A benchtop UV irradiator for 3D dosimetry laboratories with dose considerations in a spinning NMR test tube

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Abstract. Many different chemical radiation dosimeters have been fabricated over the last 20 years. In the search for new dosimeters, next to being sensitive to clinical radiation doses, several other physicochemical characteristics need to be satisfied, such as stability of the dose response, spatial integrity, temperature independence, dose rate independence and tissue equivalence. The development of new dosimeters is often hindered by a limited access to radiation facilities to irradiate hundreds of test tubes or cuvettes to study these physicochemical properties. To facilitate this basic experimental research, we propose the use of an inexpensive UVC irradiator. While care is required in extrapolating the results obtained with UV radiation to high energetic X-rays, for several studies, a UV irradiator is a handy tool for first line investigation of new dosimeters. In this study, we calculated the dose distribution in a cylindrical test tube when being rotated during UV exposure. A quantitative analysis allows the optimization of the set-up to obtain dose rates in the sample in similar order of magnitude that are delivered at a clinical Linac. Regardless the usefulness of a UVC irradiator in the laboratory for preliminary testing, it should not be a complete replacement for measurements with high energetic X-rays.

1. Introduction
Several basic experimental studies on new potential 3D dosimeters require the radiation of hundreds of samples [1-26]. Basic experimental studies aim at developing new radiation dosimeters [2-4, 19, 20, 22, 25, 26], obtaining a better understanding of the radiation chemistry of 3D dosimeters [3, 5-8, 17, 18, 21], assessing and optimising the dosimetric performance of the dosimeter in terms of dose sensitivity [2, 9-16, 20, 22, 23], stability [2, 16, 22, 25], temperature dependence [16, 20, 22, 24], dose rate dependence [16, 20, 22-24] and spatial integrity [14, 15, 16, 20, 22, 23, 25]. A fast assessment of the radiation response of new dosimeters can be assessed by exposing the potential dosimeter to UVC light. In order to relate the absorbed dose of a UVC source to the absorbed radiation dose delivered with high energetic X-rays, the light propagation through the vial needs to be considered. In this study, we relate the UVC exposure of a 5 mm NMR tube while spinning to effective radiation dose.

2. Methods and Materials
2.1. UV irradiator
A UV irradiator has been fabricated using a 9W germicide UV lamp (Philips TUV PL-S 9W/2P). The UVC power produced by the UV lamp amounts to 2.3 W. To protect the user from accidental UVC exposure, a cover was constructed from white polyurethane plates. The interior of the cover box is coated with aluminium foil tape. A UVC light intensity meter (UVC-254, ISO-9001) is also mounted inside the enclosure to monitor any fluctuations or drift in light intensity output. A cylindrical hole is made in the
enclosure for an NMR test tube. To attenuate the light intensity to levels that correspond with the dose rate obtained with a clinical Linac (6 Gy/min), the UVC light bulb is partially shielded with thin microscopy glass plates and only light reflected on the backside wall of the enclosure is used to expose the samples. Shielding glass plates were added until the UVC irradiance measured with the UVC light intensity meter matched the target irradiance and a flat irradiance profile was obtained at the sample location. When switching on the cold UVC light bulb a slow transient in the order of 2 minutes was found (figure 1b). While irradiating the samples, the light bulb was allowed to warm up for at least 5 minutes and the UVC irradiance was recorded at all times and the actual irradiance time course was taken into account while calculating the UVC dose.

Figure 1. UV irradiator set-up (a) and transient UV irradiance of the UVC germicide lamp (b).

2.2. Relating UV light irradiance to radiation dose

Irradiance is a radiometric quantity which is the radiant flux $\phi_e$ (in Watts) per unit surface area $A$ (m$^2$) and is thus expressed in W/m$^2$.

$$E_e = \frac{\partial \phi_e}{\partial A} \left( \frac{W}{m^2} \right)$$

(1)

In an absorbing medium, the irradiance is a function of depth according to an exponential decay:

$$E_e(x) = E_e(0) e^{-\mu x}$$

(2)

where $\mu$ is the light attenuation coefficient for UVC light in the medium.

The light energy absorbed in an elementary volume and per unit of time ($\dot{D}_v$) is the difference between incoming and outgoing light (figure 2) and can thus be written as:

$$\dot{D}_v(x) = \lim_{\Delta x \to 0} \frac{E_e(x) - E_e(x + \Delta x)}{\Delta x} = -\frac{\partial E_e}{\partial x} = \mu \cdot E_e(x)$$

(3)

The absorbed dose of UVC light defined as energy absorbed in a medium per unit of mass within an exposure time span $t_{exp}$ is then given by

$$D_{UV}(x) = \int_0^{t_{exp}} \frac{\dot{D}_v(x)}{\rho} \, dt = \int_0^{t_{exp}} \left( \frac{\mu \cdot E_e(x)}{\rho} \right) \, dt$$

(4)

where $\rho$ is the mass density of the medium. The term between brackets in equation 4 is the dose rate.

