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RESEARCH ARTICLE

Characterization of irradiated nails in terms of depolarizing Mueller matrix decompositions

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Abstract Mueller matrices were measured for natural (or reference) samples of human nails and samples irradiated by a 2 Gy ionizing radiation dose. The elements of the total Mueller matrix as a function of scattering angle were measured in backscattering mode at a wavelength of 632.8 nm. Several types of depolarizing Mueller matrix decompositions, namely, Ossikovsky, Williams, and Chipman, were calculated as a function of scattering angle for each nail sample. A comparative analysis of the sensitivity of the Mueller matrix decompositions in relation to the problem of emergency dose assessment in nails was performed.

Keywords Mueller matrix, depolarization, human nails, ionizing radiation dose, scattering

1 Introduction

Radiological accidents like the Fukushima Daiichi nuclear disaster on March 11, 2011 in Japan or the Chernobyl Nuclear Power Plant accident on April 26, 1986 in Ukraine, as well as possible nuclear terrorist attacks, may result in overexposure of hundreds of thousands of people. It is important to triage the potential victims to separate the so-called "worried well" from those who might have been exposed to dangerous doses (2 Gy and higher) and will require immediate medical assistance.

Two different approaches are usually considered when it is necessary to recover the emergency doses, namely, biological dosimetry and physical dosimetry [1]. Biological dosimetry measures the radiation-induced changes in the tissues of organisms, whereas physical dosimetry deals with radiation-induced centers in either biological tissues or nonbiological materials that were located on/near an individual during the accidental exposure, and therefore, may be used to assess the individual's dose. Despite considerable progress in both biological and physical emergency dosimetry [2], there is no agreement on the selection of an emergency dosimetry technique (in combination with a corresponding radiation-sensitive material) that could be appropriate for radiological triage. Many materials have been tested as potential emergency dosimeters using different techniques. Very promising results have been obtained for different components of mobile phones (surface mount resistors, integrated circuits, and display glasses) using optically stimulated and thermo-stimulated luminescence techniques [3–9]. The main drawback of emergency dosimetry using mobile phones is the destructive measurement method, which requires disassembly of the phone and seems to be very inconvenient for the phone owner. Another problem with this technique is that the doses (which in fact are doses for phone parts) need to be converted to the dose of the phone owner, which could be a challenge. In this regard, dosimetry techniques using biological tissues seem to be preferable because they reconstruct the doses directly related to individuals. Two easily available human materials are considered as possibly useful for emergency dose reconstruction, namely, teeth and nails. Both have been tested with either electron paramagnetic resonance or optically stimulated luminescence (OSL) techniques [10–15] and have shown promising results, but the corresponding emergency dosimetric techniques have yet to be developed and validated.

In our previous paper [16], we investigated the possibility of using polarimetry of human nails for emergency dose assessment. For this purpose, the

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complete Mueller matrices for three sets of samples, reference and irradiated, were measured in visible ($\lambda = 632.8\ \mathrm{nm}$) light and analyzed by computing the single value depolarization metrics, depolarization index $DI(\boldsymbol{M})$ [17,18], depolarization metrics $Q(\boldsymbol{M})$ [19], Lorentz depolarization indices and Lorentz entropy (L_1, L_2, and HL) [20], and Cloude entropy H [21,22] for all the experimental Mueller matrices. Some of these parameters characterizing the depolarization properties of the samples were found to be sensitive to a 2 Gy ionizing radiation dose. In Ref. [16], it was convincingly demonstrated that the samples under study were anisotropically depolarized [23–25]. This result indicates that depolarization metrics cannot give an exhaustive description of the depolarizing properties of the objects under study; hence, it would be extremely interesting to analyze the measured data using Mueller matrix decomposition.

The main goal of the present paper is to compare the sensitivity of existing matrix methods [26–28] in relation to the problem of emergency dose assessment using human nails. As far as we know, this is the first such analysis.

2 Samples

Nails for this study were obtained from three volunteers, denoted below as AL, F23, and Joe. Nails were collected during routine hygienic procedures and were stored under ambient conditions between clipping and submission to the research laboratory.

Large aliquots approximately 3 mm × 3 mm in size were cut from the collected nail clippings for consecutive exposure and measurement by a polarimetric technique. Samples were exposed to a 250 mCi ^{90}Sr/^{90}Y beta source located at the Radiation Dosimetry Laboratory of Oklahoma State University. The source was calibrated against a National Institute of Standards and Technology (Gaithersburg, USA) secondary standard ^{60}Co source in terms of absorbed doses to water using Luxel Al_2O_3:C OSL dosimeters. Samples were exposed at a dose rate of 0.26 Gy/s.

