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Developing a wireless sensing method for the measurement of gamma radiation dose based on the polymerization of acrylamide

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ABSTRACT

A wireless sensing method for the measurement of gamma radiation dose has been developed based on the fact that gamma rays can initiate the polymerization of acrylamide, which causes an increase in solution viscosity that can be detected with a wireless magnetoelastic sensor. The magnetoelastic sensor is able to wirelessly detect the resonance frequency shifts of a magnetoelastic foil in response to changes in solution viscosity. There is a linear relationship between the resonance frequency shift and gamma radiation dose in the range of 0–50 Gy (under optimal conditions) with a detection limit of 0.25 Gy. This method has the advantage of providing real-time, continuous measurement *in situ*. The method has been used successfully to determine the gamma radiation dose in real exposure scenarios, with satisfactory results.

1. Introduction

Gamma rays are high-energy electromagnetic waves generated by the disintegration of radionuclides. They can penetrate the skin and destroy cells and tissues, thereby causing radiation damage. The detection of the gamma radiation dose is important for the protection of personnel and the environment. The same properties that make gamma rays dangerous can also make them useful. One of their most important applications is in medical radiotherapy, especially in cancer radio-treatment (Korytko et al., 2006; Jensen et al., 2005). In the treatment of cancer with gamma rays, the radiation dose should be strictly controlled. Excessive radiation will damage normal cells and tissues, whereas insufficient doses cannot destroy the tumor cells. Therefore, it is very important to assess the gamma radiation dose accurately in radiotherapy.

In general, the determination of the gamma radiation dose is mainly based on the detection of energy transfer and absorption. At present, several dosimetries have been proposed for the determination of the gamma radiation dose. Although each has its own advantages, the traditional dosimetry devices, such as ion chamber devices (Varatharaj et al., 2010; Wilcox et al., 2008; Jones and Paulus, 2008), thermoluminescent devices (Khoury et al., 2007), diode detectors (Yokota et al., 2008; Araki et al., 2003) and film dosimeters (Varatharaj et al., 2010; Wilcox et al., 2008), are not well suited to the task of real-time, low cost, *in situ* and continuous measurement of radiation dose, and these devices are also inconvenient for use in multiple locations in three-dimensional space. On the other hand, Fricke gel dosimetry (Mangueira et al., 2010) and polymer gel dosimetry (Allahverdi et al., 2009; Vaijapurkar et al., 2008) are effective for the measurement of three-dimensional distributions of radiation doses. In the gel dosimetries, magnetic resonance imaging (MRI) (Allahverdi et al., 2009; Papagiannis et al., 2005), optical computed tomography (OCT) (Babic et al., 2008) and X-ray computed tomography (Hilts et al., 2005) are the major techniques used for measuring radiation dose. However, there are also some significant disadvantages to these gel dosimetries, such as the cost and the inconvenience of real-time continuous measurement. Therefore, it is necessary to develop new dosimetries for the determination of the gamma radiation dose.

Ten years ago, a new type of wireless sensor was developed based on magnetoelastic materials made of amorphous ferromagnetic alloys of iron, nickel, molybdenum and boron (Grimes et al., 2002). When excited by an external alternating magnetic field, such magnetoelastic sensors can magnetostrictively vibrate, and in turn, they can produce a synchronous magnetic flux that can be remotely detected by a non-contacting pick-up coil. In this way, wireless sensing can be realized. Magnetoelastic sensors have the unique characteristic of being able to wirelessly detect resonance frequency changes in the magnetoelastic strip. The resonance frequency depends on the physical dimensions of the magnetoelastic strip, the

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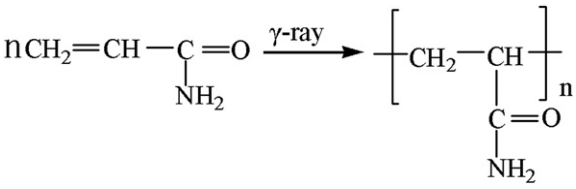
mass attached to it, and its environment. These properties allow magnetoelastic sensors to be used in various types of measurements. In recent years, magnetoelastic sensors have been used to determine physical parameters including pressure, temperature, humidity, flow rate, viscosity, and the concentrations of chemical substances such as H^+, carbon dioxide, ammonia (Grimes et al., 2002), mercury (He et al., 2009a), and calcium oxalate (Bouropoulos et al., 2005). They have also been used to detect biological substances such as glucose (Cai et al., 2004), trypsin (Wu et al., 2006), avidin (Ruan et al., 2004), and microbes (Guntupalli et al., 2007; Huang et al., 2008; Pang et al., 2007). Additionally, magnetoelastic sensors have been used to monitor biological processes such as the growth of breast cancer cells (Xiao et al., 2008) and *Mycoplasma genitalium* (He et al., 2009b).

