Advances in optical CT scanning for gel dosimetry

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1. Introduction

Optical computed tomography (CT) is physically similar to x-ray CT but is more versatile since many
powerful light sources exist and optical elements such as mirrors, lenses, polarizers and efficient
detectors are available. There are many potential forms of optical CT. Attenuation, fluorescence or
scatter, polarization and refractive index spatial changes are all examples of optical CT. To date,
optical CT for gel dosimetry has been limited to attenuation measurements that are the sum of scatter
and absorption along defined lines. Polymerization gels turn white with absorbed dose and attenuation
is due to scatter. Radiochromic gels also form a dose image due to changes in visible absorption.

This short review concentrates on the papers published since the DOSGEL 2001 meeting and
highlights experimental results and issues that are important for obtaining good quality input data for
reconstruction. The format involves selected highlights from the papers and associated points from our
experience with optical CT experimentation. The comments are intended to assist researchers
unfamiliar with optical measurements to obtain high quality transmission data, a necessary step in
quantitative gel dosimetry.

2. Results

2.1. Common elements of optical scanners

Several features are common for the optical CT systems that have been developed. Items that are
similar include: cylindrical vessels, aquariums filled with gel matched refractive index liquids,
monochromatic light sources, parallel ray geometry and filtered back projection reconstruction. The
exception is the cone-beam CT reported by Wolodzko et al that has a diffuse white light source,
imaging rays that are convergent and reconstruction employed software for SPECT imaging [1].

Notes: Refractive index matching is a simple approach to converting a lens, the gel cylinder, into a
window. This minimizes refraction during optical CT scanning.
2.2. OCTUPUS-ONE™ scanner evaluation

The only commercially available optical CT laser scanner is the OCTUPUS-ONE™, manufactured by MGS Research Inc. This instrument is constructed in a modular, open format which is excellent for research since it can be easily reconfigured. Islam et al examined the performance of this instrument for spatial resolution and dynamic range for optical absorption measurements [1]. The scanner is a “first generation” translate-rotate system. This geometry provides the greatest rejection of stray light and the greatest dynamic range for attenuation measurements. The laser source is a 0.8 mW, 633 nm He-Ne laser, with a beam diameter of ~0.8 mm full width half maximum. Front surfaced mirrors direct the beam through the liquid filled aquarium and the cylindrical object to a lens that focuses the beam onto an 8 mm diameter silicon photodiode. The aquarium was 26 cm wide and 25 cm thick and filled with a BANG® gel refractive index matched liquid consisting of glycerol and water. The laser beam was angled 5° to the window normal to reduce multiple reflections through the tank reaching the detector. The gel cylinder, was made of Barex because of its low oxygen permeability and had a diameter of 17 cm with a 1 mm wall thickness. OCTUPUS-ONE™ allowed for collection of transmission profile data to within 1 cm of the wall before the laser beam walked off the detector due to refraction. Twelve minutes were required to scan 400, in plane, projections with 136 pixels per projection. A scale of 1.4 mm per pixel resulted from these particular scanner settings. The spatial resolution is limited by the beam diameter. A “knife edge” scan determined the FWHM diameter to be 0.8 mm in this system. Comparisons of transmission measurements of aqueous solutions of Black India Ink with the scanner and an absorption spectrometer in 1 cm plastic cuvettes revealed agreement within 1% over the optical density range 0.2 to 3.1. Optical performance with well-defined scattering phantoms was not investigated in this initial study. Scatter will degrade the dynamic range for absorption measurements and reduce spatial resolution. The authors reported the optical CT measured optical density of BANG gel as a function of dose. Results show an increasing sub-linear response over the 0 to 2 Gy dose range. This trend is indicative of stray scattered light contaminating the primary attenuation measurement. The data was fit to a polynomial to generate a dose response calibration function. Doses measured with Bang gel and optical CT readout were ~85% of film measured doses. A similar under-response was reported previously by the authors for MRI readout. The authors commented that non-uniform scattering gels might present a fundamental problem because the stray light would be spatially dependent.

