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A robotic multi-channel platform for interstitial photodynamic therapy

Anna V. Sharikova^{*}, Jarod C. Finlay, Andreea Dimofte, and Timothy C. Zhu

Dept. of Radiation Oncology, University of Pennsylvania, 3400 Civic Center Blvd, Philadelphia, PA USA 19104

Abstract

A custom-made robotic multichannel platform for interstitial photodynamic therapy (PDT) and diffuse optical tomography (DOT) was developed and tested in a phantom experiment. The system, which was compatible with the operating room (OR) environment, had 16 channels for independent positioning of light sources and/or isotropic detectors in separate catheters. Each channel's motor had an optical encoder for position feedback, with resolution of 1.5 mm, and a maximum speed of 5 cm/s. Automatic calibration of detector positions was implemented using an optical diode beam that defined the starting position of each motor, and by means of feedback algorithms controlling individual channels. As a result, the accuracy of zero position of 0.1 mm for all channels was achieved. We have also employed scanning procedures where detectors automatically covered the appropriate range around source positions. Thus, total scan time for a typical optical properties (OP) measurement throughout the phantom was about 1.5 minutes with point sources. The OP were determined based on the measured light fluence rates. These enhancements allow a tremendous improvement of treatment quality for a bulk tumor compared to the systems employed in previous clinical trials.

Keywords

photodynamic therapy; dosimetry; robotic platform; PDT

1. INTRODUCTION

Photodynamic therapy (PDT) is a cancer treatment modality where photosensitizer, administered to a patient before treatment, is excited by the treatment light and reacts with triplet oxygen. The reaction produces singlet oxygen, a potent cytotoxic agent, which destroys surrounding tissues¹.

Interstitial prostate PDT is performed by inserting source and detector fibers into catheters that are placed inside a prostate using a special template. The PDT procedure requires that the entire target volume received the prescribed amount of light fluence. Our robotic platform, which is a second generation motorized clinical scanner², makes it possible to

deliver a uniform PDT light dose in a minimum amount of time, by optimizing positioning of multiple sources and performing dosimetry continuously through the treatment.

Optical properties (OP), namely absorption and reduced scattering coefficients, play significant role in the amount and distribution of light fluence in the tissues. They tend to vary from patient to patient and in different sites in one patient. It is critical to be able to measure their distributions quickly and reliably in a clinical setting. A combination of diffuse optical tomography (DOT) algorithms³⁻⁴ with multiple source and detector fibers moved in a coordinated fashion by the robotic system allows for the entire measurement to be finished in about half a minute⁵.

Photosensitizer distribution in tissue is another factor that influences PDT dose. It can be determined by measuring fluorescence signal from the photosensitizer and correcting it for optical properties. This mode can be implemented in parallel with treatment by dividing the detector signals between dosimetry and spectrometry inputs⁶.

2. METHODS

2.1 Robotic platform

The details of the multichannel robotic platform design and its development have been reported previously⁵. Briefly, the system (Fig. 1) had 16 channels with individual motion control and an optical encoder positioning feedback.

The effective travel range was 20 cm for each channel, maximum speed 5 cm/s, and the positioning resolution 0.05 mm. In addition, the platform featured lockable interchangeable fiber holders, an optical beam/detector pair for home positioning, and was operating room (OR) compatible.

2.2 Control algorithms

The algorithm development for the multichannel platform is an ongoing process. Below is a short description of some algorithms that have been implemented and tested.

2.2.1. Automated home position alignment using optical diode beam—This procedure ensures that all motor channels are positioned consistently relative to the platform frame before scanning.

1. Motor #1 moves until the fiber holder blocks the light beam and triggers the optical sensor
2. Motor backs off to unblock the sensor
3. Home (zero) position is set
4. Process repeated for all other motors

2.2.2. Travel limits activation to stop motors before the end of the track—This procedure is necessary to prevent fiber holders from slamming into the platform frame when requested destination is outside of the physical travel range. Software travel limits set

approximately 1 cm short of the track ends are turned on after the home position calibration. When a motor reaches one of the limits, it quickly decelerates and stops.

2.2.3 Scanning range adjustment around the light source (OP measurement)—

This procedure optimizes travel range of individual detectors that move simultaneously. The peak position of the light source is located during the initial scan. Subsequent multiple scans are centered on the peak position for each detector.

