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A review of clinical imaging techniques in polymer gel dosimeters

Alireza Goosheh[a,*], Seyed Mohammad Mahdi Abtahi[b], Ahmad Akhond[a], Seied Rabi Mahdavi[c]

[a] Department of Physics, Payame Noor University, Tehran, Iran
[b] Department of Physics, Imam Khomeini International University, Qazvin, Iran
[c] Department of Medical Physics, School of Medicine, Radiation Biology Research Center, Iran University of Medical Sciences, Tehran, Iran

HIGHLIGHTS

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ABSTRACT

The Persistent development of quick and accessible readout tools promises to remove one of the barriers to the adoption of gel dosimetry as an applicable method in treatment clinics. Research and development in the imaging of polymer gel dosimeters continues with a focus on imaging in three dimensions. Each technique comes with its own set of advantages and challenges. In gel dosimeter research, efforts have been made to identify and develop alternative imaging methods for polymer gel dosimeters. Gel dosimeters can obtain reliable and accurate three-dimensional dose distributions from the correlation of different polymerization stages caused by radiation. The irradiated samples are examined using magnetic resonance imaging, optical computed tomography, and X-ray computed tomography. This research describes the basic features of imaging devices and the readout of irradiated dose data. Costs, availability, portability, contrast and resolution, high-resolution image reconstruction algorithm, and image reconstruction time of radiation absorption dosimeters for imaging devices are investigated in this research. This review has been done to present the mentioned imaging features and review the research done in this field for the optimal use of different imaging methods.

KEYWORDS
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1 Introduction

Polymer gel dosimeters made from gelatin aqueous solutions are a tool for the three-dimensional determination of absorbed dose in a gelatin network (Berg et al., 2004; De Deene et al., 2002). The essential features of polymer gel dosimeters are soft tissue equivalent, human phantom shape, and the possibility of determining complex dose distributions (Baldock et al., 2010; Chen et al., 2012). For the first time, dosimetry gels were used for radiation dosimetry purposes in 1950 (Day and Stein, 1950). To study the longitudinal NMR relaxation of acrylamide-based gel, Kenan and her colleagues showed that the spin-lattice relaxation rate ($R_1 = 1/T_1$) changes with the absorption dose (Kennan et al., 1992). The initial use of polymer gel dosimeters in clinical studies was performed by magnetic resonance imaging (MRI) (Maryanski et al., 1994). The optical computed tomography method was introduced as an alternative method to MRI imaging in 1996 (Gore et al., 1996) and, then computed tomography (X-ray) was used to investigate the dose distribution (Hilts et al., 2000). Some properties of these polymer gels change due to ionizing radiation, such as spin-spin relaxation rate ($R_2 = 1/T_2$), spin-lattice relaxation rate, sound propagation speed properties, optical properties, and Hansfeld number. Considering that this change in dosimeter properties is possible by using imaging methods to read the dose-response, magnetic resonance imaging (Venning et al., 2005), ultrasonic (Mather et al., 2002), optical computed tomography (Olding et al., 2010), and computed tomography (Hilts, 2006) are used. The use of polymer gel dosimeters in clinical cases has received much attention. These gels are presented in three sections: external radi-

*Corresponding author: a.goosheh@pnu.ac.ir

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ation therapy, brachytherapy, and BNCT (Farhood et al., 2019). Trapp et al. used the MAGIC dosimeter gel to validate photon and electron treatment plans for scalp cancer (Trapp et al., 2004). NIPAM gel was used in the VMAT technique for dose distribution for two simple and complex clinical cases (Yao et al., 2017). BANG gel has been used as an eye phantom to determine the 3D dose distribution from a Ru-106 source (Chan et al., 2001). NIPAM gel has been used as a phantom for dose distribution caused by superficial brain tumors in front of the BNCT beam (Khajeali et al., 2017). Optimum imaging methods have a significant impact on reducing artifacts, and increasing the resolution and accuracy of the dosimetry gel (De Deene and Baldock, 2002). In this study, imaging methods such as: MRI, X-ray CT, Optical CT, Ultrasound, Raman spectroscopy and UV-Vis spectrometer for reading the dose-response are investigated to optimally use dosimetry gels in treatment plans. The review process was done with the initial of 460 articles. A careful monitoring and study led to the removal of 210 duplicate articles. Subsequent analysis focusing on the distinctive characteristics of polymer gels further narrowed the selection to 69 articles. The information related to these articles was extracted and presented in this research. According to the diagram in Fig. 1, it shows that MRI imaging is the most used and UV-vis is the least used in the gel dosimetry method.

