NOTE

On the use of polychromatic cameras for high spatial resolution spectral dose measurements

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Abstract

Objective. Despite the demonstrated benefits of hyperspectral formalism for stem effect corrections in the context of fiber dose measurements, this approach has not been yet translated into volumetric measurements where cameras are typically used for their distinguishing spatial resolution. This work investigates demosaicing algorithms for polychromatic cameras based spectral imaging. Approach. The scintillation and Cherenkov signals produced in a radioluminescent phantom are imaged by a polychromatic camera and isolated using the spectral formalism. To do so, five demosaicing algorithms are investigated from calibration to measurements: a clustering method and four interpolation algorithms. The resulting accuracy of scintillation and Cherenkov images is evaluated with measurements of the differences (mean ± standard deviation) between the obtained and expected signals from profiles drawn across a scintillation spot. Signal-to-noise ratio and signal-to-background ratio are further measured and compared in the resulting scintillation images. Finally, the resulting differences on the scintillation signal from a 0.2 × 0.2 cm\textsuperscript{2} region-of-interest (ROI) were reported. Main results. Clustering, OpenCV, bilinear, Malvar and Menon demosaicing algorithms respectively yielded differences of 3 ± 5%, 1 ± 3%, 1 ± 3%, 1 ± 2% and 2 ± 4% in the resulting scintillation images. For the Cherenkov images, all algorithms provided differences below 1%. All methods enabled measurements over the detectability (SBR > 2) and sensitivity (SNR > 5) thresholds with the bilinear algorithm providing the best SNR value. Clustering, OpenCV, bilinear, Malvar and Menon demosaicing algorithms respectively provided differences on the ROI analysis of 7 ± 5%, 3 ± 2%, 3 ± 2%, 4 ± 2%, 7 ± 3%. Significance. Radioluminescent signals can accurately be isolated using a single polychromatic camera. Moreover, demosaicing using a bilinear kernel provided the best results and enabled Cherenkov signal subtraction while preserving the full spatial resolution of the camera.

1. Introduction

Scintillation detectors have evolved from single point measurement devices to volumetric detectors enabling 2D and even 3D measurements (Beaulieu and Beddar 2016). The use of fluors, in the production of scintillation detectors, whether incorporated into scintillating fibers, liquid scintillators or solid plastic bulk, is motivated by the resulting scintillators water equivalence over a wide range of therapeutic energies, which enables correction-free measurements (Beddar et al 1992a, 1992b). In addition, these scintillators can perform real-time measurements with a high spatial resolution. This makes plastic scintillation detectors (PSD) attractive for small fields or highly modulated beam measurements (Xue et al 2017).

In the last few years, many photodetectors were proposed to measure the scintillation signal, each having specific strengths and weaknesses. Selecting the optimal photodetector implies making trade-offs between spatial resolution, spectral resolution and dose rates operating ranges (Boivin et al 2015). While the operating range determines the accuracy of a measurement, spatial and spectral resolutions increase its reach: a high spatial resolution may not be enough if the dose rates operating range is low.
resolution will enable dose sampling from many points in the volume while spectral resolution is advantageous for stem-effect removal and measurements with multi-point probes.

A spectral mathematical formalism has been specifically developed to isolate the signals of interest in PSD dose measurements (Archambault et al 2012). The so-called hyper-spectral/multi-spectral formalism was successfully applied to multi-point PSD measurements as well as stem-effect and temperature-dependence removal (Therriault-Proulx et al 2012, Linares Rosales et al 2019, Therriault-Proulx et al 2015). In that context, a photomultiplier tubes (PMTs) assembly and spectrometers were used to acquire the spectral information. These detectors have a high sensitivity, sensibility and spectral resolution, but provide limited spatial resolution. Cameras, for their part, have enabled high spatial resolution 2D and 3D dose measurements (Goulet et al 2014, Kirov et al 2005, Alexander et al 2020). Taking advantage of color channels, together with the spectral formalism, polychromatic cameras have the potential of combining many photodetector qualities into one device.

Polychromatic cameras typically acquire spectral information using three color channels (red, blue, green) integrated as mosaics overlaid on the sensor. Hence, the spectral information is not acquired at each pixel and is instead sampled to form incomplete color matrices. The purpose of this study is to investigate the combined use of demosaicing algorithms with spectral formalism for spectral dose imaging.

