Optimization of a fast optical CT scanner for nPAG gel dosimetry

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Abstract. A fast laser scanning optical CT scanner was constructed and optimized at the Ghent university. The first images acquired were contaminated with several imaging artifacts. The origins of the artifacts were investigated. Performance characteristics of different components were measured such as the laser spot size, light attenuation by the lenses and the dynamic range of the photo-detector. The need for a differential measurement using a second photo-detector was investigated. Post processing strategies to compensate for hardware related errors were developed.

Drift of the laser and of the detector was negligible. Incorrectly refractive index matching was dealt with by developing an automated matching process. When scratches on the water bath and phantom container are present, these pose a post processing challenge to eliminate the resulting artifacts from the reconstructed images. Secondary laser spots due to multiple reflections need to be further investigated. The time delay in the control of the galvanometer and detector was dealt with using black strips that serve as markers of the projection position. Still some residual ringing artifacts are present. Several small volumetric test phantoms were constructed to obtain an overall picture of the accuracy.

1. Introduction

In optical CT scanning, optical transmission projections are acquired at different projection angles. Four different optical scanner types have been proposed in the past [1]. The first generation optical CT scanner was made of a laser beam and a photo-detector that moved simultaneously compared to the volumetric gel phantom to measure one projection. After each projection, the volumetric gel phantom was rotated and a new projection was measured. The second type of optical CT scanner was based on the principle of a cone beam shaped diffuse light source that illuminates the volumetric gel phantom and transmission images were acquired using a CCD camera. Again after each projection the volumetric gel phantom was rotated. The third kind of optical CT scanner used a parallel incident light beam generated by a point light source and a large plano-convex lens. After passing through the volumetric gel phantom a second plano-convex lens was used to focus the light beam onto a CCD.
camera. The last generation optical CT scanner, also called the fast laser scanning configuration uses a scanning laser beam and a photo-detector.

The optical CT scanner build at the Ghent University was based on this last type of scanner using a galvanometer mirror system to sweep the laser beam towards a plano-convex lens. At this point the laser beam is refracted so that the scanning beam is perpendicular to the rotation axis of the volumetric gel phantom. The first images acquired were contaminated with several imaging artifacts. The origins of those artifacts were investigated. First, blank measurements (without phantom) were performed to isolate scanner-related artifacts. Drift of the laser, drift of the detector, incorrectly matching of the refractive index, scratches on water bath and phantom container, secondary laser spots due to multiple reflections and the time delay in the control of the galvanometer and detector were investigated.

Performance characteristics of different components were also measured such as the laser spot size, light attenuation by the lenses and the dynamic range of the photo-detector. The need for a differential measurement using a second photo-detector was investigated. Post-processing strategies to compensate for hardware related errors were developed. Finally, several small volumetric test phantoms were constructed to obtain an overall picture of the accuracy.

2. Materials and methods

2.1. Optical CT scanner

An optical CT scanner (OPTOSCAN) (figure 1) was constructed in house. We use a 2.0 mW, 632.8 nm HeNe-laser (JDS Uniphase, Model 1122p, CA, USA) with a beam diameter of 0.63 mm (1/e² points). Before reaching a galvanometer mirror system (shortened: galvanomirror), the laser beam is narrowed by two pinhole collimators to sharpen the laser beam size. The galvanomirror directs the laser beam to a plano-convex lens (Melles-Griot, Albuquerque, USA) which is positioned at focus distance (450mm) from the galvanomirror. The laser beam leaving the plano-convex lens travels in parallel lines through the gel dosimeter until it passes another plano-convex lens which guides the laser beam towards the photodetector.

Figure 1. Schematic basic design of the in house optical laser scanner. The laser beam travels towards a rotating galvanomirror. Before reaching this galvanomirror the laser beam is guided by two pinhole collimators. The galvanomirror directs the laser beam to a plano-convex lens. From this part on the laser beam travels in parallel lines through the gel dosimeter until it passes another plano-convex lens which guides the laser beam towards the photodetector. In a second configuration, the mirror next to the laser was replaced by a semi-transparent mirror whereby the transparent part of the laser beam travels towards a second detector to perform a differential measurement instead.

The photodetector is a large area balanced photoreceiver (Thorlabs, model 2307, Munich, Germany). In between the lenses a large fluid bath (32.0 x 32.0 x 25.0 cm³) is placed. Two black strips are attached to the walls of the fluid. These strips are used to correctly align all measured projections
per angular increment. The refractive index matching procedure is performed automatically based on a dry and wet off axis refraction measurement and using an automated pump system with a refractive index matching fluid (water-glycerol solution).

