Radiation-induced signals analysed by EPR spectrometry applied to fortuitous dosimetry

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INTRODUCTION

In situations of radiological emergency, when exposed people do not wear a personal dosimeter, there is a need for methods suitable to assess retrospectively the dose persons received. The majority of the methods developed to this purpose are based on the detection of the changes the ionizing radiation induced in biological samples [1-10]. The dosimeter is then coincident with the person and in most methods it provides a measurement of the biologically relevant dose. In addition to these biological dosimetry techniques it is possible to estimate the dose received by victims of a radiation accident by measuring materials that can be easily found in objects positioned on or next to the potentially exposed persons. These methods make use of physical dosimetric techniques, such as electron paramagnetic resonance (EPR) or stimulated luminescence [7], and are all based on the quantitative measurement of radiation-induced damages in inert materials, thus providing the physically absorbed dose in the sample, in the same way as with personal dosimeters measuring occupational exposure.

In contrast to biological dosimetry, the changes measured by the physical methods provide the dose induced only by external, but not internal, exposure. Moreover, in the case of partial body or non uniform exposure, no effect will be observed in the material, if it was outside the radiation field. This may turn out in an advantage, because the dose distribu-
EPR dosimetry is based on the detection of radicals resulting from reactions triggered in matter by ionizing radiation. In solids, the radicals become trapped (i.e. they are not “free”) and in some cases they can be stable over long periods of time. EPR is then the choice method for direct detection of radiation-induced radicals in solids. Ionizing radiations induce radicals in most materials, but the yield of production varies significantly. Therefore, the suitability of materials as dosimeters is mainly related to their radiation sensitivity and signal stability in time. Materials that have already been investigated are for example sugar, plastics, glass, wool, cotton. Some of them look especially attractive for the triage of potentially exposed persons, because they usually found in portable devices or personal items.

Stable radicals are also generated in solid biological tissues (nails, hair and calcified tissues). The aim of this paper is to survey the current literature about methodologies and materials that have been proposed for EPR dosimetry in order to identify those that could be suitable for population triage according to criteria such as ubiquity, non invasiveness and easiness of sample collection, presence of a post-irradiation EPR signal, negligible background signal, linearity of dose-response relationship, minimum detection limit and post-irradiation signal stability.

**EPR SPECTROMETRY AND EPR DOSIMETRY PRINCIPLES**

Electron paramagnetic resonance (EPR) spectrometry is a technique to measure the concentration of radicals in organic and inorganic materials. Radicals are detectable by EPR thanks to uncompensated magnetic moments of the spins of unpaired electrons. The measurement is based on the detection of the microwave energy that is absorbed by the unpaired electron in a resonant process as they reverse their magnetic moments in an intense magnetic field.

The principle of EPR spectrometry is described in the literature, i.e. [11]. An EPR spectrum is obtained by scanning the absorbed microwave energy while sweeping the magnetic induction field. In order to reduce noise in spectrum recording, EPR spectrometers employ high-frequency magnetic field modulation in combination with phase-sensitive detection of microwave absorption. Because of this, the resonance is not revealed as an absorption curve, but as the first derivative of the absorbed microwave energy with respect to the magnetic induction field. The first derivative of the resonance microwave absorption curve is called EPR signal, and its peak-to-peak amplitude is proportional to the spin concentration and, in turn, to the concentration of radicals.

EPR dosimetry is a method for the assessment of absorbed dose from ionising radiation. It is based on the measurement of the concentration of stable radiation-induced radicals by EPR spectrometry. The calibration of EPR signal intensity as a function of absorbed dose can be done individually for each sample by additional radiation doses delivered with a laboratory source and then EPR measurement. This approach is very time consuming and requires a direct proportionality between the EPR response and the dose for a reasonably wide dose range. As an alternative method for materials with low intersample variability of radiation sensitivity the use of a standard signal-to-dose calibration curve is possible. Measurements are typically done using X-band microwaves (around 9 GHz). It is applied, e.g., for dosimetry in radiation processing by measuring radicals of the amino acid alanine [12], determination of age in archaeological or palaeontological dating by measuring radicals in quartz and carbonates [13], and retrospective dosimetry by measuring radicals in calcified tissues [8, 9]. EPR measurements can also be performed with other microwave frequencies such as L- and Q-bands.

