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Design of an integral radiation dosimetry system optimized for modern medical applications

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Fricke gel dosimetry is a valuable method for in-phantom dose measurements in complex irradiation modalities like IMRT and BNCT. Implementation of this dosimetry technique requires dedicated instruments capable of measuring and further analysis immediately in situ at the radiation facility.
This work presents a novel and integral dosimetry system aimed to attain portability requirements. The method is based on Fricke gel dosimeters optically analyzed, thus offering several valuable advantages like tissue-equivalence and continuous 3D dose mapping.

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1. INTRODUCTION

Requirements for overall high performance of dosimetry systems increases due to the growing complexity of modern medical treatments. Non conventional treatment modalities like BNCT and hadrontherapy, as well as conventional modern methods like IMRT and tomotherapy might significantly improve diseases control.

The dosimetry system here presented employs Fricke gel solution as sensitive material. Thus, Fricke gel dosimetry versatility, like different chemical and isotopic sensitive material compositions, allows its application in different high performance ionizing radiation procedures [1, 2, 3, 4].

Dedicated methodologies and instrumentation were completely designed and constructed at LIIFAMIR^X's facility, in order to develop a portable tool for in clinical environment optical analysis of Fricke gel samples.

Specific radiation transport models were adapted with the aim of attaining relative simplified analiticaL techniques. Theoretical approaches are supported by analytic solution of Boltzmann's radiation transport equation.

As discussed in previous studies [2, 5], it is very important to have the possibility of carry out measurements at the radiation source facility. Moreover, an original Fricke gel dosimeters pre-irradiation technique allows an overall 10 % performance improvement in dose determinations [6]. Implementation of this technique requires samples' read out just few minutes after irradiation. Therefore, it becomes necessary to perform *in-situ* optical transmission measurements.

Additionally, the integral dosimetry system includes dedicated software for data acquisition and further processing [2, 5].

2. MATERIALS AND METHODS

Optical analysis theoretical justification

With the aim of providing support to the optical transmission analysis technique of Fricke gel samples, a suitable adaptation from Boltzmann's equation formalism is briefly presented. Although mathematically this deduction does not involve any complexity, it is required that each imposed analytic approximation must be carefully implemented in instrumentation design and experimental setup.

In absence of external radiation sources, Boltzmann's equation could be written as [7]:

$$\frac{1}{|\vec{v}|}\frac{\partial}{\partial t}\Psi + \vec{\Omega}\cdot\vec{\nabla}\Psi = -\mu\,\Psi + \int_{4\pi}\int \Psi K(\vec{\Omega}', E' \to \vec{\Omega}, E)\, dE'\, d\vec{\Omega}' \tag{2.1}$$

where $\Psi = \Psi(\vec{r}, \vec{\Omega}, E, t)$ represent the particle fluence (visible range photons in this case); $\vec{r}$, $\vec{v}$ and $\vec{\Omega}$ its position; propagation speed and direction; respectively. E is the kinetic energy; while t and μ state for time and linear absorption coefficient, respectively. Finally, K represents the scattering kernel.

Considering the steady-state regimen without external sources and assuming negligible scattering contributions, it follows that:

$$\frac{\partial}{\partial t}\Psi = 0 \tag{2.2}$$

Additionally, assuming monodirectional photon beam propagation, the Boltzmann radiation transport equation is reduced to the Lambert-Bier law [2, 7]:

$$\Psi(z) = \Psi_0 \, e^{-\mu z} \tag{2.3}$$

where μ represents the absorption properties of the dosimeter sensible material.

For dosimetry purposes, it is necessary to assess the correlation between visible light transmission images and the corresponding absorbed dose distributions. It can be demonstrated that in the proposed approximations, photon fluence is directly correlated with particle intensity I, thus for an appropriate constant β it holds that $\Psi = \beta I$. Hence, there is a direct relationship between photon beam intensity and Optical Density differences (ΔOD)

$$ODD = log_{10}\left[\frac{I_b}{I_a}\right] \tag{2.4}$$

where I_b and I_a refer to the recorded transmission image intensities before and after the Fricke gel samples are exposed to ionizing radiation, respectively.

It has been shown in previous studies [2, 8, 9] that optical density variations of Fricke gel solutions doped with Xylenol Orange correspond to the visible range maintaining its dependence upon the absorbed dose D. Actually, it has been experimentally evidenced [2, 8, 9] that ΔOD is linearly correlated to D within a conveniently restricted range.

The pixel-to-pixel absorbed dose $D(i, j)$ is obtained from the transmission images once offset corrections are already included, by means of [5]:

$$D(i, j) = \alpha \, \Delta OD(i, j) \tag{2.5}$$

where the constant α represents the dosimeter response calibration factor.

Design and construction of the optical transmission measurement equipment

There are relevant motivations for considering the in-home design and construction of dedicated visible light analysis instrumentation. First, the specific requirements, described in the theoretical background above, have to be accurately achieved verifying each proposed approximation. On the other hand, there is no commercially available equipment with the required characteristics. Moreover, one of the main scopes of this work is to develop a analysis instrument attaining comfortable portability as innovation.