Notes: Si photodiodes response saturates around 100 mW.cm⁻² and the saturation level decreases at shorter wavelengths. Researchers should verify the fluence rates at the detector are below saturation levels. When focusing lasers it is easy to exceed the saturation level. Gas lasers emit a spectrum of light outside the laser frequency, called plasma discharge. Typically a prism or diffraction grating and an aperture are used to isolate the required laser emission. Another simple approach is to use a narrow band pass interference filter. Mirrors act as weak polarizers because reflection is polarization dependent. Mirrors also act as polarization selectors and can introduce unwanted structure in transmission profiles through optically active materials. Dust floating through narrow laser beams is a source of noise. A clean enclosed system will provide lower optical noise, also shorter optical path lengths reduces the effect of dust. Angling the laser beam through the aquarium windows can significantly improve the smoothness of the transmission profiles due to minimization of interference fringes caused by multiple reflections within the windows. For the purposes of quantitative transmission measurements, geometries that generate interference fringes should be avoided. Antireflection coating on the air interface and thicker window materials both reduce the amplitude of interference fringes. This is a case where the highest optical quality windows may be inferior to less flat and less parallel choices. Our experience with glycerol and water as a refractive index matching liquid includes long wait times for an optically-uniform liquid to be reestablished after pouring or transferring of cylinders. The solution often appears to separate into a mixture with the viscous glycerol at the bottom of the aquarium. Variations in transmission through the liquid were often
several percent of the mean transmission for a scan period. Also as an inconvenience, spilled glycerol is sticky requiring more work to keep lab area clean. We tried Black India Ink solutions based on this paper and found their optical density decreased over several days making them unreliable in measurements spanning hours or days. Comparison of optical CT and spectrometer measurements leads eventually to a point where it is difficult to tell which measurement is more accurate. In the case of low absorption spectrometer measurements 10 cm cuvettes improve the accuracy. Scatter systems such as gelatin gels limit the range of absorption measurements due to the additional stray light. More accurate comparisons require dye doped gel systems.

2.3. Optimum scanning parameters

To accurately reconstruct an image, transmission measurements are required throughout the object. If the transmitted light level is less than or equivalent to the noise then no information is available and reconstruction artifacts are generated. Xu et al developed a method for determining the minimum transmission along all scan rays through a gel of known dose response irradiated with a planned dose distribution [2]. This calculation allows either the dose to be set for the optimum transmission range of the gel or to prepare a gel with an optimum sensitivity for the delivered dose. CT experiments were performed to determine the range of intensities that would allow a reconstruction accuracy of less than 4%. Solutions of blue food dye dissolved in glycerol-water were prepared to provide uniform absorption of the light with differing absorptions. They determined that optical densities from ~0.4–2.5, in a 17 cm diameter cylinder, met the 4% criteria. The authors mentioned this data was likely limited by “imperfect filtration of the reference liquid”.

Notes: Optimum transmission range for absorption measurements is 10–90%. Food dyes appear to be very useful for quantitative measurements. Our experience, with red and blue food dye solutions, indicates that the measured absorptions are constant over several weeks of storage. Also, filtration of solutions has a minor effect. Food dyes are considered biologically safe and they do not bind very well to materials. In contrast, most dyes and stains are valued for how well they bind to surfaces. Variations in the transmission through the refractive index matching liquid can be larger than laser intensity fluctuations and they can have a spatial dependence that makes corrections for reference liquid difficult. These liquid fluctuations may prove to be the limiting factor in this approach to optical CT.

2.4. Optical CT versus MR scanning

In order for gel dosimetry to become a widespread clinical tool speed is required. Users would prefer to irradiate a sample, quickly scan and evaluate the dose distribution and then make a decision based on the results. In 2001, Oldham et al compared ‘in-house’ laser-CT and MR scanning with the following criteria, spatial resolution ~1 mm³, 1 hour scan time, accuracy within 3% and precision within 1% [3]. Their conclusion for this particular comparison was that optical CT provided greater precision and accuracy.

Note: Quantitative MR imaging has progressed and a similar comparison may show both technologies are acceptable for the above scan criteria. It is likely that significant advances in quantitative MR imaging will result from its premiere importance in medical imaging.

2.5. Optical CT – gel dosimetry I

Oldham et al further investigated the performance of an ‘in-house’ laser CT scanner and determined the modulation transfer function supported sub-millimeter spatial resolution [4]. They also developed a technique for preparing gels with regions of differing absorption. The gels were first cast around test tubes. These tubes were then gently heated until the contacting gel melted and they were then
removed. Cool viscous gel doped with blue food dye was poured into the cavities and allowed to gel. This technique provided high optical quality phantoms for testing the optical CT performance. They also reported that “inherent noise in the refractive index matching liquid” reduced the dynamic range by a factor of four relative to air. Comparing absorption in gel phantom with laser CT and gel in cuvettes with spectrometer readout found agreement within 4%. They also calculated, using Monte Carlo algorithms, the propagation of scattered light through polymer gels.