Radical species can be produced by agents other than ionizing radiation, typically UV light and mechanical operations during sample collection. These radicals are usually different from those generated by ionizing radiation, although UV light may produce similar species. UV- and mechanically induced radicals are responsible for the background EPR signal in some materials.

Although slower than in liquids, radical recombination is not completely absent in solids. Average lifetime of radicals can range between a few hours and years. The recombination rate increases with increase of temperature and humidity. Freezing the sample after collection can slow down radicals recombination.

**MATERIALS INVESTIGATED FOR EPR DOSIMETRY IN A RADIATION ACCIDENT SCENARIO**

**Saccharides**

Saccharides are a readily available crystalline substance that is easily available in various places, including work places. Saccharides include monosaccharides (e.g. mannose, glucose, galactose, and fructose) and disaccharides (as e.g. sucrose, lactose, and maltose). Other than in the form of granular sucrose (i.e. common table sugar), they are also found in candies, sweets and pharmaceutical coverings. Monosaccharide derivatives (e.g. ascorbic acid and sorbitol) are also commonly found in food [14]. The assessment of the radiation dose by measuring sugar was reported for a few cases of radiation accidents [15-18].

All saccharides investigated in the literature presented a radiation-induced EPR signal when measured in their pure form. The EPR spectra of pure-form irradiated sugars are complex and different for each sugar type; because of the presence of several radicals and due to the hyperfine coupling [14]. For example, at least three radicals have been identified for sucrose with nine hyperfine coupling tensors with protons [19]. It is
worth noting that in most sweet industrial products, several types of sugars or sugar-like substances may appear associated, and that other substances may also induce EPR signals before or after being irradiated. The powdering of sugar produces radicals with a lineshape similar to that of radiation-induced radicals. With extreme powdering, the number of induced radicals has been reported to be equivalent to that produced by a dose of up to 10 Gy. Because of radical generation during sugar processing, some non-irradiated samples may show a background signal before irradiation [20, 21]. Current literature reports discrepancies regarding the presence of a background signal, which could be ascribed to mechanical manipulation.

The dose-response curve was found to be linear in the 0.5-100 Gy dose range for gamma rays irradiation [20-22]. A factor of 2 in the sensitivity to gamma radiation was reported for various saccharides [14, 21, 22]. The varying sensitivity to radiation in different saccharides mirrors their relative content of radicals. The lowest reported detection limit was about 200 mGy for table sugar [20] and 100 mGy using pellets of sugar and an inert silicone elastomer [23]. Lower detection limits can be achieved through signal manipulation processes.

In the first hours after irradiation, the EPR spectrum is unstable. EPR signal stability is recorded about 100 hours after irradiation at room temperature. Post-irradiation EPR signal intensity changes observed in the time interval before 100 hours depend on dose. This is indicative of a complex system, made of several radicals that contribute in different ways to the overall EPR spectrum. On a longer time scale, the number of radicals scarcely changes over several years in the natural environment, even when the atmospheric temperature varies [24]. Under conditions of high humidity there is a strong loss of signals (> 40%) [25]. Exposure to UV also induces the formation of radicals, which can contribute to the background signal if samples are not stored in the dark (table sugar). Some sugars show spectral shapes similar to those generated by ionizing radiation [14].

Radiation energy or radiation linear energy transfer dependence has also been studied for photons, heavy ions and neutrons [14, 21, 26-28]. Nakajima developed a protocol for the use of sugar as a personal monitor for radiation emergencies [29].

**Plastics**

Plastic is the general common term for a wide range of synthetic or semisynthetic organic amorphous solid materials. Plastics are typically polymers with high molecular weight, and usually contain other substances that improve performance and/or reduce production cost. Most daily life objects contain a large quantity of plastics: mobile phones, credit cards, buttons, watches, eyeglasses, etc. Plastics are easy to collect and prepare for measurement as they can be cut in small pieces without any special care.