In order to check that the proposed prototype might achieved the mentioned requirements, the first feature regards the steady-state condition of Boltzmann equation, which means that the light source must have a stable emission intensity over time.

If negligible scattering contributions are considered, it implies that the registered signal should arise only from primary beam absorption. For this reason it is necessary to prepare dosimeter samples having optimum thicknesses as the existing compromise between reducing the contributions due to scattering processes originating from the sample and a practical implementation of instrumental technique. Furthermore, it is required that the detector must be accurately aligned with the sample and the light source in order to minimize scattering signal and also satisfying monodirectional beam propagation condition.

The visible light absorption properties variations must be caused only by chemical changes generated from the sensitive material dose absorption. For this reason, it is important preparing Fricke gel samples having uniform thickness. A set of beam diffusing and flattening is incorporated to the light source in order to attain a photon beam, which might be acceptable considered as a uniform wavefront. Finally, the requirement of photon beam monochromaticity is achieved by the incorporation of optical filters.

It is known that the dose response of the Fricke gel doped Xylenol Orange presents an absorption peak at 580 nm and a transmission peak at 430 nm (low intensity in relation to the absorption peak) [2, 9]. For this reason, the equipment allows optical filters exchanges even during measurement process. Then, complementary information of the same two-dimensional dose distribution could be obtained.

Figure 1 shows a sketch of the correspondence between the proposed analytic model and the constructed instrumentation. The detection system of the equipment consists of a high-resolution CCD camera (Starlight Xpress, model SXV-H5) coupled with optical lens.

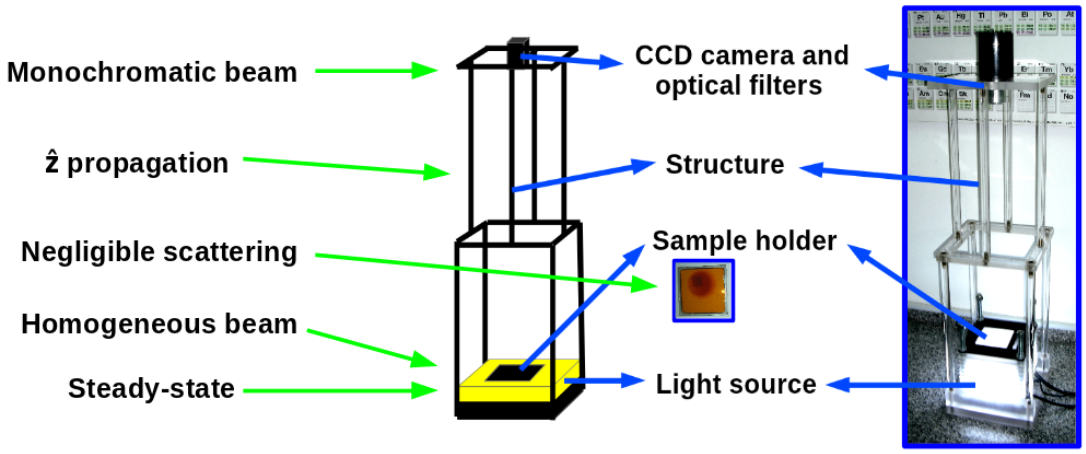

Figure 1: Design sketch and real set-up of the built equipment. Instrumental implementation of each analytic approximation is point out.

3. RESULTS AND DISCUSSIONS

Optical transmission measurement equipment response characterization

Validation of the whole in-home constructed equipment was necessary in order to check its feasibility and reliability. Read out stability and reproducibility were the first characteristics to be investigated.

In order to study response stability, images acquired at different times were compared. Due to the insertion of a reference (gray level scale) placed in the sample holder, it was possible to assess differences between successive images by comparing pattern signal. Thus, response reproducibility for different acquisitions was performed averaging profiles corresponding to the pattern gray level scale. The approach was to choose arbitrarily an average reference profile and to get the linear fit of each profile versus the reference one. In this sense, an ideal stability should perfectly match the

profiles, meaning that the linear coefficient equals to 1. The obtained slopes values for a wide set of acquisitions are shown in the Figures 2 and 3. Figure 2 shows response variations for an interval of 330 minutes. It can be appreciated from Figure 2 that the instrument exhibits a rather stable response. Actually, obtaining fluctuations between different acquisitions less than 0.5 %.

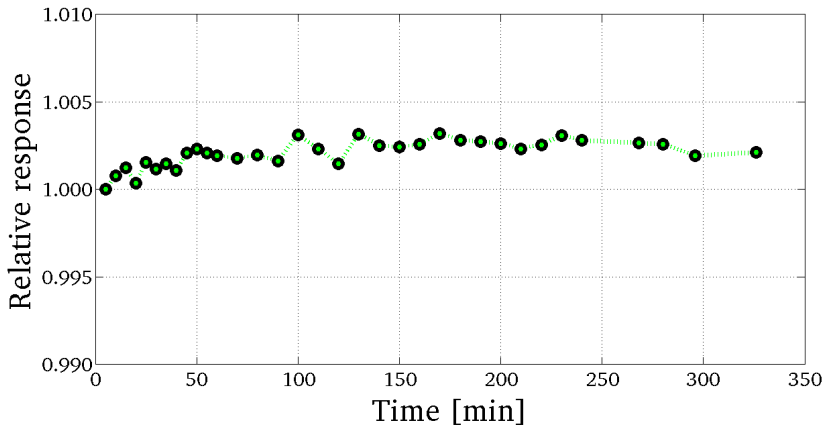

Figure 2: Response stability characterization (uncertainties are less than 10^{-3}.