Notes: The technique of varying the absorption and scatter coefficients in a controlled manner within the gel is important for simulating radiochromic and polymerization gels. Convection currents in liquids add a source of noise not found in gels. The liquids to date have been essentially non-scattering, absorbing solutions.

2.6. Optical CT gel-dosimetry II

An experimental paper, which examined several aspects of laser CT data acquisition and analysis was recently published by Oldham and Kim [5]. They described the impact on placing the sampling photodiode as close as possible to the exit window of the aquarium. In order to maximize the amount of data collected near the cylinder walls as the beam refracted off the detector. Increasing the amount of transmission data collected near the cylinder walls significantly improved the reconstructed image near the walls. Examples of different approaches to splitting the laser beam are demonstrated and they showed that large fluctuations in signal and reference beams are due to temperature fluctuations. The authors also identified that band pass filters placed at the detectors generated transmission artifacts due to beam wander across the filter. Use of the transmission values through the refractive index matching liquid to re-normalize each profile provided a more stable reference than the reference diode. Corrections for imperfections in optics such as films and scratches are made by use of profile ratios. Ratio measurements are analogous to standard absorption measurements with spectrometers, where the ratio of solution transmission to the solvent transmission in the same or similar cuvette is recorded. Corrections applied to transmission profiles prior to reconstruction were more effective than to reconstructed images. Missing data near the cylinder walls was interpolated to provide consistent input projections for reconstruction. Preliminary tests with different apertures at the detector revealed the impact of scatter on scatter attenuation coefficients is measurable. For the particular geometry and scatter coefficients examined, stray light from scatter reduced the attenuation coefficient by approximately 10%. This result has implications for both radiochromic and polymerization gels since gelatin gels have a measurable amount of scatter. A study of geometrical distortion versus refractive index of the liquid demonstrated that the optimum refractive index is a compromise between wall artifacts and geometric distortion. They also note beam refraction (and reflections) may be a serious issue with area detectors, because this stray light is sampled by adjacent detectors.

Notes: Collecting as much data as possible near the walls has a large impact on image reconstruction important aspect to address in scanner designs. Laser diodes have an emission continuum that is analogous to the plasma discharge of gas lasers. It must be eliminated prior to spectral measurements. Band pass interference filters can be tuned to higher frequencies by tilting. The central wavelength of a band pass interference filter shifts linearly to longer wavelengths with temperature. Typical values are 0.01–0.03 nm/°C (Oriel Instruments catalogue). Diode laser wavelengths increase with increasing temperature, a typical value is 0.2 nm/°C (Newport catalogue). These effects lead to temperature dependent transmission and reflection from band pass interference filters. If the band pass filter is also employed as a beam splitter then the signal and reference beams will be out of phase. This can lead to an error in ratio recording. Interference filters can be tuned to higher frequencies by tilting the filter. Band pass increases for divergent beams. It may be necessary to measure the spectrum of transmitted light in order to characterize system. The laser beam is filtered at its output to remove plasma discharge. The filtered beam can then be split to provide a reference for ratio recording. A single band
pass filter at the laser eliminates the issue of beam wander at the detector causing a transmission artifact. Coloured glass filters are often highly fluorescent. Placing these filters close to the detector can generate a stray signal. If practical, spectral filtering should be done at the exit of the light source. Otherwise tests should be performed to validate that fluorescence is not contributing to the measured signals. Stray light due to scattering within samples is a common problem in attenuation measurements. Differential absorption can improve the measurement at the cost of dual wavelength scanning.

2.7. Cone-beam optical CT scanning

Wolodzko et al demonstrated a simple scanner consisting of a diffuse light source, liquid-filled aquarium, rotating sample and a CCD camera [6]. Each transmission image contained all the slices for a given projection angle. This approach provides the easiest system to construct and takes advantage of the dramatic improvement in CCD camera performance that has occurred in recent years. In the paper a white light source was used so that any frequency could be chosen by exchange of a band pass filter.