The behaviour of plastics under ionising radiation has been extensively studied for years, because plastics are sterilized through high doses of ionising radiation. EPR is sometimes used to control the properties of plastics. EPR is also used to study graft polymerisation induced by ionising radiation. All these studies are usually performed at a very high dose of radiation. In the dose range of a radiation accident, a limited number of objects containing plastic materials have been investigated: PVC floor plates, PE-bags [30], credit cards [31] and plastic buttons [32-36]. Different authors only found plastic buttons suitable for retrospective dosimetry, in terms of dose sensitivity and signal fading. More recently, plastics from mobile phones, eyeglasses, watches, and badge holders have also been investigated [32, 36].

Most plastics exhibit different kinds of EPR signals prior to irradiation. The shape of radiation-induced signals also depends on the type of plastic. Thus, most of the irradiated plastic buttons investigated (mainly made of polyesters) exhibit a singlet line similar to the background signal [32, 34, 35]. The EPR spectra of other plastics (PMMA, Polycarbonate, CR-39 etc.) show various, more complex patterns after irradiation. Even for the same type of plastic, as for CR-39 and polycarbonate (main constituents of eyeglasses) for example, various spectrum shapes were observed [32].

The dose response was non linear for most of the investigated plastics. A linear dose response was only reported for one type of plastic from an eyeglass [32]. The lowest detection limit reported in the literature was estimated at 0.02 Gy by Nakajima for one plastic button, whereas other authors reported detection of a few Gy [34]. The variability of the dose sensitivity among plastics is remarkable, up to a factor of ten [32, 35].

For most investigated plastics, the radiation-induced EPR signals decayed with time. At room temperature, plastics lost about 50% of the signals within 20-30 hrs after irradiation. After 5-7 days at room temperature, it was nearly impossible to distinguish the radiation-induced signals from the background. Storage at a lower temperature slows down the decay, and at -30 °C the decay is almost stopped [32]. The plastic, exhibits a linear dose response, and a stable radiation-induced signal. No studies have been made on the effect of light exposure or on energy dependence. In case of a radiation accident, plastics may be measured but, owing to the fast decay of the signal observed for most plastics, there is no evidence that the dose can be successfully assessed.

**Glass**

Glass is an amorphous, usually transparent, inorganic, ceramic material which is often a mixture of silica and alkali. The properties of glass vary by adding other substances, usually in the form of oxides, e.g., lead, for brilliance and weight; boron, for thermal and electrical resistance; barium to increase
the refractive index, as in optical glass; cerium, for infrared ray absorption; metallic oxides for colouring; and manganese, for decolorizing.

Glass is rather ubiquitous as it is the constituting material of innumerable objects: windows, wind-screens, watches, display windows of electronic devices such as mobile phone screens, etc. In addition, glass is an easy-handling, chemically inert, inexpensive material and it can be reduced into small-size fragments or even particles. The use of the EPR technique to evaluate this material as potential dosimeter at low doses (in the order of 1 Gy) is recent [37-42]. Works are reported both for high dose applications [38-42] and accidental dosimetry [37-41].

Different types of glasses have been investigated. All the studies confirm that glass exhibits a specific radiation-induced signal [37-42]. The origin of the radiation-induced signal is not ascertained. A generally recognized hypothesis ascribes it to an oxygen hole centre, whereas some authors attribute the signal to pairs of exchange coupled Fe⁺ ions. All investigated glasses present a background signal, which partially overlaps the radiation-induced signal. The background signal is probably generated by impurities or metals in the glass during the manufacturing process. No additional signals are induced by mechanical stress when the glass is broken in small pieces, but crushing glass in fine powder (< 315 µm) induced some additional signals [43].

