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Ionizing Radiation Induced Radicals

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1. Introduction

When ionizing radiation passes through a material it imparts some of its energy to that material. The imparted energy may be high enough to cause a break in bonds inside the molecules or between molecules or both, in such cases, free radicals are created. The type, lifetime, extent, fate and origin of those free radicals may differ according to several factors; most of them are beyond the subject of this chapter. However, the abundance of ionizing radiation induced radicals in a material is directly proportional (unless saturated) to the amount of ionizing radiation received by that material, hence it could be a method for determination of radiation doses passively by accurate evaluation of the extent of free radicals created.

Study of radiation induced radicals is not always related to radiation dose assessment; sometimes it is of great importance to investigate what type of radicals are produced when a specific material is exposed to a specific radiation dose, and for how long those induced radicals can persist. This could be of specific interest specially when dealing with environments of high radiation levels, for example: in space environments. Behavior of radiation induced radicals may lead to further understanding of molecular interactions or molecular dynamics, or may lead to a decision on the preference of a material for a specific design from the material science point of view.

2. Use of EPR for studying radiation induced radicals

Electron Paramagnetic Resonance (EPR) is the major universal technique for investigation of radiation induced radicals. The first observation of an electron paramagnetic resonance peak was made in 1945 when Zavoisky detected a radio frequency absorption line from a $CuCl_2.2H_2O$ sample (Zavoisky, E., 1945), The first EPR study of radiation damage in materials of biological (organic) interest powders was made by Gordy in 1955 (Gordy, W., et al., 1955), Papers on irradiated dimethylglyoxine and α-alanine of Miyagawa and Gordy (Miyagawa, I., and Gordy, W., 1959), and malonic acid by McConell (McConell, H., et al., 1960) soon published and confirmed that it was possible to investigate radicals produced by irradiating single crystals, in a similar way to that which had been used to study paramagnetic ions. Brady et al (Brady et al, 1968) suggested using EPR dosimetry and the additive re-irradiation method to obtain dose estimates from accidental overexposures, where human teeth were used for the first time as radiation dosimeter. In 1962, irradiated L-

α-alanine was suggested as a possible dosimeter material in the high-dose range by (Bradshaw, W., et al., 1962) after which great efforts were made to establish dosimetry systems based mainly on alanine/EPR systems (Deffner, U., and Regulla, F., 1980, Nette, H., et al., 1993).

3. Basic principles of EPR

Electron, as a rotating charge can be considered as a very tiny magnet, and hence the single electron which moves freely in absence of external magnetic field has only two orientations if placed in the field of external magnet: aligned parallel or anti-parallel. Those two cases reflect the two energy states arise after applying external magnetic field: state of lower energy when the moment of the electron, μ, is aligned with the magnetic field and a higher energy state when μ is aligned against the magnetic field.
The two states are designated by the projection of the electron spin, m_s, on the direction of the magnetic field. Because the electron is a spin 1/2 particle, the parallel state has $m_s = -1/2$ and the antiparallel state has $m_s = +1/2$. The energy difference between these two states, caused by the interaction between the electron spin and the applied magnetic field (B_0), is shown in the following relation:

$$\Delta E = g\, \mu_B\, B_0\, \Delta m_s = g\, \mu_B\, B_0 \tag{1}$$

Where μ_B is Bohr magneton (the natural unit of the electron's magnetic moment), g is the g-factor, and $\Delta m_s = \pm 1$.
So, if this electron gains energy of ΔE transition occurs between the two spin states, if this energy is in the form of photons, then:

$$\Delta E = h.\, \nu = g\, \mu_B\, B_0 \tag{2}$$

Where h is Planck's constant and ν is the frequency of the electromagnetic radiation.
Now, resonance may occur either by scanning frequency at a constant magnetic field or by scanning magnetic field while the frequency of the magnetic field was held constant and the later is easier from the practical point of view.