2 Imaging methods

Any parameter that changes based on the polymerization of monomers in the gel due to radiation can be an appropriate election for preparing a dose map to show the dose distribution. Irradiated dose information can be obtained based on physical and chemical changes in the gel by imaging techniques (Baldock et al., 2010). Commonly used techniques for gel dosimetry systems include magnetic resonance imaging (MRI), optical computed tomography (OCT), and computed tomography (X-ray CT). Investigation of the capabilities and limitations of gel dosimetry imaging is evaluated in this study.

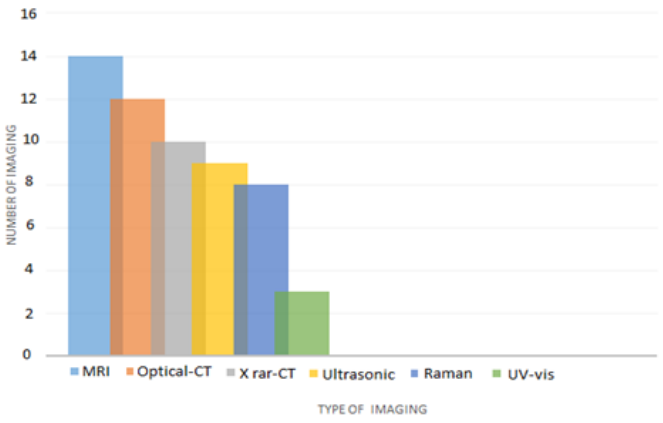

Figure 1: Diagram of the use of imaging methods in gel dosimetry.

2.1 *Magnetic resonance imaging*

Theoretically, any imaging sequence that produces an image of pixel intensity uniformly related to the absorbed dose is a possible candidate. A dose map can be obtained by calibrating each pixel intensity to the absorbed dose using a set of calibration vials irradiated with specified doses (De Deene, 2010). Exciting and changing the spin of protons in the water molecules around the polymer is a method to read the gel in magnetic resonance imaging. Upon irradiation, the spin-lattice relaxation rate ($R_1 = 1/T_1$) changes (Maryanski et al., 1993). Due to the sensitivity of the spin-spin relaxation rate ($R_2 = 1/T_2$) to gel polymerization, it is used as a function of the absorbed dose (Baldock et al., 2010). The magnetic resonance relaxation rates R_1 and R_2 depend on the molecular concentration and mobility of protons, caused by three groups of free water molecules and unreacted monomers, a growing polyacrylamide network, and gelatin (Baldock et al., 2010; Bloembergen et al., 1948). Image contrast due to radio frequency (B_1-field) inhomogeneity and eddy currents lead to image non-uniformity, which can be compensated by using T_1, T_2, and MTR maps, which are selected based on the type of irradiated gel (De Deene, 2010). Imaging parameters such as echo time, repetition time, and rotation angle are effective in image contrast (Baldock et al., 2010). Inhomogeneity in the main magnetic field B_0 and radio frequency B_1 is effective in reducing the accuracy of dose reading (MacDougall et al., 2002). Quantitative R_2 maps in the magnetic resonance method are obtained through a sequence of different T_2 images in a multiple spin-echo sequence at the same repetition period. The R_2 value in each pixel is determined by fitting the exponential curve with the corresponding pixel in the base images (Baldock et al., 2010). Since R_1 is a non-irradiated Frick dosimeter gel compared to R_2, the dynamic range of the Frick dosimeter gel is greater in relative terms for R_1 than for R_2. Therefore, R_1 mapping is preferred over R_2 mapping for Frick gel dosimeters (De Deene, 2010). In polymer gel dosimeters, T_2 is more affected than T_1, and thus T_2 and MTR maps produce the highest dose resolution (De Deene, 2010).