Figure 2. Some radiometric quantities and absorbance in an elementary volume element of absorbing medium.
2.3. **Light tracing simulation**

To calculate the absorbed dose in a 5 mm NMR test tube, the propagation of the light through the test sample needs to be determined for which a ray tracing algorithm was developed in Matlab. A total of 2000 incident rays were considered (note that only 40 rays are drawn in figure 2a and 3a for visibility). Fresnel laws were used to calculate the fraction of transmitted light at every interface between two different media. Snell’s law was used to determine the angle of refraction.

The attenuation of the irradiance along each ray is calculated according to an exponential attenuation using the absorption coefficient for the corresponding material (glass, PDMS or gelatine gel). Convergence of light rays will increase the intensity. Once all rays are calculated, the density of rays in every pixel is calculated which results in an irradiance map. The irradiance map can be converted into a dose map, using equation 4.

Two scenarios were considered: 1.) In a first scenario, the sample is static with respect to the light source. The UV light is considered to have a planar propagation outside of the phantom. Only one side of the phantom is exposed to the UV light (figure 1, 2.) In a second scenario, the sample is spinning during exposure at a rate of 500 rotations per minute. In the latter scenario, the irradiance map is first converted to cylindrical coordinates and a radial integration is performed to derive the UV dose.

3. **Results and Discussion**

3.1. **Dose calculations for the UVC lamp**

![Figure 3](image-url)

*Figure 3.* Ray tracing (a) and light intensity flux in a static (b) and rotating (c) NMR spectroscopy sample containing a silicone-based dosimeter. A radial profile through the tube is also shown (d) showing the variation of dose in the sample.
The propagation of light rays and UVC dose rate maps for a Flexydos3D sample are shown in figure 2. Refractive indices and attenuation coefficients were based on literature values \( n_{\text{glass}} = 1.5; \ n_{\text{PDMS}} = 1.418 \) [27] and \( \mu_{\text{glass}} = 3.25; \ \mu_{\text{PDMS}} = 16.4 \) [28].

Because of the high attenuation coefficient, for a non-spinning sample, the dose distribution is very inhomogeneous (figure 2b). Most UVC light is absorbed on the exposed side of the sample but the converging light rays, also create some dose that extends more deeply in the sample. When the sample is spun during exposure, the dose is smeared out more homogeneously inside the sample. The dose rate in the center of the sample is about 20% of the dose rate on the edges.

For a gelatine gel sample, the dose distribution is more homogeneous (figure 3). The convergence of UVC light rays in the sample create a focusing effect with a slightly higher dose on the side opposite to the exposed surface. For a spinning gelatine gel sample, a more homogeneous dose distribution is obtained (figure 3c – d) because of the smaller attenuation coefficient.
3.2. Experimental validation

Some NMR tube samples were exposed to UVC light with the UVC irradiator for different exposure times and some were irradiated with 6 MV photon beams in the linear accelerator. The glass tubes were then broken and the removed irradiated Flexydos3D silicone samples were scanned in the dual wavelength conebeam optical CT scanner [29]. One sample was exposed to UVC light without spinning.

![Image of exposed samples and optical CT scan](image)

**Figure 5.** Photograph of the exposed samples and optical CT scan (b) through the different samples. Zoomed in image through both a non-spinning UVC irradiated sample (c) and a spinning UVC sample (d). The pixel resolution is \(225 \mu m \times 225 \mu m\). The diameter of the phantom is 4 mm.

4. Conclusions

An inexpensive benchtop UVC irradiator for 3D radiation laboratory’s is proposed. The dose rate in the UVC irradiator is adjusted to clinical X-ray dose rates by adding additional shielding. Some improvements in the design of the UVC irradiator will be made to fully optimize the dose delivery. The UVC irradiance meter will be coupled to a PC and the integrated dose will be monitored in real time so that the UVC lamp is switched off when the required dose is reached.

It is shown through computational simulations that by spinning cylindrical samples, a higher homogeneity can be obtained. In polymer gel dosimeter samples, a relatively uniform dose distribution is achievable in a 5 mm test sample while in silicone based samples where the attenuation coefficient for UVC wavelengths is high, the heterogeneity in the sample amounts to 1:5.

It is found that the dose response of dosimeters to UVC light is comparable but not exactly the same as the dose response of dosimeters exposed to high energetic X-rays. While the UVC irradiator is found as a useful tool in the development and characterization of 3D radiation dosimeters laboratory, it should
be noted that the radiation chemistry of dosimeters exposed to UVC light may be different from the radiation chemistry in high energetic X-ray beams. It is advisable to perform ultimate tests on the Linac.

5. References
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