In a second hardware configuration, a semi-transparent mirror (pellicle beam splitter, BP145B1, Thorlabs) was used to divide the laser beam into two beams. One fraction (45%) is guided towards the galvanomirror, the second fraction (55%) is guided towards a second detector eye. With this second detector eye, it was possible to make a differential measurement of the laser beam to compensate for possible drift of the laser.

Matlab (The MathWorks, Natick, USA) code was developed in house to control the optical scanner, construct sinograms and optical density images.

2.2. Post-processing

Before the actual measurement, a blank projection (no phantom present) and a dark current are recorded. During the measurements, data is recorded and stored in a text file. The file also contains all the spatial information of the measured data points. The first post-processing step involves aligning all the measured projections in the sinogram. This is performed by searching the two black reference strips on the wall of the fluid bath in each projection. Each projection is then correctly aligned according to the positions of the black strips in the sinogram. This alignment step is also performed for the blank projection. The optical density OD’ is calculated from the transmission signal intensity using equation 1

\[ OD' = \frac{1}{\mu_{base}} \left( \frac{S(x,\theta,z)-SB}{(SD+S(x,\theta,z))-SB} \right) \]  

(1)

were SB is the mean of a blank projection (no phantom present), SD is the dark current of the photodetector and S(x,\theta,z) represents the signal at position x, angle \( \theta \) and vertical slice position z.

3D rendered image reconstructions were composed using Image J (Image J 1.38x, Bethesda, USA).

2.3. Performance measurement of different building blocks

The laser stability was evaluated by measuring the laser intensity during 30 min. The laser spot was placed at a fixed position in the centre of the lenses. Detector stability was evaluated by measuring the dark current during 30 min. The dark current was measured by covering the detector eye so that no light could enter the detector. The laser spot size was measured in between the lenses. The photodetector was mounted inside the same linear micro-precision stage where the phantom is normally mounted. Before the detector eye, a circular disc with an aperture of 50 \( \mu \)m was placed. In discrete steps of 0.125 mm the detector was moved perpendicular to the laser beam manually using the linear micro-precision stage. For each positional increment, a measurement was carried out and averaged over 100 data points.

Attenuation of the lenses was evaluated by measuring the laser intensity averaged over 1 minute with and without the lenses. A measurement of the laser intensity was performed placing the laser spot in the centre and off centre (approximately 1 cm from the edge of the lens). Finally a measurement of the laser intensity was performed with the third lens positioned in front of the detector.
Influence of the fluid bath was evaluated by acquiring 20 blank projections with the fluid bath empty. The influence of the volumetric phantom container was evaluated by acquiring 20 projections, with and without phantom container which was filled with refractive index matching fluid.

2.4. Volumetric test phantom fabrication

Three volumetric phantoms were used in this study (R: 2.6 cm, h: 6.7 cm). Two gel phantoms were fabricated with gelatine gel from porcine skin (7% (w/w)) (bloom 300, Sigma-Aldrich, Bornem, Belgium). In the first phantom needles were positioned in a spiral configuration. In the second phantom, an air space was created in the shape of a funnel, which was subsequently filled with a chemical induced polymerised nPAG gel (Gelatin (6% (w/w), acrylamide (Aam) (3%, (w/w)), N,N'-methylene-bis-acrylamide (Bis) (3% (w/w)), 0.02 g ammonium persulphate and 0.2 ml N,N,N',N'-Tetramethyl-ethylene-diamine (TEMED) all obtained from Sigma-Aldrich. A third large volumetric test phantom was constructed (R: 4.75 cm, h: 15 cm) which was filled with the same refractive index matching fluid (glycerol-water) as the fluid bath.

3. Results and discussion

3.1. Laser and detector stability

The photodetector drift was found negligible over a period of 30 min. The mean value was $-8.89 \times 10^{-4} \pm 4.14 \times 10^{-4}$ V. The discretisation levels of the detector can be clearly seen in figure 2a.

The laser stability was recorded over a period of 30 min after switching on the laser. The change in detected laser intensity is shown in figure 2b. Variations were significant in the first 10 minutes after start-up but saturate after this period (figure 3b). The mean value of the detected laser intensity after 15 minutes was $1.58 \pm 0.01$ V. From these measurements, it was concluded that before starting a measurement the laser should be turned on for at least 15 minutes. The low frequency variations in the laser intensity have not been explained.

![Figure 2](a): the detector signal over a course of 1800s (a) and the laser intensity signal over a course of 1800s (b).