The detection limit is estimated at about 2 Gy, above which linearity of dose response holds up to the level of kGy. The post-irradiation signal is not stable. During the first 24-48 h a 10-35% decay at room temperature [37, 42, 43] is observed that depends on the type of glass. After 48 h, the fading rate decreased dramatically. In addition, the fading rate varies with the temperature of storage: at low temperature (4 °C) the reduction of both fading and the rate of fading are significant [37]. At room temperature, the signal decayed by about 50% in about 50 days, and 60% in 250 days [41]. At 40 °C, decay was 20-35% after 1 h [43]. Fading-related problems can be overcome by taking advantage of fading rate variation with temperature. By optimizing the temperature and the duration of heating in order to reach rapidly the quasi signal stability (equivalent to several tens of days of decay at room temperature), dose can be estimated with relatively good accuracy. The radiation-induced signal completely disappeared and the EPR signal returned to background level when glass was heated for more than 40 min at high temperature (200-400 °C) [37-43]. This peculiarity of glass could be used to improve accuracy in dose assessment. Indeed, for each sample a background signal could be determined.

No effect of light and no radiation energy dependence for γ-radiation have been detected while sensitivity dependence has been observed for X-ray photons below 100 keV [41].

**Clothing fabrics**

**Cotton**

Cotton is the oldest and most commonly used nanoporous material. Cotton is a remarkably pure fibre, consisting of polysaccharide chains arranged into a crystalline region surrounded by an amorphous porous region. The crystalline region has a cellulose core composed of long linear macromolecules created in the condensation of several thousand β-glucose molecules. Since cotton is very often the main constituent of clothing, it has been studied for accident dosimetry, to estimate the dose received by an individual exposed to ionising radiation [44, 45]. Cotton is obviously ubiquitous and would allow mapping the dose by measuring samples in contact with different parts of the body. Some EPR studies [46] showed that the results of dose determination based on both cotton clothes and biological materials (teeth or bones) of victims of accidental radiation exposure are in good agreement.

EPR studies performed by Kamenopoulou et al. [44] reveal that the EPR spectrum of cellulose irradiated at 300 K is a triplet attributable to non-bridged oxygen radicals. Background signals, specific for each manufacturing process, were also reported.

After a non linear, preliminary stage due to the background, cotton shows a linear dose-response curve to gamma-rays in a range from about 10 Gy to 10⁴ Gy, although the signal is already detectable below 1 Gy [45]. Cotton exhibits EPR signal fading with time at room temperature, revealing the existence of several decays components. This phenomenon can be explained by the occurrence of several processes: radical recombination, electron capture, charge transfer recombination and energy transfer from the matrix to radicals. Different factors may complicate the analysis of irradiated cotton: the exposure to solar light, the residual presence of detergent molecules from the washing, the water content, the presence of dust, fat, etc. In particular, water absorption is known to change the mechanical properties of the fibre and is thought to affect pore structure [47]. All these effects should be further investigated to establish cotton as a possible fortuitous dosimeter.

**Wool**

Wool has been for centuries a popular fibre for making warm garments, it could thus be considered as a readily available fortuitous dosimeter for investigating accidental radiation exposure. Wool fibres are made up of cuticle and cortical cells held together by the cell membrane complex which forms the only continuous phase in the keratin fibre. The microscopic structure of
the wool fibre, with wool scales on its outside and the cortex inside, is quite unique. Different alpha-carbon radicals of the polymer’s main chain will be generated by the ionizing radiations, due to the different chemical composition of wool scales and cortex [48].

The published EPR analyses of irradiated wool fibre keratin were mostly performed on behalf of textile industries to improve the properties of wool products [48-50], therefore at doses in the kGy range. Except for one study [31], the use of wool has never been reported for radiation accident dosimetry purposes. Nevertheless, because of its ubiquity, further studies on wool response at lower doses might be worthy.

The EPR signal of a dry wool sample irradiated and measured in air is a singlet signal [48]. Its intensity is quite weak because of the high radical recombination due to the oxygen molecules diffused into the wool fibre. The EPR background spectra are multi-component, with a central narrower, intense signal attributed to the pigments, since the intensity of this signal increases with the amount of pigment [50].