The linear slope of the dose-response curve is considered the "dose-response sensitivity" of the polymer gel (De Deene et al., 2006), which is one of the comparable characteristics in evaluating the sensitivity of dosimeters. In this study, the sensitivity of several gel dosimeters evaluated through magnetic resonance imaging is investigated. In 2001, Oldham performed MR and CT laser scanning with spatial resolution criteria of nearly 1 mm^2, scanning time of 1 hour, accurate to within 3%, and within $< 1\%$ precision (Oldham et al., 2001). This research demonstrates that gel-dosimetry and optical-CT scanning approaches are important long-term goals of radiation dosimetry and have the potential to impact the clinic by improving and facilitating clinical dose verification for the most complex external beam radiation treatments (Oldham et al., 2001).

PAKAG dosimeter gel was examined by Rashidi et al. by MRI machine (1.5 T) (Rashidi et al., 2020). This gel

was irradiated with a photon with an energy of 6 MV in the range of 0 to 6 Gy, and the sensitivity of the gel was measured as 0.152 ± 0.07 $Gy^{-1}.s^{-1}$.

Abtahi et al. PAMPSGAT gel based on Amps (AMPS, bis, gelatin) was irradiated with a Co-60 treatment device in the range of 10 to 40 Gy (Abtahi, 2016). Imaging was done using an MRI scanner (1.5 T), and the sensitivity of the gel was evaluated at 0.065 $^{-1}.s^{-1}$ (Abtahi and Pourghanbari, 2018). This study has shown a sensitivity of 0.054 $Gy^{-1}.s^{-1}$ for 6 MV photon irradiation (Abtahi and Pourghanbari, 2018).

PASSAGE dosimeter gel based on Amps salt was evaluated with an MRI imaging scanner (1.5 T). This gel was irradiated by a Co-60 therapy device in the range of 0 to 15 Gy, and the dose rate was 50 $cGy.min^{-1}$. Sensitivity was evaluated as 0.081 ± 0.003 $Gy^{-1}.s^{-1}$ (Farhood et al., 2019). PAGAT gel dosimeter was evaluated by Venning et al. in the linear region of 7 Gy by MRI (1.5 T) (Venning et al., 2005). The sensitivity of R_2 response for 24 hours after irradiation was measured as 0.192 ± 0.005 $Gy^{-1}.s^{-1}$.

PAGBIT dosimeter gel, based on Amps ammonium salt, was investigated with 6MV photon in the dose range of 0 to 10 Gy and dose rate of 300 $cGy.min^{-1}$ (Goosheh et al., 2023). Imaging was done with an MRI scanner (1.5 T) and the sensitivity of the gel was measured 36 hours after irradiation as 0.115 ± 0.005 $Gy^{-1}.s^{-1}$.

VIPAR gel was irradiated with 6MV energy in the dose range of 0 to 12 Gy (Pappas et al., 1999). MRI imaging (1.5 T) was performed on the 4^{th}, 5^{th}, and 15^{th} days after radiation, which recorded a sensitivity of 0.098 ± 0.004 $Gy^{-1}.s^{-1}$. MAGIC dosimeter gel was irradiated with Cs-137 irradiation (Fong et al., 2001). The MAGIC gel is imaged with an MRI scanner and has a sensitivity of 0.868 $Gy^{-1}.s^{-1}$ in the dose range of 0 to 30 Gy.

MAGIC-A dosimeter gel is imaged with an MRI scanner. This gel was irradiated with a Co-60 radiation source and thermal neutron, which has a sensitivity of 0.381 $Gy^{-1}.s^{-1}$ and 0.180 $Gy^{-1}.s^{-1}$ respectively (Abtahi et al., 2016). The characteristics of the mentioned gels are shown in Table 1.

Table 1: Sensitivity and dosage range of different gels.