Immediately after irradiation, samples were sent to a research laboratory in Kiev using an express mail service; samples were tested at 5 days after exposure.

Note that the orientation of the sample obviously has a significant effect on the measurement results. In principle, all samples had the same geometry: They were longer in one direction (along the cut line) and shorter in the transverse direction. To minimize the effect of the sample geometry on the measurement results, all the samples were carefully oriented in the same way in the polarimeter.

3 Measurements of Mueller matrices

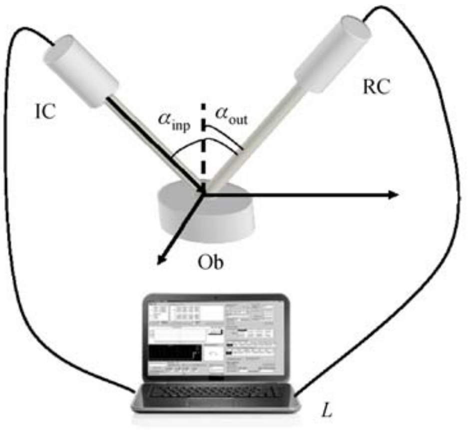


Fig. 1 Schematic illustration of the experiment, $\alpha_{\mathrm{inp}} = \alpha_{\mathrm{out}}$

The Mueller matrices were measured using the Mueller polarimeter described in Ref. [29]. The geometry of the experiment is shown in Fig. 1.

Figure 1 presents the geometry of the experiment. IC is an input channel that consists of a He-Ne laser ($\lambda = 632.8\ \mathrm{nm}$) that generates polarized light, a fixed prism polarizer, and two-phase plates, which are controlled liquid crystal cells with different azimuthal orientations and phase shift values. Ob is an object under measurement (one of the three nail samples described in Section 2). RC is the receiving channel, which consists of a continuously rotating crystal phase plate, a fixed prism polarizer orthogonal to the one in the input channel, and a photodetector. Thus, the receiving channel is actually a full-Stokes polarimeter [29].

For all three samples, we measured the complete Mueller matrices over a range of observation and input angles from 18° (this value was determined by design constraints of the receiving channel of the polarimeter) to 60° (for observation angles of $85° - 90°$, the intensity of the scattered radiation was vanishingly small).

4 Depolarization Mueller matrix models

When the degree of polarization of the output light is a function of the input polarization parameters, the depolarization is said to be anisotropic. In this case, a single value depolarization metric [16] providing a summary of depolarization by a medium apparently cannot give detailed information about all the features of depolarization. Such information can be obtained only from Mueller matrix models of depolarization. Several models have been proposed to describe anisotropic depolarization within the Mueller method. We will describe them briefly below.

The most accepted Mueller matrix describing the dependence of the polarization degree of the output light on the incident polarization is the following:

$$\boldsymbol{M}_{\Delta d}=\begin{pmatrix} m_{11} & 0 & 0 & 0 \\ 0 & m_{22} & 0 & 0 \\ 0 & 0 & m_{33} & 0 \\ 0 & 0 & 0 & m_{44} \end{pmatrix}. \tag{1}$$

The elements m_{22}, m_{33}, and m_{44} are interpreted physically as follows: m_{22} and m_{33} are the degrees of linear depolarization, whereas m_{44} is the degree of circular depolarization. If $m_{22}=m_{33}=m_{44}=d$, the Mueller matrix is an isotropic depolarizer, and when $d=0$, it is an ideal depolarizer.

The matrix $\boldsymbol{M}_{\Delta d}$ can be obtained if the Mueller matrix $\boldsymbol{M}$ of an object is presented as a product [20]

$$\boldsymbol{M}=\boldsymbol{M}_{D2}\boldsymbol{M}_{R2}\boldsymbol{M}_{\Delta d}\boldsymbol{M}_{R1}^{\mathrm{T}}\boldsymbol{M}_{D1}, \tag{2}$$

where the matrices $\boldsymbol{M}_{R1}$ and $\boldsymbol{M}_{R2}$ are the matrices of two elliptical phase plates, and $\boldsymbol{M}_{D1}$ and $\boldsymbol{M}_{D2}$ are the matrices of two elliptical polarizers.

