Quantification of the absorbed dose in 3D by means of advanced optical diagnostics based on structured illumination

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The purpose of this study was to present a novel optical diagnostic tool that corrects for undesired contribution of multiply scattered light, thus opening up for e.g. quantitative optical CT measurements of opaque samples. The approach is based on a technique called Structured Illumination (SI), which is commonly employed within microscopic imaging to enhance the depth-resolution. The concept of SI applies for many types of source-detector arrangements and the configuration employed in this paper relies on side-scattering detection. A nPAG polymer gel phantom was irradiated using 6 MV beam. Three-dimensional information was obtained by translating the sample perpendicular to the direction of light, thus sequentially probing different sections. These were then stacked together to form a 3D representation of the sample. By altering the polarization of the laser light during the data acquisition it was discovered that the aggregates responsible for the scattering of light followed Rayleigh scattering, implying that their individual sizes are smaller than, or in the order of, 500 nm.

1. Introduction

Multiple scatter of probe light with gel dosimeters limits the accuracy of transmission measurements. Development of more transparent 3D dosimeter [1] materials will minimize this problem. However, there exist several promising materials that would be more valuable if they could be optically scanned by a method that is less sensitive to multiple scatter. The geometry of the optical CT scanner is also important. Broad beam scanners have lower dynamic range than single ray scanners for scattering materials. Small acceptance angles are effective at stray light rejection. But can lead to relatively large optical CT scanners. Large diameter, telecentric optics is cost prohibitive for proposed clinical instruments. Scanned laser CT instruments are promising for scatter rejection. However, imaging through scattering media is a common problem and there may be many more optical approaches that should be investigated.

In this paper we present a novel optical diagnostic tool that corrects for this undesired contribution of multiply scattered light, thus opening up for e.g. quantitative optical CT measurements of opaque samples. The approach is based on a technique called Structured Illumination (SI), which is commonly employed within microscopic imaging to enhance the depth-resolution.
2. Material and methods

2.1 Structured Illumination

SI is an optical imaging technique [2], which can be combined with several different source-detector arrangements, such as back- and side scattering as well as transmission [3, 4]. The key feature with the technique is to add a recognizable structure to the illumination field, which will permit certain post-processing of the acquired data. Even though many different structures will suffice, it is mathematically convenient to utilize a sinusoidally varying fringe pattern, as shown in figure 1(a), as this simplifies the post-processing routines.

To explain the technique, consider a non-absorbing opaque sample into which an obstruction is placed (see figure 1(b)), being illuminated with a wide laser beam that has an intensity profile according to that shown in figure 1(a). The transmitted light falls upon a screen, positioned behind the sample. A portion of the incident light will scatter away from the optical path, never to be detected. Other photons will propagate through the sample exit unperturbed, thus leaving a faithful shadow of the obstruction on the screen. Equally important, the spatial distribution of these undisturbed photons will follow the sinusoidal intensity pattern that was superimposed on the beam profile. A third group of photons will be scattered, either once or several times, yet still fall upon the screen. In contrast to the unperturbed light, the position where these photons end up on the screen is more random, meaning that (1) they will not cast a faithful shadow of the obstruction and (2) they will be independent on the sinusoidal intensity pattern. Removing this latter intensity contribution is key in order to probe a turbid sample accurately. Separating these two contributions can be achieved by acquiring three images, between which the incident line structure is shifted 1/3 of the sinus period. A filtered image (IS) is then attained by calculating

\[ I_5 = \sqrt{(I_0 - I_{120})^2 + (I_0 - I_{240})^2 + (I_{120} - I_{240})^2} \]

where \( I_X \) denotes the three intensity modulated laser images (\( X \) is the spatial phase of the modulation). Equation (1) effectively removes all image features that are identical in the three images while all unique features are preserved. Since the end position (on the screen) for the scattered photons is random their intensity contribution will be nearly identical in all three images and thereby removed in equation (1). In contrast, by shifting the line structure the unperturbed light appears different in the three raw data images and is therefore not filtered out in equation (1). Figure 2 shows an example of a SI measurement performed for transmission imaging according to the setup given in figure 1(b). Here one of the three modulated beams is shown, together with a comparison between a non-filtered transmission image and an SI image. Notice how the contrast (between the obstruction and its

![Figure 1](image1.png)

**Figure 1.** (a) Example of a laser beam with a sinusoidally modulated intensity field. (b) Transmission measurement of a turbid sample, the different possible outcomes for the photons are color-coded, red = unperturbed light, green = undetected scattered light and blue = scattered (singly and multiply) detected light.