To date, although progress has been made toward the application of magnetoelastic sensors, few studies have focused on utilizing them for the measurement of radiation doses. In this study, we applied wireless magnetoelastic sensors to the detection of the gamma radiation dose. Gamma rays can initiate the polymerization of acrylamide to form polyacrylamide, resulting in an increase in solution viscosity. The reaction can be expressed as follows:



As the reaction proceeds, the change in solution viscosity can be monitored by using a wireless magnetoelastic sensor. The degree of polymerization is related to the gamma radiation dose, and the solution viscosity is related to the degree of polymerization. Thus, the gamma radiation dose can be determined by measuring the resonance frequency shift of the sensor. Based on these facts, we developed a wireless sensing method for the measurement of the gamma radiation dose, a method that provides real-time, *in situ*, and continuous monitoring with features that make it sensitive, simple, and convenient. The method has been applied successfully to the measurement of the gamma radiation dose in real exposure scenarios, with satisfactory results.

2. Experimental methods

2.1. Materials and reagents

A magnetoelastic ribbon of Metglas alloy 2826 MB with a composition of $Fe_{40}Ni_{38}Mo_4B_{18}$ was obtained from Honeywell Corporation (Morristown, NJ, USA). Polyurethane Bayhydrol 110 was obtained from Bayer Corporation (Pittsburgh, PA, USA). Analytical grade acrylamide was used. A ^{60}Co gamma ray source was provided by the National Key Laboratory of Radon, University of South China (Hengyang, China).

2.2. Fabrication of sensor

The magnetoelastic ribbon was cut into foils with dimensions of 6 mm × 2 mm × 28 μm. The foils were ultrasonically cleaned in water and acetone, and they were dried under a stream of nitrogen. Both surfaces of each foil were dip-coated with a 1 μm layer of polyurethane Bayhydrol 110, and the polyurethane-coated foils were dried in air and then annealed at 150 °C for 2 h to form an anti-rust layer.

2.3. Wireless sensing apparatus and principle

Fig. 1 illustrates the experimental setup for wireless magnetoelastic sensing. A magnetoelastic sensor was inserted into a coil comprising an exciting coil and a response coil. The coil was connected to a signal excitation and detection system. The entire system was controlled with a computer. When the sensor was excited by a time-varying magnetic field, it liberated and emitted a corresponding response signal. The detection system was then able to detect the resonance frequency and amplitude of the signal. No physical connections between the sensor and the detection system are required for signal telemetry. The fundamental resonance frequency f_0 of the sensor in air is given by (Stoyanov and Grimes, 2000)

$$f_0 = \frac{1}{2L}\sqrt{\frac{E}{\rho_s(1-\sigma^2)}} \tag{1}$$

where E is Young's modulus of elasticity, σ is the Poisson's ratio, ρ_s is the density of the sensor material, and L is the longitudinal dimension of the sensor. When the sensor is immersed in a viscous liquid, the shift in the resonance frequency of the sensor is given by (Cai and Grimes, 2000)

$$\Delta f = f - f_0 = -\frac{\sqrt{\pi\rho_l f_0}}{2\pi\rho_s d}(\eta)^{\frac{1}{2}} \tag{2}$$

where f is the resonance frequency of the sensor in the viscous liquid, Δf is the shift in the resonance frequency, d is the sensor thickness, and ρ_l and η are the density and viscosity of the liquid, respectively. When ρ_s, ρ_l, d, and f_0 are constant, Eq. (2) can be expressed as follows:

$$\Delta f = -k\cdot\eta^{\frac{1}{2}} \tag{3}$$

2.4. Procedure

A magnetoelastic sensor was placed in a test tube (1 cm inner length) containing acrylamide solution and sealed. The tube was inserted into the exciting-response coil. Gamma irradiation of the acrylamide solution was carried out using the ^{60}Co gamma ray source. The irradiation was performed at ambient temperature. The resonance frequencies of the sensor in air and in the solution before and after irradiation were measured with the wireless sensing apparatus.

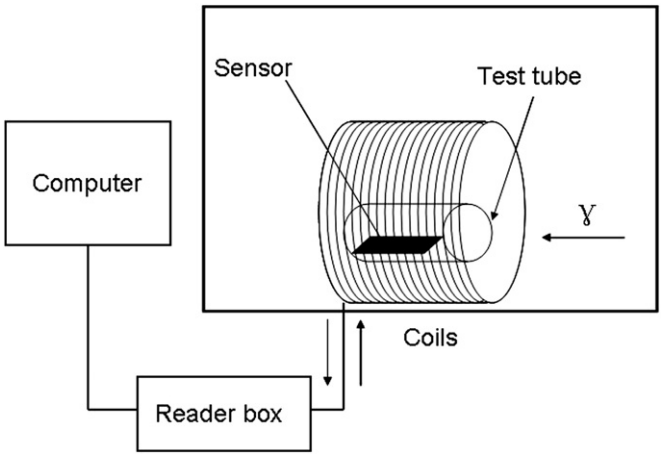


Fig. 1. Schematic illustration of experimental setup for the wireless magnetoelastic sensing measurements.