However, the first multiplicative matrix model of a depolarizing medium was apparently the model proposed in Ref. [21]. In this model, the Mueller matrix of the depolarizing medium is represented as the product of deterministic Mueller matrices describing the linear birefringence, linear dichroism, etc., and a depolarization matrix of the form

$$\boldsymbol{M}_{W}=\begin{pmatrix} 1 & A_1 & A_2 & A_3 \\ 0 & P_1 & 0 & 0 \\ 0 & 0 & P_2 & 0 \\ 0 & 0 & 0 & P_3 \end{pmatrix}, \tag{3}$$

where P_1, P_2, and P_3 represent the degree of polarization of horizontal and vertical, linear with azimuths +45°, and −45°, and left and right circular polarization, respectively. The values in the first row of the matrix in Eq. (3), A_1, A_2, and A_3, are quantitative estimates of the depolarization asymmetry for the above three pairs of orthogonal input polarizations. This matrix is the reduced form of the Mueller matrix studied in Ref. [30].

Another example of the depolarization matrix was given in Ref. [22]:

$$\boldsymbol{M}_{\Delta}=\begin{pmatrix} 1 & 0 & 0 & 0 \\ m_{12} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix}. \tag{4}$$

This matrix is used in the following matrix model of a depolarization object:

$$\boldsymbol{M}=\boldsymbol{M}_{\Delta}\boldsymbol{M}_{R}\boldsymbol{M}_{D}, \tag{5}$$

where $\boldsymbol{M}_{R}$ is the matrix of a retarder, and $\boldsymbol{M}_{D}$ is the matrix of a diattenuator.

It can be seen that the matrices describing depolarization, $\boldsymbol{M}_{\Delta d}$, $\boldsymbol{M}_{W}$, and $\boldsymbol{M}_{\Delta}$, contain different numbers of parameters, which generally have different positions in the matrices. Further, we intend to establish which of $\boldsymbol{M}_{\Delta d}$, $\boldsymbol{M}_{W}$, and $\boldsymbol{M}_{\Delta}$, and which exact elements in them, are the most sensitive to radiation exposure of nails.

5 Results and discussion

Using the measured Mueller matrices of the nail samples, the depolarization matrices $\boldsymbol{M}_{\Delta d}$, $\boldsymbol{M}_{W}$, and $\boldsymbol{M}_{\Delta}$ were calculated for all observation angles.

Figure 2 represents the dependence of the elements of matrix $\boldsymbol{M}_{\Delta d}$ on the observation angle for samples AL, F23, and Joe.

As shown in Fig. 2, the nonirradiated and irradiated samples can be discerned from elements m_{22}, m_{33}, and m_{44} for all the nail samples. However, a comparison of the matrix $\boldsymbol{M}_{\Delta d}$ for different samples reveals that different elements at different angles of observation exhibit different sensitivity to radiation. For samples AL and F23, the most sensitive element is m_{22} measured at 18°, but for sample Joe, the most sensitive element is m_{44} observed at 42°.

Comparable results were obtained for matrices $\boldsymbol{M}_{W}$ and $\boldsymbol{M}_{\Delta}$ for different nail samples, as shown in Figs. 3 and 4.

As shown in Fig. 3, the nonirradiated and irradiated samples can be discerned for all the nail samples. For sample AL, this can be done using elements A_1, A_3, P_1, P_2, and P_3; for sample F23, the elements A_1, P_1, P_2, and P_3 may be used, and for sample Joe, all the elements are sensitive to 2 Gy irradiation exposure. For each sample, the following elements measured at the following angles were the most sensitive to radiation exposure of nails: for AL and F23, P_1 measured at 18°, and for Joe, P_3 measured at 42°.

As shown in Fig. 4, the nonirradiated and irradiated samples can be discerned using elements m_{22}, m_{33}, and m_{44} for all the nail samples. For each sample, the following matrix elements measured at the corresponding angles were the most sensitive to radiation exposure of nails: for AL and F23, m_{22} measured at 18°; for Joe, m_{44} measured at 42°.

In conclusion, for all the tested depolarization matrices of nails, the highest sensitivity to radiation exposure for any specific sample was observed for the same diagonal element measured at the same angle. The values of this sensitivity were: ≈ 0.07 for sample AL, ≈ 0.1 for sample F23, and ≈ 0.15 for sample Joe. Thus, all the tested depolarization matrices are equally sensitive to radiation exposure of nails.