Type of gel	Dose range (Gy)	Sensitivity ($Gy^{-1}.s^{-1}$)
PAKAG	0 - 6	0.152
PAMPSGAT	10 - 40	0.065
PASSAGE	0 - 15	0.081
PAGAT	7	0.192
PAGBIT	0 - 10	0.115
VIPAR	0 - 12	0.098
MAGIC	0 - 30	0.868

2.2 Optical CT imaging

Irradiation of the gel leads to an increase in the density of the polymer particles and changes the apparent state of the gel to a cloudy state. The increase in the refractive index is proportional to the increase in the dose in the bands of the absorption spectrum of irradiated gels as the primary mechanism of optical contrast in the optical computed tomography imaging method (Baldock et al., 2010). This method, which was proposed in 1996 as an alternative to 3-D dosimetry imaging (Gore et al., 1996), could be introduced as a less expensive imaging method than MRI scanning (Oldham et al., 2001). For optimal use, the light source of the detector should be turned on for at least 2 hours of warm-up before the start of imaging and until the completion of the last scan (Olding and Schreiner, 2011). The stray light perturbation is one of the factors that increase artifacts and other inaccuracies in this method (Olding et al., 2010). Olding et al. showed that the three-dimensional readout of gel dosimetry with optical computed tomography compared to MRI has a reasonable agreement with the benchmark $1 \times 1 \times 1$ mm^3 spatial resolution, imaging time of 60 minutes, and 3% accuracy (Olding et al., 2010). Artifacts arising from angled scatter reduce the measurement accuracy (Olding et al., 2010). Research in this field showed that the largest sources of stray light perturbation in the system were identified as being due to angled scatter from the dosimeter gelatin matrix and refraction from the jar wall interfaces (Olding and Schreiner, 2011).

Papadakis et al. used an optical CT scanner developed to measure the relative three-dimensional dose distribution of N-Vinylpyrrolidone-based polymer gel, which is capable of measuring the three-dimensional dose distribution in a wide dose range and high resolution (Papadakis et al., 2010). Readout images are in good agreement with MR imaging and have three features: high photo production speed, low cost, and ease of system design (Papadakis et al., 2010).

A study was conducted to optimize the results of a CT scan to determine the sensitivity of high-dose gel (Xu et al., 2003). For a better agreement, the relative percentage dose distribution obtained from CT scanning method and treatment programs, for example, IMRT, is recommended that the uniformity of the gel, reduce the scanner noise and improve the performance of the image reconstruction algorithm (Xu et al., 2003).

Doran et al. used a CCD-based optical CT scanner to obtain the 3D dose distribution of the gel (Doran et al., 2001). In this research, it was shown that the costs are much lower than the MRI method. However, the external beam treatment method for large samples has a challenge for the optical computed tomography method due to traveling a long way through the sample (Doran et al., 2001). Significant signal attenuation requires a detector with high sensitivity and dynamic range (Doran et al., 2001).

BANG gel was evaluated in research using an optical CT device and showed that it has a high ability as a scanner in 3D imaging. However, it should be subjected to more tests before being used in clinical cases (Islam et al., 2003). In this study, the dose distribution obtained from the gel was measured and compared in optical computed tomography with radiochromic film. The dose distribution in gel and radiochromic film was very similar except in the areas with steep dose gradients and high dose areas (Islam et al., 2003).

Measurement of brachytherapy sources using MAGIC gel has been performed using optical CT imaging (Heard

and Ibbott, 2004). This research showed that the costs of using optical computed tomography are far more convenient and cheaper than MRI and can provide higher resolution for brachytherapy treatment (Heard and Ibbott, 2004).

The dose-response characteristics of BANG3 gel were investigated in the range of photon energy therapy of 6 and 10 MV and electron radiation of 12 and 16 MeV using optical CT (Xu et al., 2010). The optical response of the gel was evaluated as linear and independent of energy (Xu et al., 2010).

2.3 X-ray CT imaging

This method is proposed to measure the three-dimensional dose distribution with high spatial accuracy and to verify coherent radiation techniques in three-dimensional polymer gel dosimeters (Hilts et al., 2000). The change in the linear attenuation coefficient is mainly attributed to the change in the electron density due to the outflow of water from the polymer clusters, which allows us to use X-ray CT as a scanning technique (Baldock et al., 2010).

