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Energy dependence of Fricke-xylenol orange gel and gel based on Turnbull blue for low-energy photons

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Abstract. The paper describes the energy dependence of two types of radiochromic gels, a Fricke-xylenol orange gel (FX gel) and a gel based on Turnbull blue (TB gel), on low energy photons between 14 and 145 keV. Gel samples were irradiated at reference photon fields at the Czech Metrology Institute and evaluated by two independent optical methods. Measurements revealed that the response of the TB gel is independent on photon energy down to at least 14 keV photons, while the FX gel is energy dependent for photons below roughly 50 keV.

1. Introduction

One of the aims of the Joint Research Project "Metrology for radiotherapy using complex radiation fields" (MetrExtRT) [1], a collaboration of European metrological institutes, is to determine the absorbed dose-to-water distribution around miniature electronic brachytherapy X-ray sources INTRABEAM® (Carl Zeiss, Germany) and AXXENT® (XOFT, USA). The dose distribution should be determined by radiochromic gels therefore information about gels energy dependence is necessary. Although there are papers describing the energy dependence of the FX gel (e.g., [2]), no detailed study related to the energy dependence has been done on the TB gel.

2. Materials and Methods

2.1. Cuvettes

Classic spectrophotometric cuvettes with inner dimensions of 1.0 × 1.0 × 4.5 cm^3 and 0.1 cm thick polystyrene walls were used. In order to avoid photon attenuation one wall was removed and replaced by (6.03 ± 0.14) µm thick transparent Mylar foil. The cuvettes were faced towards the beam by this wall during irradiation.

2.2. *Fricke-xylenol orange gel*

The Fricke-infused xylenol orange ion indicator gelatine-based gel (FX gel) was firstly described in [3]. It is the most often used radiochromic gel because of its high dose sensitivity. A drawback is the diffusion of dose patterns [4] due to which the evaluation of dose response should be done shortly after irradiation. Composition of the FX gel was as follows: deionized water (96% w/w), edible gelatin (Natura, Czech Republic; 4% w/w), ferrous ammonium sulphate (0.5 mM), xylenol orange (0.05 mM), and sulphuric acid (50 mM). Finished gel in liquid form was poured into the cuvettes and put into a refrigerator to solidify.

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2.3. *Gel based on Turnbull blue dye*
The radiochromic gel based on Turnbull blue dye (TB gel) uses phytagel instead of more common gelatin. It has lower dose sensitivity than the FX gel but it does not suffer from diffusion of dose patterns [4]. Composition of the TB gel was as follows: deionized water (99.75% w/w), phytagel (Sigma Aldrich®; 0.25% w/w), potassium ferricyanide (0.5 mM), ferric chloride (0.5 mM), and sulphuric acid (1.0 mM). Finished gel in liquid form was poured into the cuvettes and put for the whole night into a refrigerator to solidify.

2.4. *Irradiation*
High-dose-rate X-ray spectra [5] and ^{60}Co photon beam [6] were utilized for the experiment due to their high air kerma rate necessary for delivering sufficient dose in reasonable time. Parameters of photon beams and the reference values of air kerma at the reference point are presented in Table 1. The reference point was the front wall (Mylar foil) of a cuvette. The targeted air kerma was 4 Gy and 15 Gy in case of FX gel and TB gel, respectively.

Table 1. Parameters of photon beams and air kerma rate at the reference point.

Beam quality	Mean energy (keV) [5]	Air kerma rate (Gy/h)[c]
H020[a]	14	16.2
H030[a]	20.1	15.7
H060[a]	38.1	11.6
H100[a]	57.4	14.9
H200[a]	99.4	15.1
H280[a]	145.1	22.2
^{60}Co[b]	982.4	78.4

[a] High-dose-rate X-ray spectra [5]. The number means bias voltage in kilovolts.
[b] Chisobalt radiotherapeutic unit. For this energy only, a 4 mm thick PMMA sheet was placed just in front of the cuvettes. It is the reference photon energy.
[c] At the front wall of cuvettes with gel.

2.5. *Monte Carlo simulations*
The aim of the Monte Carlo (MC) simulations was to obtain, for each gel and each photon beam, a conversion from reference air kerma at the reference point to absorbed dose-to-gel averaged over the whole volume of the gel in a cuvette. The MC simulations were performed using a general-purpose code MCNPX™ in version 2.7E [7]. A simple model of experimental geometry included a cuvette with the gel, a realistically defined photon beam and, in case of ^{60}Co beam, a 4 mm thick PMMA plate in front of the cuvette to achieve electron equilibrium.

2.6. *Evaluation of gel response*
Gel response was evaluated by two independent optical methods: by measurement of spectrophotometric absorbance with a UV-VIS spectrophotometer and by determination of a CCD absorbance from photographs taken with a sensitive CCD camera [8].

3. Results
MC simulated dependences of conversion factors from reference air kerma to mean absorbed dose-to-gel averaged over the whole volume of gel inside a cuvette are presented in figure 1. The mean absorbed dose inside the gel per unit air kerma at the cuvette front wall significantly decreases for photon energies below 50 keV due to increasing photon self-absorption with decreasing energy.

