A novel optical calorimetry dosimetry approach applied to an HDR Brachytherapy source

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Abstract. The technique of Digital Holographic Interferometry (DHI) is applied to the measurement of radiation absorbed dose distribution in water. An optical interferometer has been developed that captures the small variations in the refractive index of water due to the radiation induced temperature increase \( \Delta T \). The absorbed dose \( D \) is then determined with high temporal and spatial resolution using the calorimetric relation \( D = c \Delta T \) (where \( c \) is the specific heat capacity of water). The method is capable of time resolving 3D spatial calorimetry. As a proof-of-principle of the approach, a prototype DHI dosimeter was applied to the measurement of absorbed dose from a High Dose Rate (HDR) Brachytherapy source. Initial results are in agreement with modelled doses from the Brachyvision treatment planning system, demonstrating the viability of the system for high dose rate applications. Future work will focus on applying corrections for heat diffusion and geometric effects. The method has potential to contribute to the dosimetry of diverse high dose rate applications which require high spatial resolution such as microbeam radiotherapy (MRT) or small field proton beam dosimetry but may potentially also be useful for interface dosimetry.

1. Introduction
Interferometry is a widely applied investigative technique in many fields of science and industry where it is typically utilized to measure small displacements and refractive index changes. As the refractive index of water is temperature dependent, interferometry can be used to measure very small temperature changes in a transparent water cell. The concept of our method, namely Digital Holographic Interferometry (DHI), is illustrated in figure 1. A laser beam is split into two arms, with one arm traversing the water cell and the other serving as a reference beam. Both arms are recombined on the camera plane to produce an interferogram, also referred to as a hologram. A temperature rise in the cell due to irradiation is encoded in subsequent interferograms as a change in the phase difference of the interfering light waves. From this information it is possible to determine the spatial distribution of the change in refractive index \( \Delta n \), from which the temperature change and ultimately the absorbed dose to water can be inferred. The output of DHI is digitally reconstructed and unwrapped 2D phase maps from which a time-series of two dimensional maps of the absorbed dose at each time instance can be obtained.
The idea to use holographic interferometry for radiation dosimetry dates back to 1971 and was demonstrated by Hussman [1] and Miller et al. [2] using holographic photo paper as the recording medium. Nicolau et al. [3] and more recently Ackerly et al. [4] also worked on related optical calorimetry. The current work uses a different optical set-up and modern digital image recording and reconstruction by means of the Fresnel transformation which enables the acquisition of images in video frequency rather than at a single time instance.

The ultimate aim of this work is to develop a digital interferometer capable of accurately measuring absolute 4D deposition of radiation dose in water. The current work describes our initial prototype which we applied to dosimetry of a conveniently available high dose rate (HDR) brachytherapy source for first proof-of-principle results. Results are presented for dosimetry in two spatial dimensions plus a times-series.

Figure 1: Illustration of the principles of DHI as applied to radiation dosimetry.

2. Methods and Materials
A Lensless Fourier Transform Digital Holography configuration was selected to simplify both the experimental set-up and the reconstruction algorithm [5]. The main difference to previous approaches is that for convenience the reference beam is converted into a spherical wave. A standard lab He-Ne laser light source was used with a PixeLINK™ 1.3 Megapixel CMOS Monochrome camera as the holographic recording medium, with 6.7μm pixel resolution. Numerical reconstruction and analysis was carried out in in-house developed MATLAB (The Mathworks, Natick, MA, USA) code. Figure 2 shows the optical components of the detector.

Figure 2: Set-up with the red line marking the laser beam.

The temperature distribution $\Delta T$ in the water cell after irradiation was determined by reconstructing the phase difference encoded in the holograms, unwrapping of the phase information [6] and by making use of the relationship between optical pathlength/refractive index and temperature.
Dose $D$ was then calculated by the calorimetric relation: $D = c \Delta T$, where $c$ is the specific heat capacity of water. As the sensitivity of the approach scales with the magnitude of the temperature change a high dose rate (HDR) Ir-192 brachytherapy source with 480.2 GBq activity was selected for a proof-of-principle measurement. 1 Gy absorbed dose corresponds to a rise in temperature of $\sim 0.0003^\circ C$ and a phase change of $\sim 0.002$ radians or $\sim 0.1^\circ$. The source was housed within a GammaMed Plus afterloader and the total irradiation time was 420 seconds. Images were taken at a frequency of 1.4 Hz, with an exposure time of 15 ms. The initial absolute temperature was obtained by the use of a digital thermometer. Measured results were compared to the dose distribution as modelled by the Brachyvision treatment planning system.

3. Results

Figure 3a) shows the recorded hologram as captured by the CMOS sensor, with the tip of the HDR source applicator visible at the bottom. Figure 3b) shows the hologram after reconstruction, phase unwrapping and conversion to a 2D temperature map. The location of the profile in the Brachyvision model is shown in c).

The relative dose distribution along a profile measured by DHI and that calculated in Brachyvision is compared in figure 4a. To show the time resolving capability of this approach several instances from the time-series obtained with DHI are shown in figure 4b, revealing the increasing dose and the subsequent flattening out of the distribution post-irradiation due to heat diffusion.

4. Discussion

Research into many new therapeutic applications of radiation, each with its unique dosimetric needs, has presented us with dosimetry challenges that have not been faced before. Spatial calorimetry has a possibility to contribute to the dosimetry toolbox in fields such as microbeam radiation therapy (MRT), narrow field proton beam dosimetry, high dose rate brachytherapy (HDR), or interface
dosimetry, amongst others, due to its potential to non-invasively resolve small temperature gradients in water to sub-millimetre accuracy.

The application of digital holographic interferometry for radiation dosimetry, a novel optical calorimetry method, has been presented and initial results with an HDR brachytherapy source show that it is indeed possible to use DHI for radiation dosimetry. The results obtained and shown in figures 3 and 4 represent only the relative dose distribution as no reliable absolute calibration had been carried out. Nevertheless the results are encouraging as the relative dose distribution is in agreement with the model from the treatment planning system despite some inherent noise in the signal. The results presented were essentially the raw data as no noise filtering was applied to the captured holograms nor in the Fourier domain during the reconstruction. However, a 3x3 median filter was applied to the phase map. It is also anticipated that with higher quality optical components as well as a higher spec camera the signal-to-noise ratio can be improved. Figure 4 shows the time resolving capabilities of the approach and indicates the magnitude of the heat diffusion. It is indeed an area of further work to model the well-defined heat dissipation as a function of time.

A current limitation of the approach is that the dose determined at each point represents a line integral perpendicular to the direction of radiation incidence and thus underestimates the dose slightly. If the radiation source has rotational symmetry such as for narrow pencil beams or at a distance from a Brachytherapy source, the Abel Integral [7] can be used to approximate the corrected 3D dose distribution. For non-symmetric dose distributions full volumetric resolution may be achieved through the use of multiple angles and tomographic reconstruction.

5. Conclusion
A prototype digital holographic interferometer has been successfully applied to measure radiation dose distributions from an HDR source, thus establishing the potential for use of the technique as a radiation dosimeter for HDR applications [8]. A time-series of two dimensional maps proportional to absorbed dose were acquired and relative dose profiles taken from these were in agreement with modeled results from Brachyvision. The method is calorimetric, directly measuring the spatial distribution of absorbed dose to water at high resolution, independently of beam type, energy, and fundamentally the dose rate (apart from heat diffusion), without perturbing the radiation beam. The next step is an absolute calibration of the system and the application of the DHI set-up to the measurement of radiation fields where the above properties may contribute towards overcoming current dosimetric difficulties.

6. References
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