6 Concluding remarks and directions for future research

The obtained results show that nail tissue is a medium with

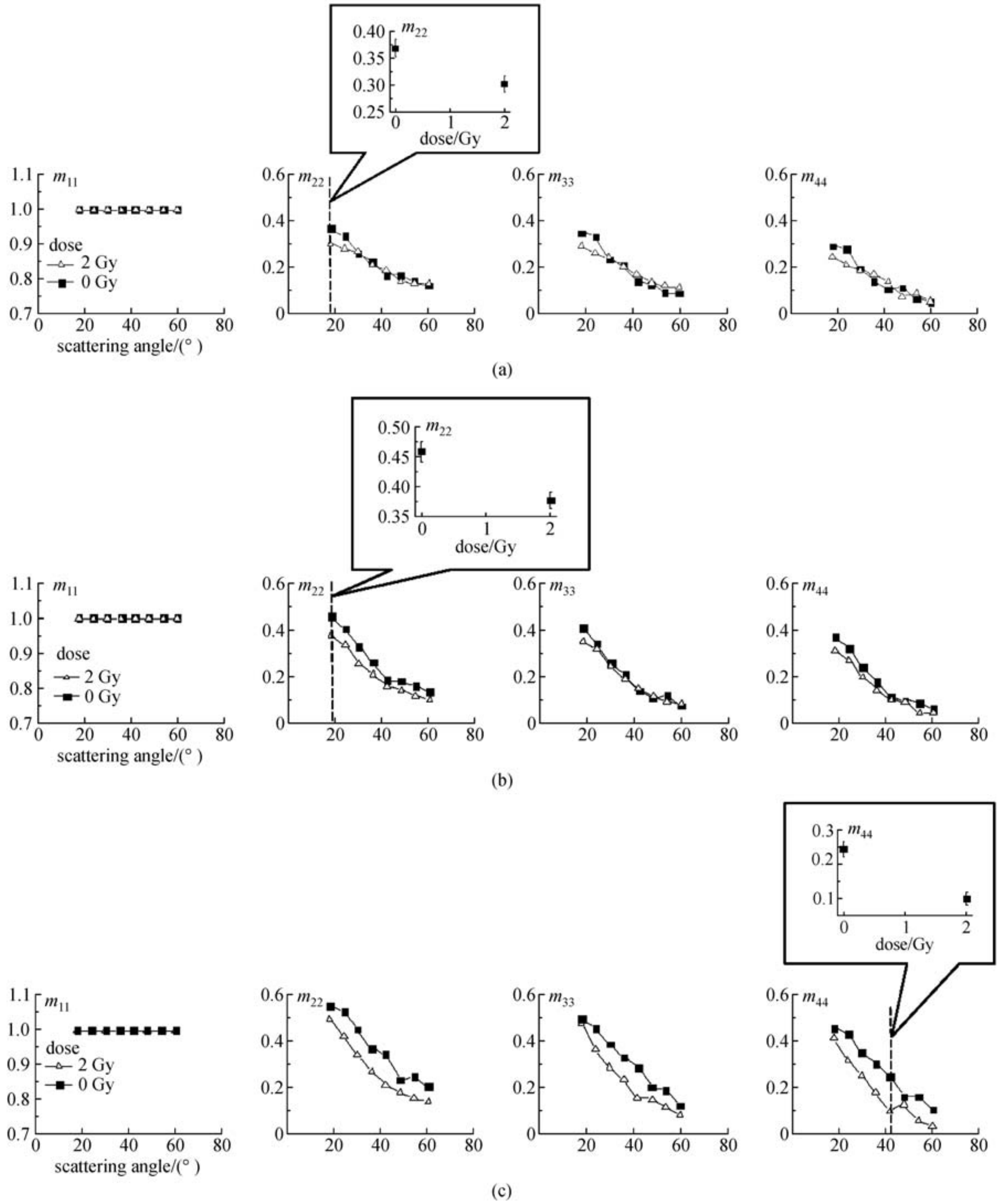
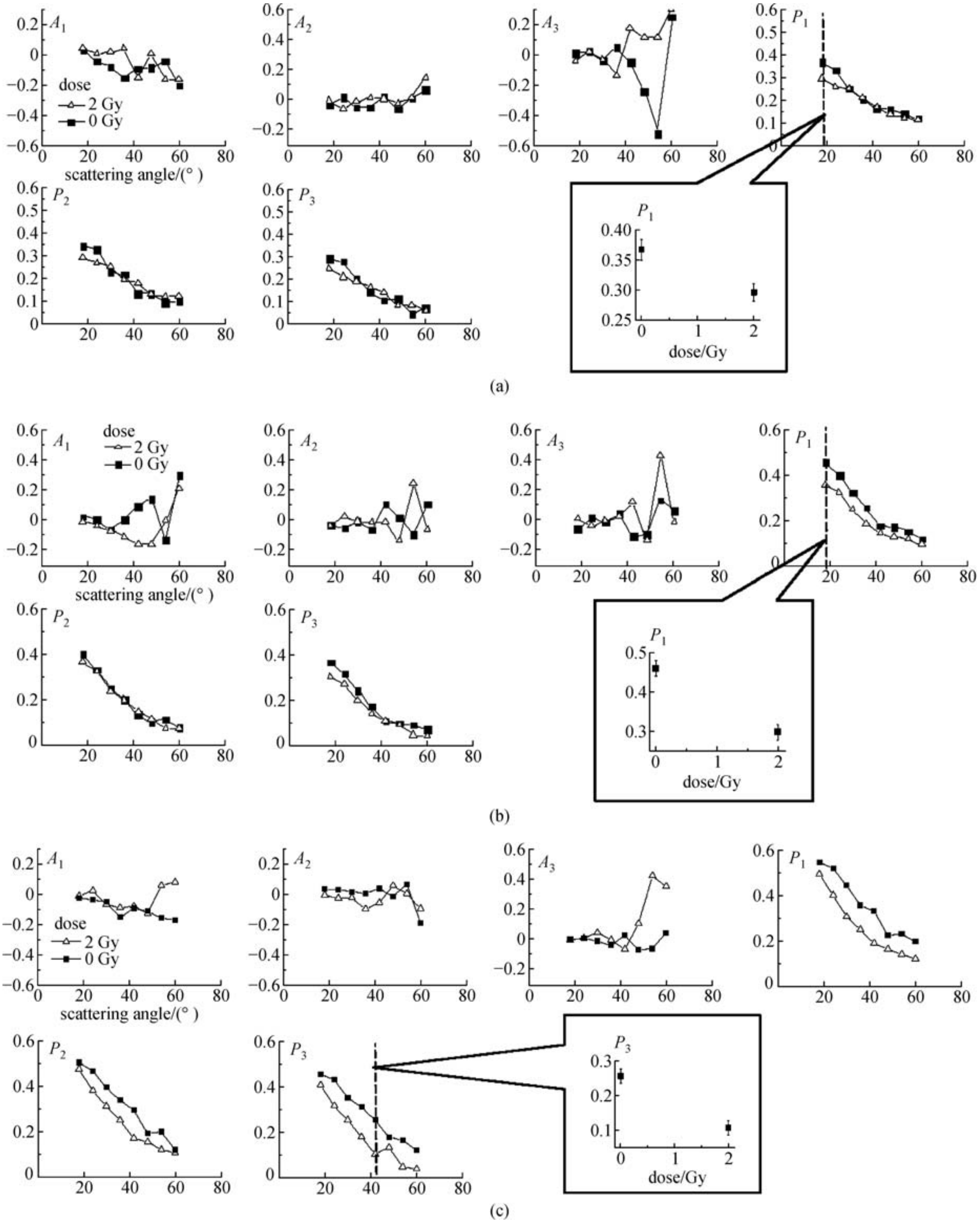


