Marker trajectory assessment in optical cone beam computed tomography scanner geometry

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Abstract. Measured trajectories of markers on vessel wall and beads on a plumb are compared with calculated trajectories for transmission images obtained with Vista16™ optical cone beam scanner. Effective pixel size was 0.11 mm. An algorithm was developed to measure trajectories for the plumb line phantom and a semi-automatic version was required for the gel filled vessels due to overlap of markers and seam projections at maximum lateral positions. It was found that for 15 cm diameter vessels, the vessel edge was not visible due to divergence in cone beam geometry. Accounting for this effect was necessary in order to remove artefacts from calculated vessel trajectory. Displacement differences were found to be less than 0.1 mm for the plumb line, 0.3 mm for a bead and 1 mm for markers on gel filled vessel. Minimization of the vessel marker trajectory deviation will provide a more accurate approach to refractive index optimization. No optical aberrations were detected from the trajectory analysis and manufacturer scanner alignment and geometrical calibrations were independently verified.

1. Introduction

The Vista16™ optical cone beam computed tomography (CT) scanner from ModusQA has a 16 cm field of view. Adding a 1.5 cm diameter aperture at the source reduces stray light in transmission images [1]. One consequence of reducing stray light is the need for higher optical quality cylindrical plastic vessels for 3D radiochromic hydrogel dosimetry. While initial images and 3D reconstructions of coloured solutions with in-house constructed custom vessels are promising, inspection of pre and post scans often reveal displacements due to limitations of the custom mounts for these custom vessels. Improvements in custom vessel design and reproducible mounting is ongoing. However, image registration is a powerful method to improve CT reconstruction without placing prohibitive demands on the imaging system. An example of this is the IsoCal phantom and imaging protocol used to characterize the kilovoltage and megavoltage imaging systems on Varian medical linear accelerators [2]. X-ray cone beam CT scanner geometry calibration has been addressed by many researchers [3-5]. Often the calibrations involve analysis of small spheres or wires at optimum locations in a custom calibration cylinder. Preliminary results of writing millimeter wide lines into a radiochromic and photochromic genipin hydrogel have been presented at a previous IC3DDose conference [6].

In this study 1 mm black ink marks were placed on walls of custom gel cylinders and 2 mm beads were attached to a plumb line. Trajectories were measured from optical cone beam CT scans of these phantoms. The plumb line follows the same trajectory as the ink mark on the vessel wall. The trajectories
in the horizontal plane containing the optical axis are also in the sinogram for this plane. Comparisons
of measured and calculated trajectories provide information on the system’s geometry and deviations
due to aberrations. For example, trajectory deviations should determine: rotational symmetry of rotary
bearing for sample mount, accuracy of rotational increments, net spherical aberration, refractive index
uniformity of gels and impact of differences in refractive indices of gel, vessel wall and outside liquid.

2. Methods

Black ink marks were added to a custom polyethylene terephthalate (PETE) vessel, 50 and 100 mm
above the bottom and adjacent to the single, 1 mm wide, black, wall seam, see figure 1. Vessel wall
thickness was 0.25 mm and the outer diameter was 148.2 mm +/-0.2 mm. Optical CT scanning was
performed with a Vista16 cone beam scanner provided by ModusQA modified to a 1.5 cm diameter
source. A 12% propylene glycol aqueous solution provided optimum field of view for ClearView™ gel
in this vessel. The pixel size corresponded to 0.11 mm in the rotation axis plane. The vessels rotate
counter clockwise when viewed from above and are mounted with the seam at the source side on the
optic axis. One thousand projections were acquired over 360 degrees per scan. Images were exported
from VistaScan as PNG files and processed in MATLAB. A plumb with small beads was attached to
outer diameter of an end disk used for custom vessel fabrication. The plumb line, (0.3 mm diameter,
black fishing line), allows measurements of reference trajectories in solution without the aberrations due
to the vessel and gel. The beads were constructed from short lengths of black plastic tubing crimped to
the line.

The optical axis was determined by recording images of a transparent ruler placed vertically in
the filled aquarium, resting on the bottom at the camera side and source side. Similarly, the ruler was
placed horizontally, resting on the side of the aquarium again at the camera side and source side and
recording images. Inspection of the images determined the row and column that did not diverge. The
intersection was the optical axis. This value was within 2 pixels of the center pixel of the s ensor. An
image of the aquarium half-filled provided another measure of the height of the optic axis and horizontal
alignment and up down tilt of the camera. No adjustments of the camera position from manufacturer
were performed. Aquarium dimensions were measured with a machinist’s vernier, <0.5 mm uncertainty.
Rotation axis was measured by several methods and was found to be within 2 pixels, 0.2 mm of the
optic axis.