The change in the linear damping coefficient is caused by an increase in the mass density due to the redistribution of mass in the structure or a change in the gel volume (Baldock et al., 2010). In this method, the contrast of the image depends on the radiation dose (Jirasek and Hilts, 2009). As the absorbed dose increases, the CT number increases. CT dose sensitivity of the gel can be increased by increasing the monomer concentration or by using agarose-based polymer gel dosimeters, however, the combination that provides the highest CT dose sensitivity does not necessarily change the dose resolution optimization (Trapp et al., 2001).

X-ray CT imaging of polymer gel dosimeters usually produces low-contrast images due to the low sensitivity of this technique, and several images must be averaged for each piece to use this method (Baldock et al., 2010). Reconstruction algorithms are practical on image noise (Baldock et al., 2010).

CT imaging is sensitive to density change due to radiation (Hilts et al., 2000). The research done by Hilts et al. has analyzed the response of CT number of PAG gel and compared it with the MRI method. Despite the low dose resolution in the CT technique, it has provided accurate localization of high-dose gradients for radiotherapy cases (Hilts et al., 2000).

A study has been conducted to obtain the effects of CT imaging device radiation on CT number response in nPAG normoxic gel. The response of the gel to the 140 kVp photon energy emitted from the CT scanner is much lower than the response to the 6 MV photon emitted from the accelerator device (Baxter et al., 2007).

A small density change occurs in the polymer gel after irradiation. As a result, it changes the X-ray attenuation of the gel (μ) and therefore the CT number (NCT), which leads to a dose-dependent contrast in the irradiated CT gel images (Jirasek and Hilts, 2009).

Gel formulation can affect the shape and range of the CT dose response and the extent (and in some cases) of the quasi-linear region (Hilts et al., 2004; Venning et al., 2004). The change in measured gel density (or change in NCT) is the result of two factors: 1) the amount of polymer formed and 2) the change in density that occurs in the monomer-to-polymer conversion (Jirasek and Hilts, 2009).

The choice of CT technique (kV, mA.s) does not affect the sensitivity of the polymer gel dose response. However, the temperature of the tube has an effect and the CT scanner must be thoroughly warmed up before imaging (Hill et al., 2005). The scanning technique has a tremendous effect on the image noise and thus the dose resolution (Hilts et al., 2005; Trapp et al., 2002). Studies show that CT imaging remains an attractive possibility for polymer gel dosimetry with further work on improved formulations for polymer gel dosimetry and increasing dose-response sensitivity currently underway. Therefore, this technique is closer to MRI and optical computed tomography in its clinical application.

Hill et al. obtained the computed tomography dose index of normoxic polymer gel using X-ray CT to determine the patient dose and compared it with the ionization chamber (Hilts et al., 2005). This research showed that normoxic polymer gel dosimeters are a helpful tool for determining CTDI and dose distribution with a CT scanner (Hilts et al., 2005).

A study was conducted on NIPAM gel using a CT scanner with increased dose sensitivity and improved dose resolution (Chain et al., 2011). Research showed that gelatin had a mild effect on dose sensitivity and this formulation led to an increase in dose resolution (0.052) for X-ray CT readout (Chain et al., 2011).

PAG gel was irradiated with a 6 MV energy beam and a maximum dose of 8 and 15 Gy and imaging was done by CT (Audet et al., 2002). This research showed that the image contrast was too low to accurately determine the relative dose in the 8 Gy (Audet et al., 2002).

MAGIC normoxic polymer gel dosimeter was irradiated by a Co-60 source and imaged with X-ray CT (Hill et al., 2005). This study showed that the maximum sensitivity is equal to 0.115 ± 0.005 $Gy^{-1}HUs^{-1}$ and although the sensitivity is lower compared to PAG gel, it has a more extensive absorption dose range (Hill et al., 2005).

PAG gel was irradiated with a 6 MV photon energy beam and examined with a CT scanner, and the dose resolution was compared with MRI and optical computed tomography methods (Hilts et al., 2005). This study showed that the dose resolution with a CT scanner is 67% lower than MRI and optical CT, but the imaging time is much lower (Hilts et al., 2005).