2. Theory and methods

2.1. Spectral imaging

Spectral approaches are based on the idea that the signal results from a linear superposition of spectra (Archambault et al 2012). In that case, a measurement can be described as:

\[ M = R \cdot D, \]  

where \( M \) is the measurement matrix, \( R \) is the detector response and \( D \) is the dose. The detector response is the matrix containing the individual spectra from each radio-luminescent element as measured by the optical system and obtained from calibration. Then, from equation (1), the dose can be extracted from a measurement using the prior detector response:

\[ D = R^+ M, \]  

where \( R^+ \) is the Moore–Penrose pseudo inverse (i.e. \( (R^TR)^{-1}R^T \)). For the demonstrated case of a scintillating probe, the spectra are either read by a series of color sensitive detectors (discrete spectra) (Linares Rosales et al 2019) or a spectrometer (near-continuous spectra) (Therriault-Proulx et al 2012, Jean et al 2021). In that context, each channel, or spectral band, measures the spectral information coming from the same sensitive volume. Spectral acquisition using a polychromatic camera complexifies the approach as the spectral information is not sampled at each pixel, but rather forms incomplete color matrices.

In this work, we used a polychromatic camera with a Bayer filter (Alta U2000, Andor Technology, Belfast, United Kingdom). Each block of 4 pixels contains two green, one red and one blue sensitive pixels as presented on figure 1.

To retrieve the complete spectral information, one has to work with incomplete color mosaics for each color. Processing these matrices into a full-color image is called demosaicing. Different demosaicing algorithms were tested, each of which can be classified in one of two categories: clustering and interpolation methods. Each demosaicing algorithm was tested from calibration to dose measurements.
2.1.1. Clustering method
A first approach is to cluster pixels into groups of 2 × 2 pixel comprising one blue (B), one red (R) and two green (G) pixels from the Bayer pattern of the sensor. Green pixel values are averaged. Spectra consisted of the mean R/G, G/B and B/G ratios taken over a region of interest. The strength of this method is that it does not rely on interpolation that may bias the results. However, it assumes that the same signal is seen by the individual pixels, which might not hold true in regions of high dose gradients. Furthermore, it reduces the camera’s spatial resolution by a factor of two.

2.1.2. Interpolation methods
Another approach is to estimate the missing color contributions to a pixel using interpolation from the neighboring pixels. For example, a blue pixel will be interpolated from surrounding green and red values. In that case, green values can be expected to be better estimated as it is sampled twice more often than the other colors in a Bayer mosaic. Four interpolation-based demosaicing algorithms were tested: the OpenCV demosaicing algorithm (Bradski 2000), a bilinear kernel algorithm, the demosaicing methods published by Malvar et al (2004) and that published by Menon and Calvagno (2007). The OpenCV and bilinear algorithms both use the following convolution kernels for green $K_G$, blue and red $K_{R/B}$, pixels interpolation:

$$
K_G = \frac{1}{4} \begin{bmatrix}
0 & 1_G & 0 \\
1_G & 4 & 1_G \\
0 & 0 & 0
\end{bmatrix}, \quad K_{R/B} = \frac{1}{4} \begin{bmatrix}
1_R/B & 2_R/B & 1_R/B \\
2_R/B & 4 & 2_R/B \\
1_R/B & 2_R/B & 1_R/B
\end{bmatrix}.
$$

(3)

The $K_{R}, K_{G}$ and $K_{B}$ kernels are respectively applied to the incomplete red, green and blue matrices. The approaches developed by Malvar and Menon, which were developed for photography, further aim at using inter-color correlation, i.e. information from other surrounding colors, to estimate each contribution. For example, the algorithm published by Malvar et al defines convolution kernels for estimating the green value at a blue or red pixel $K_{G→R/B}$, the red or blue value at a green pixel in a red or blue line $K_{R/B→G}$, the red or blue value at a green pixel in a red or blue column $K_{R/B→G}$ and the red or blue value at a blue or red pixel $K_{R/B→R/B}$ (Malvar et al 2004):

$$
K_{G→R/B} = \frac{1}{8} \begin{bmatrix}
0 & 0 & -1_R/B & 0 & 0 \\
0 & 0 & 2_G & 0 & 0 \\
-1_R/B & 2_G & 4_R/B & 2_G & -1_R/B \\
0 & 0 & 2_G & 0 & 0 \\
0 & 0 & -1_R/B & 0 & 0
\end{bmatrix},
$$