The most general form of the algorithm used to detect marker trajectories uses a semi-manual
approach, where the user periodically inputs the new region of interest. For data sets with lower noise,
a fully automated approach was used. On a given frame, the algorithm searches a particular region of
interest for a connected group of pixels with brightness values below a particular threshold. The region
of interest image is binarized about this threshold. Depending on details of the marker being searched
for, other operations are then performed. For instance, for a bead hung on a plumb line, the image is
eroded by a suitable structural element to remove the line. If part of the opaque vessel seam or other
artefact is present in the region of interest, the program can account for this when selecting the proper
region. The geometric center of the final pixel group is then calculated, and the new region of interest
centered around that point in the next frame. For markers placed near an opaque seam, the algorithm
switches to tracking the seam at points where the marker approaches the edge of the image. Since the
seam is vertical in the image, this allows for column number data to be extracted for more frames, though
obviously row number data cannot be gained this way. The row number is thus linearly interpolated
over in these regions.

Once the trajectories have been detected in projected space, they are transformed into physical
space for comparison with theoretical values. The vessel diameter, aquarium thickness (parallel to the
optic axis) and location of the rotation and optic axes are measured. The divergence of the system, which
could not be reliably ascertained from physical measurements, was selected by forcing frames where a
rotating plumb line are calculated to appear furthest left and right with the frames where this is actually
observed. With these parameters, the actual trajectory of a marker in physical space is calculated and
compared to theoretical values assuming perfectly-cylindrical vessels and no unforeseen optical effects.
Obviously, this displacement is highly sensitive to the value used for the vessel diameter. It is also extremely sensitive to the divergence. The limit of 1000 total frames in a rotation, because of the ultimate method used to calculate divergence, limited the precision with which the divergence could be measured, and thus furnished perhaps the largest source of uncertainty. The displacement was, surprisingly, much less sensitive to slight alterations in the values used for aquarium thickness and rotation axis position, though knowledge of the pixel where the optic axis lay in the image was crucial for removing distortion.

3. Results

Figure 1, shows transmission image of vessel containing an irradiated gel with marker positions identified by arrows. This projection corresponds to the markers and seam on the camera side of the vessel in the vertical plane of the rotation axis. Image window and level were adjusted to make markers more visible. The side and bottom edges correspond to the camera side of the aquarium and the corner tabs are from the source side. These edges are used for autocalibration of the magnification. No significant optical distortion inherent to the scanner geometry was found. The plum line with beads and weight suspended in solution is seen in right panel. The plum line is at the same radius as the vessel wall of the left panel. Figure 2, is a plot of the difference between measured and calculated position of marker or bead versus projection number. The first projection corresponds to the marker or bead in the vertical plane of the optic axis on the camera side of the trajectory. The trajectory differences for each bead on the plum line had a unique pattern and are thought to be due to asymmetries in the bead shape, kinks in line from crimping beads and swaying in the line during scan rotation. This is consistent with line trajectories near the beads having maximum differences 50% smaller (1 pixel difference) than the beads (3 pixels). However, larger differences associated with gel filled vessel were found. The distortion approached 1 mm (approximately ten pixels in images) near the edge of the projection. Note the differences are less for the source side of the trajectory. This is expected since the calculation assumes single uniform refractive index ignoring vessel and gel. It appears differences are primarily due to a slight mismatch between the refractive index in the gel and that of the surrounding propylene glycol solution in the scanner, rather than effects due to the interface with the vessel. In particular, where the refractive index is too low outside the vessel, parts of the vessel near the projection’s edge appear further from the optic axis, and where it is too high they appear closer to the optic axis. Also, comparison to datasets using a custom vessel 10 cm in diameter further suggest that the distortion depends more on the distance from the optic axis than on the angle at which incident light rays meet the vessel.

![Figure 1](image1.jpg)

**Figure 1.** Projection 1 images: (left) markers along custom vessel seam indicated by arrows and filled with irradiated ClearView™ gel, seam at source side, (right) beads on plumb line, at source side. Vista16 aquarium with 12% propylene glycol water solution.
Figure 2. Plot of trajectory position difference between projection image and calculation. Projection range 250 to 750 corresponds to camera side of trajectory. Missing data ranges correspond to marker overlapping vessel seam at edge of vessel. Marker is upper marker of figure 1, gel vessel. Bead is second from top on plumb line. Bead line is a segment beside bead.

4. Conclusion
Small marks on the vessel walls can be used to measure trajectories at different heights relative to the optic axis. For custom vessels with a dark seam and adjacent markers overlapping positions occur near maximum lateral distance in projection plane. Both the dark seam and small marks on vessel wall can be used to measure trajectories and provide geometrical data for accurate optical CT reconstructions. For example, differences between measured and calculated trajectories can be used to optimize the refractive index of the solutions. Trajectories differences can also provide a measure of aberrations in transmission images. It is anticipated that trajectories may be helpful for assessing optical performance of different gels and vessels.

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