Further analysis reveal that most of the radicals formed from the surface of wool fibres are short-lived radicals (they decay within about 200 h), while the radicals from the cortex of wool fibres are mostly long-lived ones (stable after 400 h). The rate of signal decay increases with sample handling. The scales, particularly densely cross-linked with disulfide bonds, are the most susceptible to any outside interferences [49].

As for UV irradiation effects, Mamedov et al. [50] reported that a triplet spectrum is observed under the effect of UV-irradiation at -196 °C; as temperature is increased to room temperature, this signal becomes a doublet. As the dose of UV-irradiation increases, the EPR signal increases while the strength of wool keratin diminishes. Further studies are needed to investigate in detail the dosimetric properties of wool.

**Biological materials**

**Nails**

The presence of a radiation specific EPR signal in fingernails and toenails has been known for about 20 years [51, 52]. Because of the current need of finding ubiquitous dosimeters for the fast triage of potentially exposed people, for some years now EPR dosimetry with fingernails has reawakened the interest of investigators [2, 53-56]. The main practical advantage of nails is hard keratin, consisting of a crystalline fiber phase and of an amorphous protein matrix phase. The fiber phase consists of α-helical peptide chain coiled to stable micro-fibrils. The matrix phase is mainly stabilized by cysteine-cysteine disulfide bridges. The two phases are linked through secondary bonds.

After cutting and prior to irradiation, nails exhibit a complex, unstable EPR spectrum. Two non-radiation components in the EPR spectrum of fingernails were first defined by Symons et al. [51]. The first non-radiation signal was termed mechanically-induced signal (MIS) because it is induced by the clipping of fingernails at sampling and was attributed by Chandra and Symons to sulphur centered radicals generated by the break of the disulfide bridge [52]. The second non-radiation signal in the EPR spectrum of a fingernail was labelled as background signal (BKS), its origin unknown [53]. The so called BKS has been recently shown to originate from the mechanical stress at the time of fingernails cutting [54], with the paramagnetic species induced by mechanical stress located at the edge of the cut [56]. With a simple treatment in water the first MIS (MIS1) is completely eliminated, while the BKS (renamed MIS2) is considerably reduced. The origin of both MIS has been recently explained by Reyes et al. by plastic and elastic deformation generated by the cuts of the nails [54]. It is worth noting that the shape of MIS2 is identical to the radiation induced signals. Moreover, after having reached a minimum after the water treatment, its intensity increases with time.

The dose response depends strongly on the water content and on the state of mechanical stress of the sample. For mechanically stressed samples and/or dried samples dose response is linear up to 100 Gy, while for unstressed samples (after water treatment) the dose response is not linear. The effects of light and radiation energy dependence for photon have not been studied yet. The behaviour of EPR signals in nails is highly complex and more research is needed to establish a method for radiation accident dosimetry.

**Hair**

The easiness of collection has suggested investigating body and scalp hair as a fortuitous dosimeter as well. Hair is mainly composed of α-keratin, -the same group as nail keratin- and melanin. Melanin is an amorphous, insoluble, heterogeneous dark biological polymer containing a population of intrinsic, semiquinone-like radicals [57, 58].

Kudinsky et al [59] recorded a clear signal in hair after a 640 Gy irradiation, typical of a sulphur center radical in α-keratin. However unirradiated hair shows also an EPR signal due to the melanin semiquinone-like radical, that obscures the radiation induced signal at doses of a few tens of Gy. It is clear that in unirradiated samples the background signal varies from very small for blond hair, to values equivalent to several Gy for dark brown hair, its intensity depending on melanine content [1, 59]. Kudinsky et al performed irradiation and measurements at 20 and 13 °C, respectively, with doses of 50, 100 and 600 Gy, and found a non linear dose
response, indicating the presence of several radical species [59]. They also showed that EPR signal intensity decreases exponentially with time with a single, colour-dependent, characteristic decay constant [59]. For doses lower than 50 Gy, signal loss was about 95% 120 hours after irradiation. Otherwise, the radiation free radical decay process can be virtually stopped if the sample is stored in liquid nitrogen at 77 K. Further studies are required concerning the role of the moisture content of the hair sample (relative humidity of 15% in the work described above).