Research has shown that phantom design, CT image characteristics and imaging technique, time requirements, dose-response characteristics, and achievable dose resolution are all critical considerations. Specific recommendations for optimizing X-ray CT system performance include using polyester phantoms for vial imaging, minimizing phantom size when possible, maximizing tube voltage to reduce noise, and increasing voxel size that is clinically appropriate. CT image uniformity and dose-response repeatability are both important to dosimeter accuracy. Due to the optimization of the technique, it has been shown

that the dose resolution in gel computed tomography provides dosimetry close to that of MRI and OCT in a shorter imaging time (Hilts et al., 2005).

2.4 Other imaging methods

Ultrasonic imaging is capable of detecting structural changes caused by chemical reactions to ionizing radiation. Ultrasound has been proposed as an alternative 3-D method for gel dosimetry reading. The ultrasonic properties of MAGIC gel based on the pulse-echo dosimetry system technique have been investigated by Atkins et al. (Atkins et al., 2010). In this research, the speed of sound, damping coefficient, and density of MAGIC gel were measured in a wide range of temperatures and doses. A non-linear relationship between ultrasonic attenuation and dose was observed (Atkins et al., 2010). The speed of sound was 1550.3 ± 1.5 ms and the dose sensitivity was 0.14 ± 0.03 $ms^{-1}.Gy^{-1}$ at 25 °C. This study showed that lowering the temperature leads to a decrease in the sensitivity and speed of sound (Atkins et al., 2010). The variation of acoustic properties with temperature suggests that temperature management should be considered in developing any pulse-echo dosimetry system and temperature-dependent calibration (Atkins et al., 2010).

Research on the dependence of ultrasonic attenuation coefficient with dose and frequency in MAGIC gel exposed to homogeneous fields of ionizing radiation was done (Crescenti et al., 2007). Research showed that the damping coefficient differs for all frequencies in the range of 2 to 6 MHz and increases with increasing frequency in a quasi-linear region (Crescenti et al., 2007).

The research was conducted to make a MAGIC gel with ultrasound imaging properties equivalent to human body tissue (Goharpey et al., 2020). In this study, by adding compounds to MAGIC specific gel, the parameters of sound propagation speed and damping coefficient were calculated in the dose range of 0 to 50 Gy (Goharpey et al., 2020). The results of the research showed that the edible gelatin used in this study was a suitable substitute for commercial gelatins and could form images of breast tissue equivalence due to scattering by graphite particles (Goharpey et al., 2020).

Mather and her colleagues irradiated the dosimeter gel based on acrylamide with a cobalt source of 60 to 50 Gy and compared its ultrasonic parameters with the MRI method (Mather et al., 2002). The investigation showed that this gel has a sensitivity of 1.8×10^{-4} $ms^{-1}.Gy^{-1}$ and a wider dynamic range than the dose-response curve obtained in the MRI method (Mather et al., 2002).

Raman spectroscopy, which investigates the orientation of molecules or the change of vibrational state in molecules in the interaction of light and matter, is a desirable method for discovering information about the state of matter and chemical reactions (Bong et al., 2011).

Research was conducted to quantitatively analyze the rate of polymerization and the rate of change of monomers by monitoring the amount of radiation by Raman spectroscopy. The results showed a decreasing rate of monomer, while polymerization showed an increasing trend. The sensitivity parameters for monomer and polymer chains were in the range of 2.6 ± 6.0 Gy and 2.3 ± 7.2 Gy, respectively, which indicates a relatively good adaptation of the monomer reduction rate and the polymerization increase rate (Bong et al., 2011).

Research has been done to investigate the effects of oxygen permeation through the phantom wall on gel polymerization through Raman spectroscopy (Chacón et al., 2019). This study showed that Raman spectroscopy is the only method capable of providing direct information on the extent of polymerization and the nature of polymer formation (Chacón et al., 2019). Dosimeters stored in nitrogen instead of air had a similar response (Chacón et al., 2019).