3.2. Laser spot size
The measured intensity profile across the laser spot is shown in figure 3. A Gaussian function was fitted to the profile and a full-width-at-half-maximum of 1.27 mm was measured.

3.3. Attenuation of the lenses

The attenuation of the laser intensity by the lenses was evaluated. A 9.43% attenuation of the laser beam by lenses 1 and 2 was detected (figure 1) with the laser beam travelling through the centre of the lenses. When the laser beam travels 5.4 cm off centre through the lenses, the attenuation amounted to 12.52%. With lens 3 in place, the attenuation of the whole lens configuration measures 16.81% for the laser beam travelling through the centre and 16.65% for the laser beam travelling off centre. The reason for the difference between attenuation in the centre and off centre is probably due to a larger portion of multiple reflections reflected away from the detector when the laser beam enters the lens by an angle.

3.4. Differential measurement

The need for a differential measurement was investigated. The exiting laser beam was split in two fractions by a semi transparent mirror (transmission: 55%, reflection: 45%). The reflected fraction travelled towards the galvanomirror. The transmitted fraction travelled towards the second eye of the detector. A differential measurement would correct for possible laser drift. To see if a differential measurement performed better, measurements were compared with and without the second measurement. It was seen that the use of a differential measurement resulted in only an offset in the intensity data. It was concluded that a differential measurement is not required. This was also consolidated from the detector and laser stability measurements.

3.5. Refractive index matching fluid

To match the refractive index of the water-glycerol solution with the refractive index of the gel dosimeter an automated procedure has been developed. The principle is based on a dry and wet off-axis refraction measurement of the gel dosimeter. Based on the determined refractive index of the gel and the fluid, the required glycerol concentration is determined. The concentration dependence of the refractive index was also determined experimentally. Using recorded data on the concentration glycerol in the fluid, the difference in concentration can be adjusted using an automated pump and mixing system (figure 4).

3.6. Influence of the water basin and volumetric phantom container...
Projections of in the empty fluid bath were recorded to investigate scratches on the glass wall (figure 5). When the refractive index matching fluid was pumped in the fluid bath the variations in the data signal became significantly smaller. This may be explained by filling of the scratches by the refractive index matching fluid. Refractions of the laser beam will not be enhanced as much when passing from glass to matching fluid as from glass to air. Turbulences and little dust particles in the water could also induce variations in the signal. It was found advantageous to wait at least 1 hour after filling the fluid bath before measuring.

Projections with a blank volumetric phantom, i.e. a cylindrical phantom filled with the refractive index matching fluid, were measured to investigate the influence of the container on the signal. It was found that scratches on the wall of the volumetric phantom induce artefacts in the projections (figure 5).

For measurements of small volumetric phantoms, a small fluid bath (14.2x7.5x5.5 cm³) was used to minimize the amount of refractive index matching fluid.

3.7. Post processing

Synchronization problems between the input of the projection data and the output of the galvomirror were detected. This resulted in shifted projection in the sinogram which caused severe artifacts. Also when OD’ calculations were performed with misaligned data projection versus bank projection, a magnification of the ringing artifacts became apparent. To compensate for these errors a Matlab (The MathWorks) script was used to detect signal voids in the top and bottom of the sinogram from black strips on the wall of the fluid bath (figure 6).

Severe misalignments were dealt with using the black strips. However, some sub-pixel shifts between acquired projections and blank measurements could still result in minor artifacts. Further optimisation is needed to minimize further ringing artifacts.

3.8. Test QA volumetric phantoms

The first 3D reconstructing images of QA volumetric phantoms were very promising (figure 7).
Figure 7. Reconstructed 3D images of test volumetric phantoms.

4. Conclusion

A fast laser scanning optical CT scanner with a fully automatic refractive index matching system refractive was constructed and optimized at the Ghent University. The first images acquired were contaminated with several imaging artifacts. The origins of artifacts were investigated. Drift of the laser and the detector was found negligible after 15 minutes warm up of the laser. When scratches on the water bath and phantom container are present, these pose a post processing challenge to eliminate the resulting artifacts from the reconstructed images. Secondary laser spots due to multiple reflections on the lens system needs to be further investigated. The time delay in the control of the galvanometer and detector were dealt with using black strips that serve as markers of the projection position. Still some residual ringing artifacts are present. Several small volumetric test phantoms were constructed to obtain an overall picture of the accuracy. Further optimisation is required to obtain a better accuracy and precision.

References

[1] Oldham M 2004 Optical-CT scanning of polymer gels J. Phys.: Conf. Ser. 3 122-135