(4)

$$
K_{R/B→G} = \frac{1}{8} \begin{bmatrix}
0 & 0 & 0.5 & 0 & 0 \\
0 & -1_G & 0 & -1_G & 0 \\
-1_G & 4_R/B & 5_G & 4_R/B & -1_G \\
0 & -1_G & 0 & -1_G & 0 \\
0 & 0 & 0.5 & 0 & 0
\end{bmatrix},
$$

(5)

$$
K_{B→G} = (K_{R/B→G})^T
$$

(6)

$$
K_{R/B→R/B} = \frac{1}{8} \begin{bmatrix}
0 & 0 & -1.5_B/R & 0 & 0 \\
0 & 2_R/B & 0 & 2_R/B & 0 \\
-1.5_B/R & 0 & 6_B/R & 0 & -1.5_B/R \\
0 & 2_R/B & 0 & 2_R/B & 0 \\
0 & 0 & -1.5_B/R & 0 & 0
\end{bmatrix}.
$$

(7)

By introducing these kernels, the Malvar algorithm estimates the missing pixel values using gradient correction interpolations. Finally, the demosaicing method proposed by Menon et al further uses gradients estimated by green, red and blue values to predict all colors, in a complex 4-step algorithm (Menon and Calvagno 2007). First, two green matrices are constructed using directional, horizontal or vertical, interpolation. The resulting $G^H$ and $G^V$ matrices are then used to predict the gradient direction and to guide the red and blue components interpolation. Finally, a refining step corrects interpolation artifacts in all three channels caused by the edge direction selection. For more details, the reader is encouraged to refer to the original manuscripts (Malvar et al 2004, Menon and Calvagno 2007).

2.2. Calibration and dose measurements
Spectral imaging using demosaicing methods were tested using a phantom that consists of a circular disk of transparent plastic containing an array of 19 green plastic scintillators (BCF-60; Saint-Gobain Crystals, Hiram, OH, USA) (Cloutier et al 2021, 2021). The scintillators were polished on both ends. The phantom is subject to
the emission of two signals that need to be distinguished: the scintillation signal produced from the fibers and the Cherenkov signal produced in the bulk. Figure 2 presents both radioluminescent spectra of interest together with the camera channels quantum efficiency.

The phantom bulk is made of a urethane compound (ClearFlex 30; Smooth-On, Macongie, USA) cast in a 6 cm diameter and 1.2 cm thick circular mold. The scintillating fibers are 1.2 cm long and have a 1 mm diameter. The scintillating fibers were embedded in the phantom so that they are 1.5 cm equidistant from each other. For calibration, scintillation spectra were obtained by irradiating the phantom under a 120 kVp orthovoltage photon beam (Xstrahl 200, Camberley, United Kingdom). This energy is below the Cherenkov threshold and thus ensures that only scintillation is acquired, neglecting fluorescence. To measure the Cherenkov emission spectra, an additional disk was manufactured, having the same dimensions as the first one, except that no scintillating fibers were inserted. The Cherenkov spectrum was acquired by placing that additional phantom at the isocenter of a single direct 6 MV, $6 \times 2$ cm$^2$ field size, 600 MU min$^{-1}$ dose rate photon beam (Clinac iX, Varian, Palo Alto, USA). The same irradiation beam was used for dose measurements with the scintillating phantom aligned on the isocenter of the linac. Considering the RBG channels of the camera together with the two radioluminescent sources, equation (1) becomes:

$$\begin{bmatrix}
M_R \\
M_C \\
M_B
\end{bmatrix} =
\begin{bmatrix}
R_{R,BCF46} & R_{R,Cherenkov} \\
R_{C,BCF46} & R_{C,Cherenkov} \\
R_{B,BCF46} & R_{B,Cherenkov}
\end{bmatrix}
\cdot
\begin{bmatrix}
D_{BCF46} \\
D_{Cherenkov}
\end{bmatrix}.$$  

(8)