4. Radiation induced radicals in biological molecules

Study of radiation induced radicals in biological molecules or molecules of biological origin is of high concerns in order to understand their impacts on functional and/or structural changes of such molecules after exposure to ionizing radiation. In the following sections, there are two examples for studying radiation induced radicals using EPR in biological molecules: bovine hemoglobin as a biological molecule of animal origin, and chitosan as a biological molecule of plant origin.

4.1 Bovine hemoglobin

4.1.1 Structure

Structure of bovine Hb is shown in Figure (1). It is composed of two pairs of non-identical subunits, alpha and beta. Each alpha–beta pair is more closely associated than they are with each other, but the overall arrangement is roughly tetrahedral (http://www.bmb.uga.edu/wampler/tutorial/prot4.html) (Marta et al., 1996).

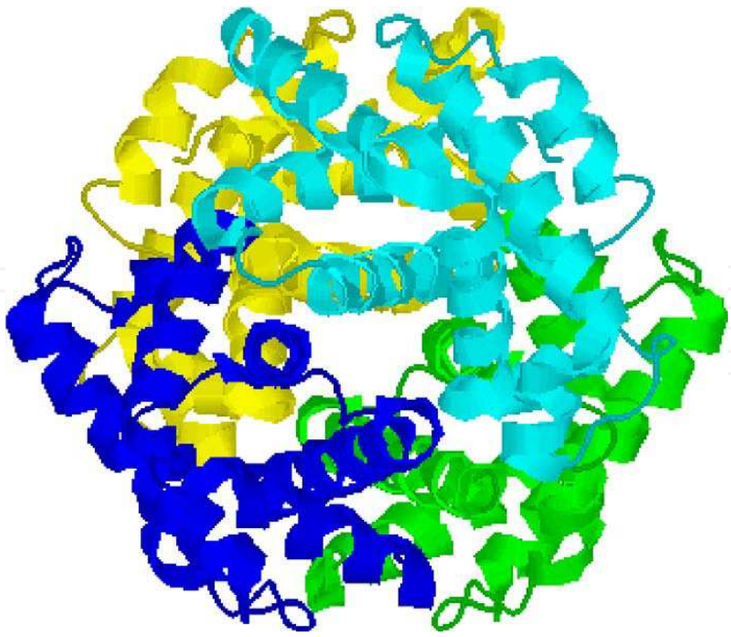


Fig. 1. Bovine Hb is composed of two pairs of non-identical subunits, alpha and beta. Each alpha–beta pair is more closely associated than they are with each other, but the overall arrangement is roughly tetrahedral.

4.1.2 EPR spectra of bovine hemoglobin

Fig. 2 represents the EPR spectra of unirradiated (solid line) and 743Gy gamma irradiated sample (dotted line). Major features of Bovine Hb EPR spectrum are comparable to the human one (Ikeya, 1993). About four features comprise the spectrum of g-factor equal to 5.91017, 4.27507, 2.14737 and 2.00557, respectively. The first two signals are due to Fe (III) of high spin form (S ¼ 5/2). The first signal (S1) is associated with oxidized heme iron, which clarifies its indication to methemoglobin (MetHb), in which a water molecule replaces O2 ion as a ligand of iron (Wajnberg and Bemski 1993). The second signal (S2) is corresponding to non-heme Fe(III) ions at sites endowed with rhombic symmetry, which is not associated with species involved in blood, such as transferrin which causes an EPR signal near g = 4.3 (Ślawska-Waniewska et al., 2004). From Fig. 2, it is clear that S2 is greater than S1, while this is not true in case of human Hb spectrum (Ikeya, 1993). This means higher nonheme iron content in bovine Hb than that of human. The nature of bovine Hb itself or the deterioration of its molecular structure and hence the decomposition of heme during sample preparation may give reason for the increase of non-heme iron content.