2.3 PVC phantoms

We have made solid phantoms from PVC plastic (Fig. 2) imitating optical properties of healthy tissues and tumor by generally following a procedure described in the literature⁷. We controlled phantom OP by adding specific amounts of titanium oxide (scattering) and carbon black (absorption) to the plastic mixture. The advantage of PVC phantoms over silicone ones is the ability to image PVC phantom structure using ultrasound. A heterogeneous phantom can be made by combining different PVC mixtures during or after the plastic cooling.

3. RESULTS

3.1 Robotic platform performance tests

We have performed various tests of the robotic platform. Fig. 3 shows the scanning range adjustment algorithm at work. During the initial scan (left) the light source peak positions registered by the detector fibers differed by 2 to 5 mm. After the range adjustment, all peaks were lined up within 0.1 mm for the subsequent scans (right).

To make sure that the motor positioning was consistent after the source peak location, we have determined the difference between signals recorded on two subsequent scans (Fig. 4). The largest differences, observed in the case of smaller source intensity, did not exceed 5%, and typically were below 1%.

We have also checked the precision of the home position alignment. For this, the entire OP scan was repeated after the re-homing procedure. As can be seen from Fig. 5, detector signals before and after re-homing agreed within a fraction of a millimeter, despite the fact that this test included all uncertainties from scanning and homing procedures.

3.2 Optical properties measurements

Optical properties of a PVC phantom were determined using robotic platform and dual motor systems. Calibrated light fluence profiles recorded by the detectors were used to extract the effective attenuation coefficient $\mu_{\text{eff}} = (3 \mu_a \mu_s')^{1/2}$, and separate it into the absorption coefficient μ_a and reduced scattering coefficient μ_s' of the phantom. Fig. 6 shows light fluence data, fit profile and theoretical curve based on the extracted OP for one of the scans. The fit results, averaged for each detector channel, the entire robotic platform set, as well as dual motor data, are summarized in Table 1. The relative standard deviation between the channels was quite large, especially for the μ_s' (45%) and μ_a (31%). It could be primarily attributed to the uncertainties in catheter separation between the source and detector

channels. While the fitting algorithm assumed constant separation distance, the actual catheter separation could differ by as much as 1 mm (out of 5) on the two sides of the phantom. The results for μ_{eff} were less sensitive to these errors, with relative standard deviation of 11% between channels. The agreement between the robotic platform and dual channel system results was within the uncertainty for all optical properties, and did not exceed 8%.

4. DISCUSSION

4.1 Conclusions

The second generation robotic multichannel platform has demonstrated a significantly faster performance than the first generation dual motor system, due to a combination of its mechanical properties and advanced algorithms optimizing the range of motion for individual channels. It completed an optical properties scan with point sources for the entire phantom in about 1.5 minutes. The home location accuracy of the system was about 0.1 mm. Repeated OP measurements of the same phantom location typically agreed within 0.3%. Comparison of the OP data with dual motor measurements agreed within uncertainty.

4.2 Future work

We are currently developing algorithms for the interstitial PDT source scanning to deliver uniform light dose in a minimum amount of time. We are also implementing diffuse optical tomography (DOT) algorithms for the robotic platform to obtain inhomogeneous OP distributions in solid phantoms. Finally, we plan to measure interstitial PDT dose distributions by combining light dose dosimetry with photosensitizer fluorescence data.

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Figure 1. Multichannel robotic platform (right) and dosimetry system (upper left) assembly for optical properties measurements.

Figure 2.
PVC phantoms: with tissue (left) and tumor (right) OP, and four detector fibers around a light source fiber (665 nm) inserted through catheters.

Figure 4.

Positioning consistency test between subsequent scans: initial scan (upper left), subsequent scans (lower left and right), and the difference between the subsequent scans (upper right). Notice different vertical scale for the upper right plot.

Figure 5. Home positioning precision test: initial (left) and subsequent (right) scans before and after re-homing procedure.

Figure 6. Optical properties fit for a single scan: light fluence data (black), fitted curve (red) and theoretical curve (green).

Table 1

Optical properties of the “tumor” phantom measured using the dual motor and robotic platform systems.

Measurement	μ_a , 1/cm	μ_s' 1/cm	μ_{eff} , 1/cm
Dual Motor average	0.31	14.46	3.68
Robotic Platform average	0.32	13.41	3.38
Ch1 average	0.32	13.07	3.56
Ch2 average	0.32	13.77	3.62
Ch3 average	0.2	20.71	3.5
Ch4 average	0.44	6.09	2.85
STDEV	0.10	5.98	0.36
STDEV/Average, %	31%	45%	11%
DM-RP % difference	3%	8%	8%