Fig. 2 Dependence of elements of the matrix $\boldsymbol{M}_{\Delta d}$ on observation angle for samples (a) AL, (b) F23, (c) Joe

complex polarization properties characterized by anisotropic depolarization. These properties are changed by exposure to an ionizing radiation dose. We demonstrated that analysis of depolarization matrices yields significantly more information about the object under investigation than the use of single value depolarization metrics [16] alone. In particular, the features of depolarization associated with the orientation and ellipticity of the polarization of the input radiation and described by diagonal elements of the depolarization matrices were established.

Thus, the Mueller matrix method is a promising technique for studying such objects. Next, experiments will be conducted on nail samples obtained from individuals of different ages, genders, and races to check the possible variability of the found effects. Dose responses for the most sensitive elements of matrices

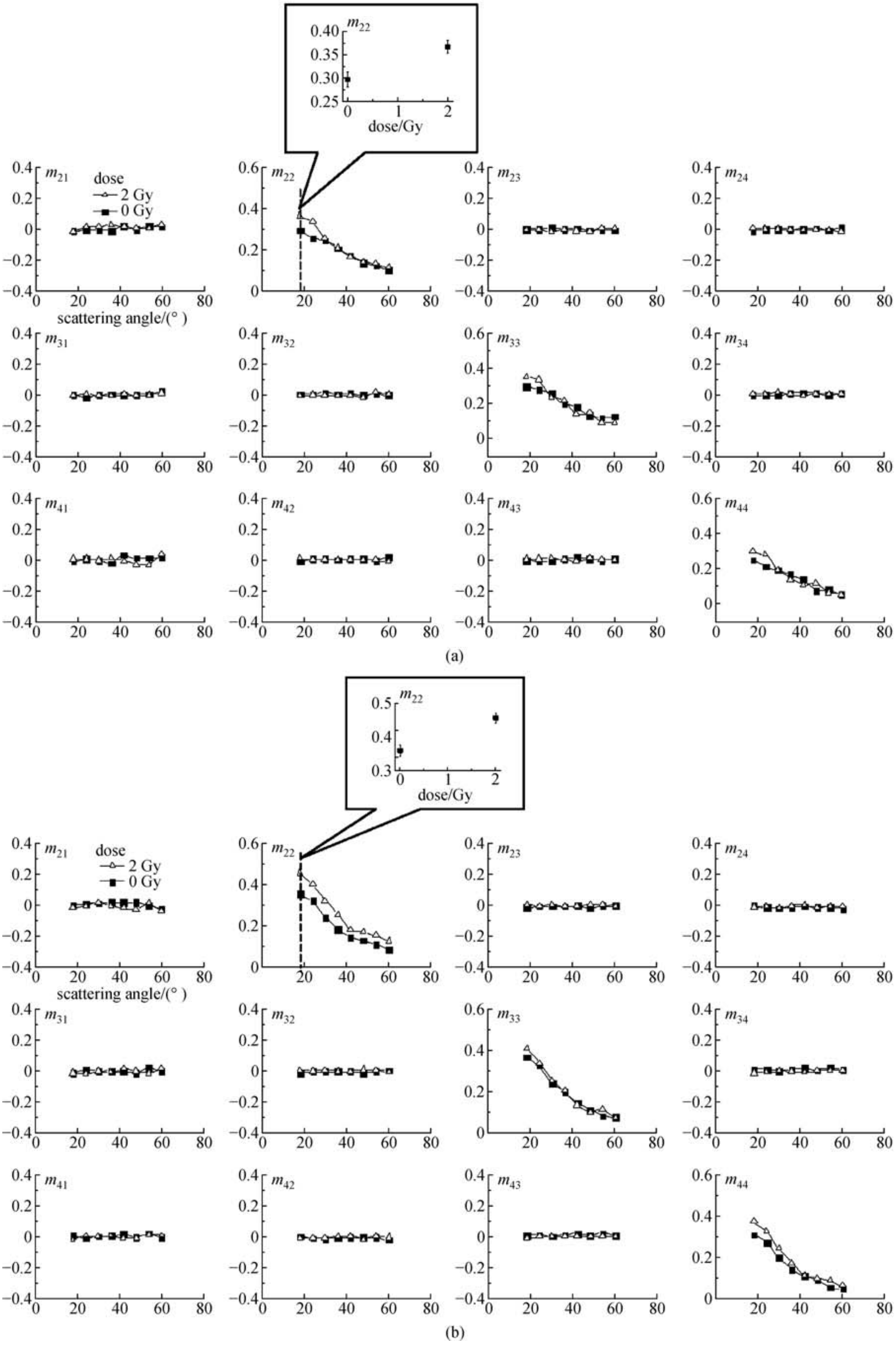


(a)

(b)

(c)

Fig. 3 Dependence of elements of the matrix $\boldsymbol{M}_W$ on observation angle for samples (a) AL, (b) F23, (c) Joe


m_{22}
0.40
0.35
0.30
0.25
0
1
2
dose/Gy
m_{21}
dose
2 Gy
0 Gy
scattering angle/(°)
m_{22}
m_{23}
m_{24}
m_{31}
m_{32}
m_{33}
m_{34}
m_{41}
m_{42}
m_{43}
m_{44}
0.6
0.4
0.2
0
−0.2
−0.4
20
40
60
80
m_{22}
0.5
0.4
0.3
0
1
2
dose/Gy