At about the first hour, a thermal effect is evident, associated primarily to the illumination source, leading to a minor relative signal increase. This effect modifies finally the readings no more than 0.5 %. Anyway, the dedicated post acquisition processing accounts for this effect by means of pattern based correction algorithms.

Besides, successive acquisitions were performed with the aim of characterizing the reproducibility of the equipment response. This time, lectures were compared for different test configurations that were characterized by means of varying two parameters: the "on time" (since the apparatus is turned on until the first signal is acquired) and the "off time" (since the machine is shut down and re-started). Parameters values and the corresponding results are shown in Figure 3.

	On time [*min*]	Off time [*min*]
Configuration 1	2	10
Configuration 2	10	2
Configuration 3	2	2

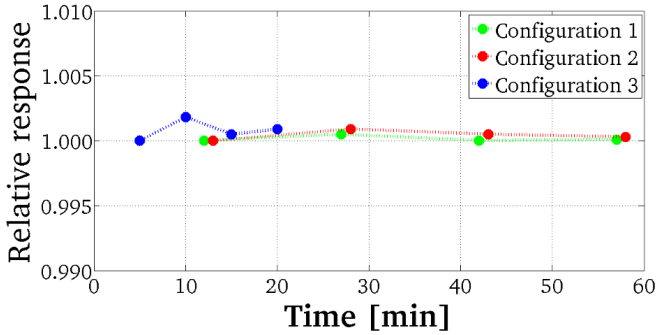

Figure 3: Response reproducibility characterization (uncertainties are less than 10^3). Configurations' parameters are shown in the table. The first point (not plotted) for each configuration was taken as reference value.

According to the obtained results the equipment for optical transmission attains a reproducible response between different lectures with minor variations (less than 0.2 %).

As an overall test, there was quantified integral response of the equipment. It was realized directly by an histogram containing all the comparisons performed between different measurements. From this process, it was possible to ensure that the built equipment achieved a reliable comprehensive response, with variations between different readings less than 1 %.

Dosimetry system feasibility

Once equipment characterization was already performed, it was possible to check its feasibility as part of the integral dosimetry system. Samples of Fricke gel dosimeter layers were prepared and irradiated with photon beams from a conventional X-ray tube. Dosimeter layers were optically analyzed with the developed equipment and data processing was performed with the associated subroutines. Sensitive material elaboration protocol is described in previous works [5]. Data processing and visualization is provided by the dedicated software developed in MATLAB platform (The MathWorks Inc, Natick MA, USA).

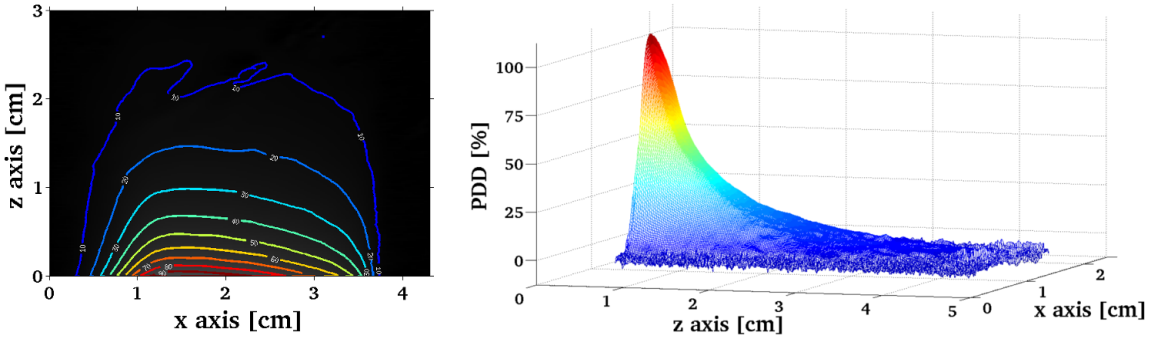

Figure 4: *Left:* Isodose curves plotted on the $|DeltaOD$ distribution. *Right:* 3D visualization of the absorbed dose distribution.

4. CONCLUSIONS

This work has showed that the proposed analytic model is suitable for its accurate experimental implementation for optical transmission analysis. The model has a robust support by radiation transport theory, thus ensuring its validity. Additionally, the equipment designed and constructed following the proposed analytic model has a dependable integral response achieving overall uncertainties less than 1 %.

The innovative portable characteristic of the constructed equipment allows *in-situ* applications of Fricke gel dosimetry, therefore enabling its utilization for daily clinical scopes as well as making easier its use at irradiation facilities like nuclear reactors (BNCT) or ion beam treatments (hadrontherapy).

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