For each measurement, the camera was positioned on the treatment couch, 50 cm from the isocenter. A 12 mm focal length objective lens was coupled to the camera. Five frames of 1 s were acquired ($\approx 10$ MU to each frame). Background frames, i.e. images in absence of radiation, were subtracted from the signal images and median temporal filter, over five acquisitions, to further correct the remaining transient noise (Archambault et al. 2008). For each demosaicing algorithm tested, a signal-to-noise and signal-to-background analysis was performed to quantify the sensitivity and detectability of the resulting images of scintillation. These were defined as:

$$SBR = \frac{\mu_{\text{spot}}}{\sigma_{bg}}, \quad \text{SNR}_{\text{avg}} = \frac{\mu_{s}}{\sigma_{s}}, \quad \text{SNR}_{\text{spot}} = \sqrt{\text{SNR}_{\text{avg}}}.$$  

(9)

$\text{SNR}_{\text{avg}}$ is the SNR where pixels from each scintillating fiber is treated individually whereas $\text{SNR}_{\text{spot}}$ (Lacroix et al. 2009) is that when pixels forming a spot are treated as a group. Finally, the crest factor was further computed to quantify the detectability of the scintillation signal over the Cherenkov signal. The crest factor is defined as the peak to average ratio (PAR) where the peak is determined by the scintillation and the average is the remaining Cherenkov emission. Higher PAR are expected for methods that accurately removed the Cherenkov contribution on scintillation images.

2.2.1. Reference scintillation signal

To compare the resulting spatial accuracy of the different demosaicing methods, we further acquired a reference measurement using a single scintillating fiber excited by a UV light source (Globe, Montreal, Canada) having its peak wavelength around 475 nm. The resulting scintillation signal was imaged by a monochromatic camera (Atik 414EX; Atik Cameras, Norwich, United Kingdom).

![Figure 2. Theoretical scintillation and Cherenkov radiation normalized spectra (left axis) along with the colored channel quantum efficiency of the Alta U2000 CCD camera (right axis).](image-url)

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3. Results and discussion

Figure 3 illustrates the raw, un-corrected, image of the scintillating phantom comprising both Cherenkov and scintillation signals. Since the BCF-60 scintillation spectra is peaked in the green filter channels, these pixels have a higher intensity than blue and red channels. This can be more easily see in the close-up. Figure 4 presents Cherenkov and scintillation dose images that were obtained using the different demosaicing algorithms. In all cases, the spectral method isolated the Cherenkov signal, mainly produced in the bulk, from the scintillation signal generated from the 19 scintillating fibers. Therefore, scintillating fibers locations are visible as lower intensity regions on the Cherenkov images whereas the Cherenkov signal is totally removed from the scintillating images. Looking at the scintillation spots obtained with the clustering method, the figure highlights the spatial resolution reduction imposed by this method. Figure 5 shows a profile taken accros a photoexcited scintillating fiber imaged by a monochromatic camera. The intensity measured follows a gaussian function having a FWHM of 0.06 cm. As a consequence, scintillation spots obtained from the different demosaicing methods, presented on figure 4, are expected to follow a 0.06 cm FWHM gaussian curve. Figure 6 presents profiles drawn across a scintillating spot compared to the expected signal for both scintillation and Cherenkov images. For the scintillation images, differences up to 20% are obtained using the clustering algorithm, which are
attributed to volume averaging being more present. Differences of (mean ± standard deviation) 3 ± 5% are obtained using the clustering algorithm on the scintillation images. The bilinear and OpenCV algorithms presented differences of respectively 1 ± 3% and 1 ± 3%. Similar results were expected for these algorithms since demosaicing is performed along the same convolution kernels. However, it was found that the OpenCV routine rounds its output values, which slightly biases the calibration spectra. This explains the differences between the bilinear and OpenCV results. Malvar and Menon algorithms presents differences of 1 ± 2% and 2 ± 4% respectively, as the spot width seems to be overestimated. Still, these algorithms are the ones that best reproduced the gaussian shape of the signal. Taking into consideration the different demosaicing formalisms, these result are not surprising because the Malvar and Menon kernels are the most akin to a gaussian kernel. For the Cherenkov images, comparison is trickier since a reference is hard to establish at the scintillating fibers location, not knowing the true Cherenkov contribution in the scintillating volume. Hence, the reference Cherenkov signal is the one obtained from the bulk without fibers and figure 6 right panel can only be interpreted with confidence from [−0.2, −0.1] and [0.1, 0.2] cm. Outside of the fibers region of interest, the Cherenkov contribution is well estimated by most algorithms, i.e. differences remained below ±1%. Overall, similar performances are obtained within the same family of algorithms, namely the clustering, bilinear, and inter-channel correlation (Malvar and Menon) based algorithms.