Melanin is susceptible to UV irradiation, because it works as a potent radical scavenger correlated with its role as protector against UV induced free radicals [60, 61].

The different melanin types are distinguishable by EPR studies, where the signals of photo-generated extrinsic radicals are distinct. The intensity of the melanin signal is directly proportional to the UV dose applied, up to saturation that depends on the quantity and type of melanin present in hair [60, 61]. Therefore, for radiation dosimetry purposes, the use of body hair unexposed to sunlight is more suitable than scalp hair.

The presence of interfering signals and a low-time stability of the EPR signal renders hair less suitable than fingernails. Fundamental understanding of the EPR spectrum could improve suitability of hair as a dosimetric material.

Calcified tissues

The main mineral component of human calcified tissues such as teeth and bones is hydroxyapatite, Ca_{10}(PO_4)_6(OH)_2, and its radiation-induced radicals are used for dosimetry. Tooth enamel is the most mineralized tissue in the human body, with a hydroxyapatite concentration of approximately 97%; bones contain up to 70% hydroxyapatite. The exposure to ionising radiation mainly generates stable CO_2- radicals from carbonate impurities, which are attached to or incorporated into hydroxyapatite crystals during formation. The concentration of CO_2- radicals is measured by EPR spectrometry and used to determine the absorbed dose. The radiation induced signal is stable over decades in living tooth enamel, while for bones it may be affected by bone remodelling. Detection limit for tooth enamel has been reported in the 20-200 mGy dose range, according to the measurement method, while for bones it is a few Gy. Owing to its low detection limit, tooth enamel can be used for verification of dosimetry in epidemiological radiation studies [9]. Tooth enamel and bones are also established matrices for the assessment of absorbed dose by persons after acute radiation exposure as in an accident [62-66]. In the case of localized exposures, bone biopsies from the irradiated region of the body may be very pertinent when duration and scenario of exposure are not known [64, 65]. Reconstructions of individual doses by EPR on tooth enamel were done for survivors of the atomic bomb explosions in Hiroshima and Nagasaki [67], the population exposed by the Chernobyl accident [68], nuclear workers in South Ural [69] and residents of the Techa river valley [70].

X-band EPR dosimetry with human calcified tissues is a reliable but invasive technique, and as it requires tooth extraction and bone biopsies, it is of limited availability for accident dosimetry. Therefore, for tooth enamel, two alternative approaches are under study by which to measure tooth enamel radicals either in vivo (i.e. without tooth extraction) or in small biopsies (rendering the measurement less invasive).

Tooth enamel in vivo dosimetry

An alternative approach to the X-band is given by the EPR instrumentation operating at lower microwave frequencies (L-band) that allows one to measure volumes as large as a whole tooth, i.e the measurement on teeth may be made in situ, without extraction [71-76]. In comparison with the X-band, L-band spectrometry poses several problems. Firstly, EPR signals are broadened at the low frequencies, resulting in a poorly resolved spectrum. Secondly, as calibration curves for non extracted teeth are not feasible, alternative approaches are under analysis to convert the signal reading to dose. At present, it is claimed that the minimal detectable dose is 1 Gy, with an uncertainty of 0.5 Gy, a value to be expected only under the best operational conditions [75]. More realistic estimates of detection limit are probably about a few Gy, with larger uncertainties. In vivo bone measurements have been investigated in a human finger, but in addition to calibration and reproducibility problems, a poor sensitivity and a minimum detectable dose of about 60 Gy were also reported [77].

Tooth enamel Q band dosimetry

Microwave frequencies higher than the X-band (i.e. at the Q-band) have a higher signal-to-noise ratio and a smaller measurement volume. These properties have suggested the use of the Q-band spectrometer for the measurement of tooth enamel biopsies. Romanyukha et al. [78] have proved that the measurement of a biopsy of 4 mg is feasible. Due to the lower reproducibility of sample positioning and thus of the EPR reading in the Q-band, the minimum detection limit is expected to be about six times higher than for the X-band dosimetry. Moreover Q-band EPR spectrometry has several technical drawbacks, not to mention the low accessibility of the instrumentation.