Different light absorption of irradiated gels is measured by UV-Vis spectrophotometer (Rabaeh et al., 2018). The investigation of radiochromic gel based on FAC and gelatin was performed UV-Vis spectrometer at 550 nm at a dose range of 1 to 170 Gy. The gels turned pink due to radiation and the dose-response was measured linearly up to the range of 25 Gy (Gafar and El-Ahdal, 2016). The investigation of this research is to use the UV-Vis meter to measure the optical density of the colored gel clarified by radiation, which is simpler, faster, and more economical than MRI. This method is helpful for various radiation processing applications, for low-dose dosimetry applications (Gafar and El-Ahdal, 2016).

The dosimetry characteristics of acrylamide-based hydrogel (PAC) were investigated using a UV-Vis spectrometer in the dose range of 0 to 100 Gy (Soliman et al., 2022). In this research, glycerin was used in the hydrogel matrix to increase the response and sensitivity of the dosimeter to radiation. This study showed that the sensitivity of the gel increased by 30% (Soliman et al., 2022).

3 Results and Discussion

For gel dosimetry to become a widespread clinical tool, speed is needed. Users prefer to irradiate the sample, scan and assess the dose distribution quickly, and then decide based on the results. Choosing the type of imaging method varies depending on the conditions and type of gel. Familiarity with the features and application of any type of scanner can effectively help with accuracy and error reduction in gel dosimetry research. The features and challenges of commonly used imaging methods are shown in Table 2.

3.1 Magnetic resonance imaging method

Unlike other imaging methods, MR scanning of polymer gel dosimeters offers many degrees of freedom. Several quantitative MR features (such as T_1, T_2, and MTR) can be imaged, and several different MR sequences can be used for these features. Each feature or sequence generates a quantitative dataset of MR image parameters (De Deene, 2010).

Magnetic resonance imaging is possible for non-homogeneous gels with arbitrary shapes (Baldock et al.,

Table 2: The features and challenges of commonly used imaging methods.

Method of imaging	Advantages	Challenges
MRI	Use of non-homogeneous gels with arbitrary shapes	High costs and limited access
Optical-CT	High availability, cheap and providing high resolution	Dynamic limitation of dose and stability of ambient temperature
X-ray-CT	High accessibility, speed and facility of use	Low sensitivity and contrast
Ultrasound	Low cost and portability	Dependence on radiation dose and irradiated gel

2010). It also has advantages such as obtaining different parameters and creating image contrast for more accurate positioning of soft tissues, the ability to reflect biological characteristics such as tissue oxygenation and intravenous injection, and imaging capability without increasing radiation load to the patient (Lee et al., 2018).

Dosimetry challenges are the presence of a strong magnetic field. When the magnetic field is oriented perpendicular to the radiation beam, Lorentz forces act on the secondary electrons and cause hot and cold spots in the tissue transfer regions, such as the radiation beam leaving the tissue to the air (Lee et al., 2018).

3.2 Optical CT imaging method

Optical computed tomography is physically similar to X-ray CT, but because it is adaptable to many more powerful light sources optical elements such as mirrors, lenses, polarizers, and efficient detectors are available. There are many potential weaknesses in optical computed tomography such as attenuation, scattering, polarization, and spatial changes of the refractive index. Optical CT for gel dosimetry is limited to attenuation measurements, defined as the sum of scattering and absorption along the path. Polymerized gels become cloudy with absorbed dose and as a result, the attenuation is due to scattering. Radiochromic gels also form a dose image due to changes in visible absorption (Jordan, 2004).

With the increasing use of complex treatments such as IMRT and stereotactic radiosurgery, there is an urgent need for a dosimeter that allows accurate 3D dose distribution measurement. Complex 3D dose distribution from IMRT and radiosurgery plans The results show that precise 3D dose distribution with high resolution is feasible. However, there are some dosimetry issues with gel dosimeters and radiochromics as technical and practical issues with optical CT scanners. some of these issues are: (1) consistency of sensitivity and uniformity of gel dosimeters (2) optimal sensitivity for the dynamic dose range, and desired signal-to-noise ratio for an optical CT scanner (3) logical scan speed (Wuu and Xu, 2011). Compared to MRI, optical computed tomography is convenient, inexpensive, and capable of providing high resolution for measuring the desired brachytherapy sources (Heard and Ibbott, 2004).