The resulting sensitivity and detectability of scintillation images is presented in figure 7 where SNR and SBR analysis are conducted over the 19 scintillating fibers. Overall, the Cherenkov subtraction from the images resulted in higher SBR, or detectability, in the scintillation images, except for the OpenCV method. This reinforces the benefits of spectral Cherenkov correction. Moreover higher SBR are obtained using Malvar and Menon algorithms which is attributed to a higher portion of the signal falling into the scintillation dose channels. As for the SNR analysis, bilinear demosaicing resulted in the higher performances, while the clustering method degraded the SNR from raw images. Still, for all methods, SNR and SBR remained higher than the detectability

Figure 5. Reference scintillation signal obtained from a UV photo-excitation. The signal fits a gaussian ($r^2 > 0.99$).

Figure 6. Profiles drawn across a scintillation spot in both scintillation (left) and Cherenkov (right) images obtained with the different demosaicing methods.
(SBR > 2) and sensitivity (SNR > 5) thresholds according to the Rose criterion (Bushberg et al. 2011). SBR analysis was conducted using the standard deviation of the noise $\sigma$, which corresponds to a region of interest without any source of light. On the scintillation images, similar $\sigma$ were found in the bulk region where Cherenkov was removed.

As for the scintillation detectability over Cherenkov signal, figure 8 presents the PAR of the raw image in comparison to the scintillation images obtained with the different demosaicing algorithms. Cherenkov emission removal through the hyperspectral formalism increased the detectability of the scintillating fibers by an order of magnitude in all cases when compared to raw images not corrected for Cherenkov emission.

Typically, dose measurements from scintillating spots are based on the integrated scintillation signal over a region of interest (Klein et al. 2011). Figure 9 shows, for each scintillating spot and demosaicing method, the relative scintillation signal difference integrated over a $0.2 \times 0.2$ cm$^2$ ROI. Here, the reference signal corresponds to a 2D Gaussian obtained from the reference photoexcitation measurements. Integrated ROI spot difference of (mean $\pm$ standard deviations) $24 \pm 4\%$, $7 \pm 5\%$, $3 \pm 2\%$, $3 \pm 2\%$, $4 \pm 2\%$ and $7 \pm 3\%$ are obtained from the raw, cluster, OpenCV, bilinear, Malvar and Menon demosaicing methods. These results are a good indicator of the expected dose accuracy enabled by each of the tested methods in a context where the Cherenkov signal would significantly vary between measurements. Hence, the resulting dose accuracy from scintillator-based measurements not only depends on the capabilities of the system to isolate the Cherenkov signal, but also on the variability of the Cherenkov production and coupling between the measured irradiation conditions. Beside Cherenkov removal, the dose accuracy depends on other measurement considerations such as, but not limited to, scintillators polishing, photodetector quantum efficiency, scintillation yield, optical distances or cameras dark noise (Lacroix et al. 2009).

Overall, the demosaicing techniques provided Cherenkov and scintillation signal separation in good agreement with the expected dose. The bilinear algorithm presented the best performance with regards to the dose spatial accuracy, detectability and sensitivity. The bilinear kernel enabled scintillation and Cherenkov

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**Figure 7.** SBR and SNR analysis conducted on the scintillation images generated with the different demosaicing algorithms. Raw measurements correspond to the analysis of the images not corrected for Cherenkov signals. The spread results from the analysis on the 19 scintillating fibers.

**Figure 8.** Peak to average ratio (PAR) on the images generated with the five demosaicing algorithms in comparison to the raw images. For each algorithm, analysis was conducted over the 19 scintillating spots.
signal separation, within 3% agreement, while preserving the full spatial resolution of the camera. Furthermore, SBR and spot SNR were enhanced following the bilinear deconvolution compared with the raw images.