ESTABLISHED AND OPEN ISSUES REGARDING MATERIALS CANDIDATE FOR FORTUITOUS DOSIMETRY IN POPULATION TRIAGE

The current scientific literature proposes a number of materials as potential candidates for fortuitous
EPR dosimeters in radiation emergencies. Although all these materials present a post-irradiation EPR signal, not all of them are suitable for the early phase following a radiation mass casualty. Indeed, some of them do not fulfill part or any of the properties required for dosimetry in population triage, such as high ubiquity of the material, easiness and non-invasiveness of sample collection, a negligible background signal, a minimum detectable dose of a few hundreds of mGy, rapid reading, a post-irradiation time stability compatible with the delay from exposure to measurement. In the specific case of EPR dosimeters, for samples presenting significant inter-sample variability, it is also required that a direct proportionality holds between the EPR response and the dose in a reasonable dose range.

This paper surveys the current literature about these materials, analysing whether or not they meet the dosimetric requirements for population triage. The properties of the materials are schematically reported in Table 1. The materials are grouped in two categories: 1) inert materials that can be easily found in items usually worn or carried in pockets or handbags (clothing fabrics, plastics, glass, sugar); and 2) solid biological tissues (nails, hair, tooth enamel, bone). Although for some materials there are only preliminary studies which do not yield a complete picture, it is already possible to identify potentials and limitations.

Pure sugar has a very good radiation sensitivity, linear dose response and good signal stability, which explains the large number of studies on this material. However pure sugar is rarely found on a person’s body, whereas the properties of other kinds of sugars (as those present as additives in food) are not as good as those reported in the scientific literature. Every type of sugar requires individual dose calibration, which limits its use for triage. Materials that can be expected to be easily available for use in accident dosimetry are plastics and glass, normally found in portable electronic devices, such as handy phones, music players, etc. that nowadays are probably the most ubiquitous objects found on persons in developed countries. However, the radiation-generated EPR signals of plastics exhibit strong signal fading, which makes dose evaluation difficult for delays longer than two days after the incident, and application for triage is limited due to significant variability of dose response properties for different kinds of plastics. In glass, the radiation-generated EPR signals exhibit only moderate fading and variation of dosimetric properties. Clothing fabrics are very attractive because of their ubiquity, but the existing studies are not sufficient to give a complete picture of their applicability. Moreover the studies are limited to cotton and wool, whereas other more ubiquitous clothing materials, such as synthetic textiles, should be also investigated.

EPR dosimetry with human calcified tissue is a reliable but invasive technique, and only of limited availability for accident dosimetry. Currently under development there is an L-band EPR spectrometer for in vivo dosimetry and a Q-band method for dosimetry of small biopsies. In any case, both methods are in an early phase of development and are available only in very few laboratories around the world. As for human biological materials, nails are a potential tool for dose reconstruction by EPR in acute exposures because of

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<th>Table 1</th>
<th>Summary of the main characteristics required for dosimetry in population triage for the materials described in this review</th>
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<td>Category</td>
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<td>Inert materials</td>
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(-) Not detected. (*) under optimal conditions of detection.
their easy availability. A first protocol for emergency EPR dosimetry with fingernails was developed but, owing to signal fading, it was found applicable only within few hours following the incident. Investigations are ongoing to extend the time range of applicability. Hair has also been investigated because of its obvious ubiquity and because of the possibility of mapping body dose distribution by using body and scalp hair. However the high intersample variability is a limiting factor and the few existing studies do not indicate any reliable potential for its use in radiation emergencies.

CONCLUSION

In conclusion, the material that seems to better fulfill the majority of the above requirements for population triage and can be considered as the most promising candidate is glass. Furthermore, various objects containing glass can be carried by a single person, e.g., handy phone(s), music player, watch, allowing thus for a more accurate dose assessment in case of partial or heterogeneous exposure.

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