![Figure 2](image2.png)
surrounding) is considerably reduced in the non-filtered image. This reduced contrast is, as explained, a direct consequence of detecting scattered- and multiply scattered light and attempting to quantify the optical properties of the sample using the non-filtered image would render large errors.

2.2 Experimental set-up
As mentioned, the concept of structured illumination applies for many types of source-detector arrangements and the configuration employed in this paper relies on side-scattering detection. In the current configuration, laser light with a wavelength of 532 nm is formed into a thin (vertical) sheet of light and the sinusoidal modulation is applied along the vertical direction (see figure 3). The line structure is created by guiding the laser light through a transmission grating, comprising alternating opaque and transmissive stripes, which effectively casts shadows with a sinusoidal shape. Light that is scattered at a 90 degrees angle is collected by a CCD detector. Three-dimensional information is obtained by translating the sample perpendicular to the direction of light, thus sequentially probing different sections. These are then stacked together to form a 3D representation of the sample.

2.3 Preparing and irradiation of polymer gel phantoms
The normoxic polyacrylamide gel (nPAG) used in this experiment contained 89% w/w ultra-pure deionised water, 3% w/w acrylamide, 3% w/w N,N’-methylenebisacrylamide, 5% w/w gelatine and 10 mM tetrakis(hydroxymethyl)-phosphonium chloride (chemicals from Sigma Aldrich, Germany). The mixing procedures are described elsewhere [5]. Two gel phantoms from the same batch were prepared (100x50x40mm³). One sample was used for background subtraction and the other sample received 3 Gy in dose maximum using a 6 MV 2x2 cm² beam entering the short end.

3. Results and discussion
Figure 3 shows an overview of the result for the performed measurement, the top row shows 2D sections while 3D views of the sample are given in the bottom row. The XY-view, in which the data is averaged over the Z-direction, shows a stronger signal where the x-ray beam enters the sample, as is expected due to attenuation. The same trend is seen in the YZ-view. The acquired data also suggests that there is a weak, yet detectable inhomogeneity along the Z-direction. This is most probably an image artifact arising because of the Z-scanning; as the sample is traversed along the Z-direction, the camera focus changes because of an increased optical path for the signal beams. The effect can be reduced by choosing a high f-number, which was the approach used during the current measurement, yet ultimately the effect must be corrected for.

The presented data is, at present, not quantitative. Two approaches should be considered in order to achieve this end. First, the Rayleigh scattering intensity can be quantified, given that a reference signal can be provided. Different reference samples could considered, such as a cuvette with a given amount

Figure 2. Example of an SI measurement on a turbid sample based on transmission imaging. (a) A sinusoidally intensity modulated laser light beam. (b) Transmission image without any filtering, with an estimated contrast of 49% (between obstruction and its surrounding). (c) SI transmission image where all scattered light has been filtered out, showing an estimated contrast of 98%.
of dye giving rise to a certain fluorescence signal or a sample with a well-defined number of scattering particles. Second, the incident and transmitted light intensity could be measured simultaneously and mathematically coupled to the scattered light intensity in each pixel to give an estimate of the local extinction coefficient, as demonstrated by Wellander et al [6].

![Figure 3](image)

**Figure 3.** Overview of the results. Note that the 2D-sections are averaged along the third dimension.

4. Conclusion
In summary, the presentation describes the possibility of employing an imaging technique known as Structured Illumination to eventually use as means to quantify the radiation dose in 3D dosimetry. Relying purely on visible light, the approach has the prospect of reducing both cost and experimental complexity. In this first investigation, SI is combined with side-scattering detection, where 3D information was obtained by mounting the sample on a translational stage. Other experimental arrangements have been discussed and an example result from a transmission imaging setup has been shown.

By altering the polarization of the laser light during the data acquisition it was discovered that the aggregates responsible for the scattering of light followed Rayleigh scattering, implying that their individual sizes are smaller than, or in the order of, 500 nm. This further implies that it could be possible to eventually determine the size of the scattering particles by probing the sample at two (or more) different wavelengths. Whether this in turn could be coupled to the radiation dosage needs, however, to be investigated.

5. References
[1] Baldock C et al 2010 *Phys. Med. Biol.* **55** R1-63
[2] Neil M A A et al 1997 *Opt. Lett.* **22** 1905-7
[3] Kristensson E et al 2008 *Opt. Lett.* **33** 2752-54
[4] Kristensson E et al 2012 *Opt. Express* **20** 14437-50
[4] Ceberg S et al 2010 *Phys. Med. Biol.* **55** 4885-98
[5] Wellander R 2011 *Meas. Sci. Technol.* **22** 125303-15