3.3 X-ray CT imaging method

X-ray Computed tomography can be used to measure radiation-induced changes in the linear attenuation coefficient of polymer gel dosimeters. The minimum detectable dose in computed tomography imaging for sensitive compounds is high, usually greater than 1 Gy (Jirasek, 2010). Furthermore, the dose resolution (95% confidence) remains high (multiplicity) and is much higher than MRI (Trapp et al., 2001). This fact is mainly responsible for the lack of clinical applications of polymer gel dosimetry using CT (Jirasek, 2010). The primary limitation of X-ray CT for gel dosimetry scanning is the low contrast and poor dose resolution of dose images generated by the system (Jirasek et al., 2010). The low contrast is mmainly due to the low dose sensitivity of the polymer gel formulation flow for X-ray CT imaging (Jirasek et al., 2010).

To improve the dose resolution, image filtering has been performed after acquisition (Hilts and Duzenli, 2004). While some filters look promising, it should be noted that filters can extend semi-dark regions and filter performance can vary based on the specific image in question (Jirasek, 2010).

The advantages of CT are access to CT scanners in clinical radiation therapy environments, ease and speed of obtaining images, and relatively insensitive and stable CT dose response to environmental factors. The disadvantages of working with CT are very low sensitivity of CT number to dose and applying additional dose to the gel (Jirasek and Hilts, 2009).

3.4 Ultrasound imaging method

Ultrasound imaging of polymer gel dosimeters was first presented by Mather et al. in 2003 (Mather et al., 2003) and is based on the change in the ultrasonic properties of the irradiated polymer gel. Although ultrasound techniques may not necessarily be superior to current evaluation techniques such as MRI, they have some potential advantages such as relatively low cost and portability. Ultrasound research is expanding to develop tools capable of imaging dose distribution with ultrasound (Mather et al., 2002).

The use of this polymer gel imaging method is promising, but research has shown that both the ultrasonic velocity and attenuation in the irradiated gel are dose-dependent and, in addition, strongly dependent on the type of polymer gel under irradiation (Jirasek, 2010).

3.5 Raman spectroscopy method

Raman spectroscopy of the PAG dosimeter was first proposed by Rintoul et al. (Rintoul et al., 2003). They utilized the fact that the loss of monomers may be monitored by corresponding changes to the Raman spectrum (Rintoul et al., 2003). Reconstruction of the dose-depth dependence was performed using the analysis of the main components of the irradiated gel.

Recent research has shown that Raman microscopic imaging is potentially feasible for polymer gel dosimetry. For example, it can be used in clinical cases for brachytherapy bead dose distribution (Jirasek, 2010).

4 Conclusions

While magnetic resonance imaging and optical computed tomography were the primary methods for imaging polymer gel dosimeters, alternative methods such as X-ray, CT imaging, and ultrasound imaging are currently under development. The development of imaging technology promises more use of polymer gel dosimeters and its more clinical applications.

Magnetic resonance imaging has higher costs and more limited access than other options, and the ability to reflect biological features and imaging without increasing radiation load on the patient is one of the prominent features of this method. Optical computed tomography measurements are being refined as researchers explore current limitations. It has been found that scanning techniques where temperature plays a significant role in quantitative measurements, providing the most accurate data require a stable temperature environment. Refractive index compatibility of liquids appears to be a current limitation to reproducibility in measurements. Optical computed tomography may require the development of complex scanners that incorporate active beam steering to eliminate the refractive index matching requirement.

The stability of dose-response to environmental factors in computed tomography is one of its characteristics, and very low sensitivity can be mentioned as an essential challenge in this method. In the ultrasound imaging method, the characteristics of low cost and portability, dose-dependent attenuation, and strong dependence on the type of gel are the challenges of using this method. Raman tomography imaging, while not comprehensively tested on polymer gel dosimeters, offers an exciting possibility for high-resolution "fine" imaging of the dose distribution.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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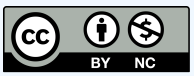

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