Notes: The key to the successful rejection of stray light in this geometry is the imaging pinhole. The image forming rays are divergent, however at small angles parallel-ray, filtered back-projection generates useful images. Monochromatic light sources are expected to have a larger dynamic range compared to filtered white light sources because of the limitations of optical filters.

2.8. Broad-collimated beam optical CT

Doran et al have demonstrated another geometry for fast 3D scanning that involves forming a transmission image on a screen placed at the exit window of the aquarium and collecting CCD camera images of the back surface of the screen [7]. The light source consists of a mercury arc lamp, band pass filters, a pinhole and collimating optics.

Notes: This system has the inherent advantage of tunability of the light source. In principle a monochromator and Xe lamp would provide a continuously tunable imaging spectrometer. A current limitation of the system is acceptance of stray light from scatter, reflection and refraction. All forward directed light contributes to the recorded image.

2.9. Additional comments related to our experiences with liquids and optical CT

Optical CT scanning with refractive index matching liquids currently involves open systems for placement of the gel samples. Several litres of liquid are used in current scanners. Experimenters should consider: toxicity, safety (flammable), vapour pressure, viscosity, chemical stability, colour stability, disposal and corrosive nature of solutions when choosing suitable materials for experimentation. For example, alcohols may present a safety issue if large amounts become airborne in a small room. Viscous liquids may take a long time to relax after pouring into the aquarium or transferring samples. Pure, glycerol can take several hours to relax. We have observed a settling action in sucrose-water and glycerol-water solutions with the denser liquid moving to the bottom of the aquarium. This effect can be observed by leaving the system undisturbed for a few hours and then stirring the liquid. Corrosive materials such as acids and salt solutions give good optical results but spills can etch metals. Bubbles are an annoyance and cause large decreases in transmission for the rays they intersect. Cold solutions that warm up during a scan release dissolved gas, forming bubbles. Dirt on surfaces provides nucleation sites for bubble formation. Vacuum filtration reduces bubble formation for short scans. Detergents have been employed to reduce surface tension and minimize bubble formation but at the expense of introducing additional scatter in the liquid. Many aqueous
solutions have been reported to obtain refractive indices between 1.33 and 1.37, the typical range for gelatin gels. Examples include: glycerol, ethylene glycol, propylene glycol, sucrose, NaCl, and other commercially available refractive index matching liquids. We have found propylene glycol–water solutions to be suitable. Refractive indices are temperature dependent. This effect can be used to finely tune the refractive index or as a method to observe temperature gradients and convection currents in liquids. Continuous stirring of the liquid may provide a method of maintaining optical uniformity.

In order to improve the dynamic range of the transmission measurements colored solutions are used. These solutions need to be non-fluorescent. In the case of light sources that are not monochromatic, the absorption should be uniform over the spectral range of the light. This suggests that black dyes should be ideal. Our experience with black inks found the transmission to decrease with storage time. The food dyes seem to be good candidates for use in gel phantoms and reference solutions. They are soluble in water and do not strongly bind to surfaces, non-toxic and inexpensive.

The successive placement and removal of sample vessels in the liquid-filled aquarium can lead to the deposition of films on the inner window faces and on the outer cylinder wall. The mechanism is similar to the dip technique for forming Langmuir-Blodgett films. These films can change the optical transmission and scatter properties of these surfaces which in turn causes reconstruction artifacts. Care must be taken to ensure cleanliness through the experiments.

2.10. Fluorescence in xylenol orange gels

In a recent paper by Gupta the emission spectra of the ferrrous-benzoic acid-xylenol orange (FBX) was reported showing an emission peak around 550–575 nm when excited with blue light [8]. This fluorescence may be an issue for quantitative optical CT absorption measurements of FX gels with blue light as well. A preliminary experiment demonstrated the yellow-green fluorescence from gelatin gels with and without xylenol orange was dominated by emission from the gelatin itself. Providing a cautionary note that gelatin fluorescence is a potential source of error in transmission measurements. Excitation at 590 nm did not induce a measurable level of fluorescence at longer wavelengths.

3. Conclusions

Optical CT measurements continue to be refined as researchers explore the current limitations of the scanning techniques. It is recognized that temperature plays a large role in quantitative measurements and the most precise data will require a stable temperature environment. Refractive index matching liquids seem to be the current limitation on reproducibility in transmission measurements. The pursuit of more precise measurements may require development of more complex scanners that incorporate active beam-steering to eliminate the refractive index matching requirement.

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