Previous studies using volumetric scintillators typically treated Cherenkov removal by subtraction of the setup’s contribution (Frelin et al 2008, Goulet et al 2014, Rilling et al 2020, Delage et al 2018). In particular, Frelin et al proposed a Cherenkov discrimination technique based on spatial modulation imposed by a semi-transparent chess-board pattern (Frelin et al 2008, Collomb-Patton et al 2009). However, these techniques cannot take into account Cherenkov produced directly within the scintillating material. Moreover, these approaches are more difficult to apply for phantoms that deform during measurements. Deformable scintillation-based dosimeters (Cloutier et al 2021, 2021) could especially benefit from robust 2D and 3D Cherenkov signal removal. Use of the spectral formalism proposed in this study enabled the separation of the scintillation signal from the Cherenkov signal while preserving spatial information.

Cherenkov filtering using cameras was initiated for scintillation probe measurements (Frelin et al 2005, Lacroix et al 2008, Guillot et al 2011, 2013). In particular, the method presented by Lacroix et al first proposed spectral measurements using a polychromatic camera, but only took advantage of the blue and green pixels, treated in clusters (Lacroix et al 2008). Approaches presented by Frelin et al and then Guillot et al used two monochromatic cameras in front of which a dichroic filter divided the raw signal into two contributions reaching each of the cameras (Frelin et al 2005, Guillot et al 2011, 2013). Frelin et al also presented a setup using a single monochromatic camera where measurements were reproduced through different spectral bands (Frelin et al 2008). Recently, a Cherenkov spectral analysis was conducted along the same lines, whereas the spectral information was simultaneously acquired from three cameras sensitive to different spectral bands (Alexander et al 2021). Hence, for these previous techniques, no demosaicing techniques were necessary. In our case, the combined use of Bayer filter cameras and demosaicing algorithms provides the advantage of a simplified measuring set-up where a single camera is necessary. The approach here is also different since the method takes advantage of all three colored channels of Bayer cameras and relies on individual calibration of the different spectra. This is expected to make the method more robust and dose measurements more accurate.

A limitation of Bayer pattern cameras, however, is that spectral bands cannot usually be optimized to a specific emission spectra (i.e. Bayer pattern are ‘one-size-fits-all’). Therefore, this limits the reach of the method to spectral emission falling into the typical blue, green, and red channels of standard polychromatic cameras. Moreover, Bayer cameras cannot be directly implemented in intensified systems, because the intensification process does not preserve the spectral integrity of the signal reaching the sensor (Andor). Recently, triggered and intensified cameras have been demonstrated to be well suited to suppress room lighting in the context of in vivo 2D scintillation and Cherenkov dosimetry (Tendler et al 2019, 2019, Bruza et al 2018). The proposed photodetector included a gated camera coupled to an intensifier. In order to preserve the spectral signature of the signal, the Bayer filter would have to be placed before the intensifier which would need further developments and validation. Hence additional work will be needed to use Bayer pattern cameras for clinical dose measurements where the dosimeter cannot be shielded from in-room lighting.

Demosaicing methods have initially been developed for photography using perceptual metrics based on human vision. Therefore, lesser work has investigated their use for radiance data analysis. Still, the bilinear,
Malvar and Menon algorithms have recently been compared in the context of hyperspectral spectroscopy (Eskelinen and Hämäläinen 2018). In that context, the use of the advanced methods (Malvar and Menon algorithms) resulted in an overall error increase of 9%–14% compared to the bilinear results. These conclusions therefore agree with the results obtained in this work. This suggests that convolution kernels developed specifically for photography might be less suitable for radiometry applications. Interestingly, for photography applications, the channel interpolation methods resulted in similar PSNR and SSIM indicators compared to a bilinear method. However, the images reconstructed by inter-channel correlation methods have sharper edges (Lapray et al 2014).

4. Conclusion

Demosaicing algorithms were investigated in the context of spectral imaging using polychromatic cameras. Image demosaicing using a bilinear kernel presented the best performance, resulting in accurate spatial dose measurements and increased detectability and sensitivity in comparison to the raw images. Together with a polychromatic CCD camera, the Cherenkov signal was accurately isolated from the scintillation signal using the spectral formalism. Given these results, the combined use of demosaicing algorithms and spectral formalism makes polychromatic cameras a promising tool for improved volumetric dose measurements.

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