattering coefficients (1/m) of tissue n, g is the optical anisotropy factor, and \(c_n\) is the speed of light in tissue.

RESULTS

Synthetic (sphere) model

Our algorithm is tested on spheres of 30mm and 80mm diameters (normal range of LAHNC size) with infinitely differentiable sinusoidal force field on their surfaces. The force prediction is very close to the applied force field in benchmark. The maximum surface offset between benchmark and predicted shape is 0.7mm among all cases (normal uncertainty in ultrasound imaging).

Real tumor model

Our algorithm is also tested on a real tumor model reconstructed from CT scanning. Smooth force field is applied on tumor surface for simulating realistic bending behavior. The prediction of the displacement field is quite accurate, with the maximum offset on the surface being within 1mm (normal uncertainty in distance measurement using ultrasound imaging).

CONCLUSION

- Developed an optimization algorithm
  - Initial tumor shape and fiducial markers -> deformed shape
- Demonstrated effect of deformation in I-PDT procedure
- Light propagation modeling
- Mathematical formulation of force field smoothness
  - Laplacian energy
- Fast computation in predicting deformation
- 1.3s in sphere case and 5.5s in real tumor case
- High prediction accuracy
  - within typical ultrasound imaging resolution