(a)

(b)

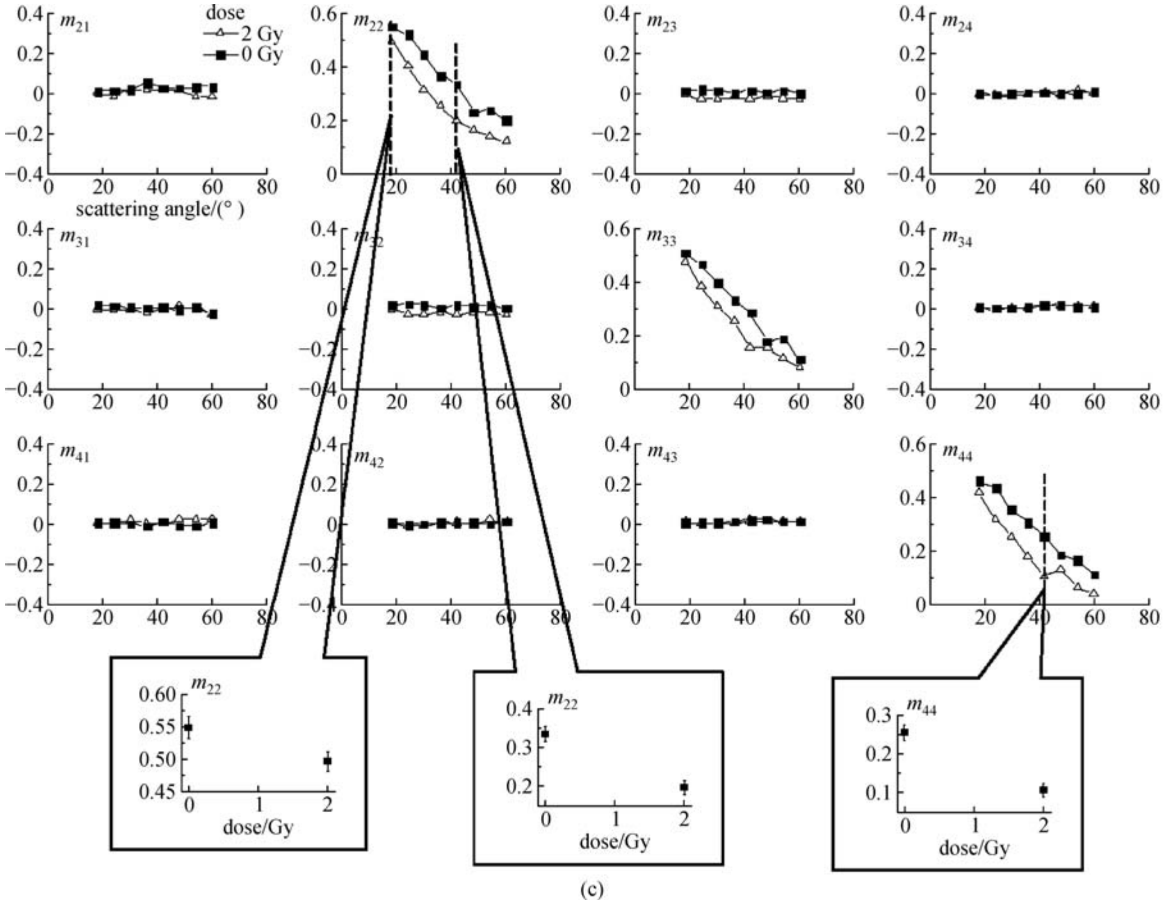


Fig. 4 Dependence of elements of the matrix $\boldsymbol{M}_\Delta$ on observation angle for samples (a) AL, (b) F23, (c) Joe

$\boldsymbol{M}_{\Delta d}$, $\boldsymbol{M}_W$, and $\boldsymbol{M}_\Delta$ should also be obtained. The long-term goal of this research is the development of an *in vivo* dosimetry technique that could be used to triage people after a possible large-scale radiological accident.

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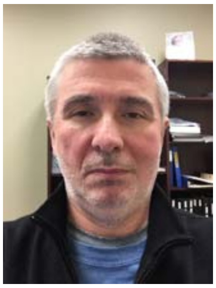

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