Figures 2 and 3 show measured energy dependence of both radiochromic gels. Data are normalized to the ^{60}Co beam gel response. The results are in agreement with previous investigations done for the limited range of photon energies [9]. The TB gel does not show the energy dependence for low energy photons. The assumption is that this is caused by very high weight fraction of water in the gel reaching 99.75%. However, the measurement uncertainties are higher compared to the FX gel due to lower dose

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response of the TB gel. Although irradiated to lower dose the FX gel responses were higher and the uncertainties of FX data are lower. This gel is energy dependent for low energy photons where the response decreases by 8% and 20% for high-dose-rate X-ray spectra with the mean photon energy of 20 keV and 14 keV, respectively.

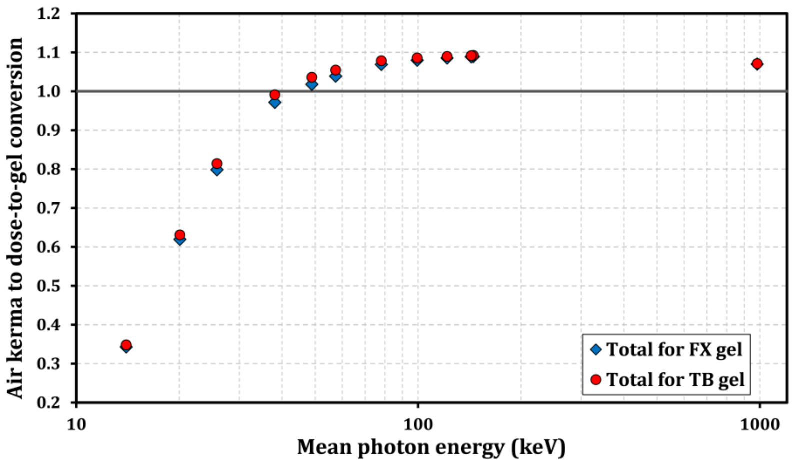

Figure 1. Dependence of the conversion factor from reference air kerma to dose-to-gel as a function of mean photon energy for FX gel (blue diamonds) and TB gel (red circles). The plot includes more high-dose-rate X-ray beams [5] than used in the experiment. Data point around 1000 keV corresponds to ^{60}Co beam with 4 mm PMMA placed in front of a cuvette.

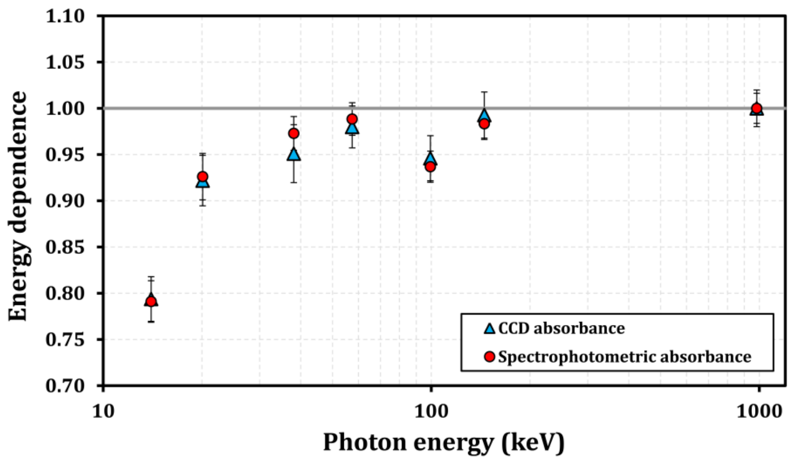

Figure 2. Energy dependence of the FX gel as determined by measurement of CCD absorbance (blue triangles) and spectrophotometric absorbance (red circles).

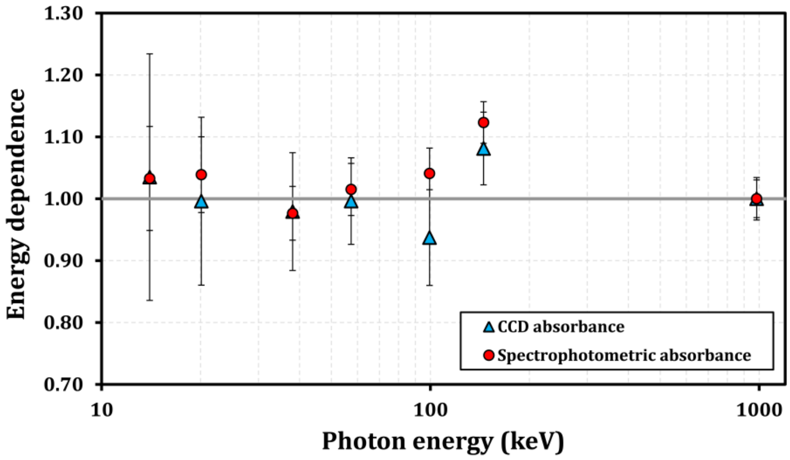

Figure 3. Energy dependence of the TB gel as determined by measurement of CCD absorbance (blue triangles, larger uncertainties) and spectrophotometric absorbance (red circles, smaller uncertainties).

It is noted that the same behavior of gels energy response is obtained by both evaluation methods – optical spectrophotometry and photographing by a CCD camera.

4. Conclusions

The energy dependence of two types of radiochromic gel dosimeters was determined for X-ray photon beams with mean energy from 14 keV to 145 keV, and for ^{60}Co photons (mean energy of photon spectrum 982 keV). The TB gel does not show energy dependence, while sensitivity of the FX gel decreases at photon energies below 40 keV. The energy dependence of the FX gel should be taken into account in planned measurements of spatial dose distribution around electronic brachytherapy X-ray sources using this radiochromic gel.

5. Acknowledgement

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