Third signal group (S3) is associated with low spin derivatives of ferrihemoglobin called ''hemichrome'', copper proteins and some transition-metal complexes (Rachmilewitz et al., 1971). Hemichromes are low spin derivatives of ferric Hb brought about through discrete reversible or irreversible changes of protein conformation (Venkatesh et al., 1997). The purity of our sample is about 95%, hemichromes are not easily to be separated from Hb molecules but the rest which is about 5% may contain some of these hemichromes that produce S3. Changes in normal Hb under the effect of time, pH and protein denaturants such as urea or salicylate can form different kinds of hemichromes with different endogenous ligands; hence hemichromes form the primary step to the destructive pathway for denaturation (Venkatesh et al.,1997).

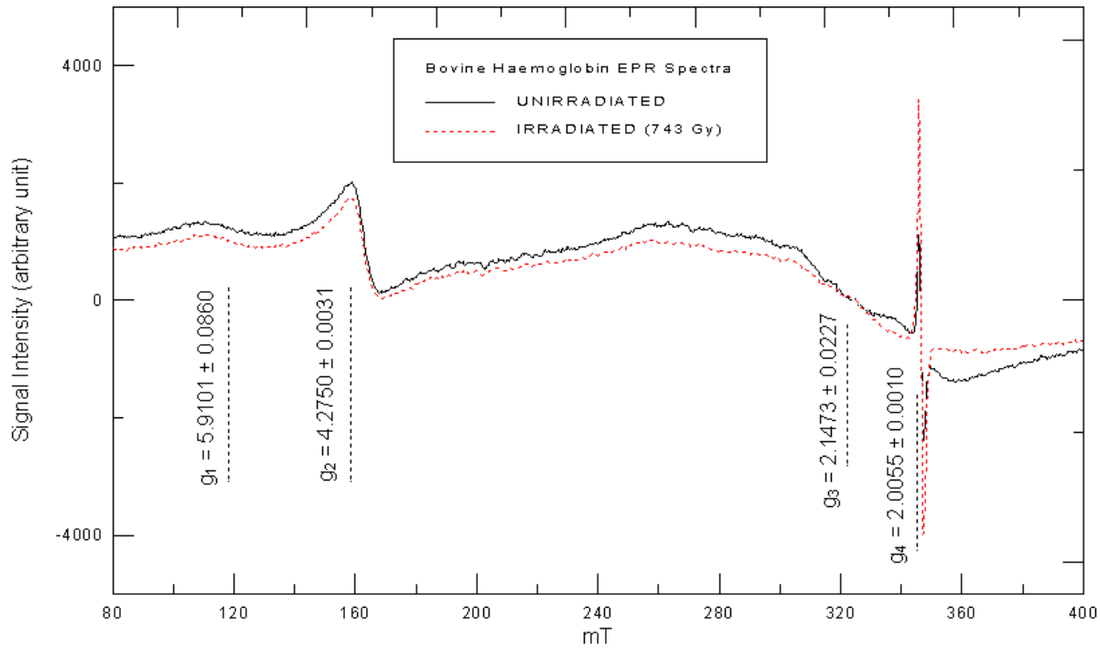


Fig. 2. EPR spectra of unirradiated and 743Gy gamma irradiated bovine Hb samples recorded at room temperature.

With regard to the fourth signal (S4), it appears as a singlet with no hyperfine structures as shown in Fig. 2. This signal is attributed to free radicals in hemoglobin formed by the degradation of blood constituents (Miki et al., 1987). Several investigators agree that at least two different kinds of radicals are formed on the protein (Kelman et al.,1994; Gunther et al., 1995). Although the formation of peroxyl radicals is well proven (Ikeya, 1993; Miki et al.,1987), this kind of radical constitutes only a fraction of the total concentration of radicals (Svistunenko et al.,1997a, b). The globin-based free radical (HB(Fe(IV)=O)) was suggested to be major contributor for S4 (Svistunenko et al., 1997a,b). Many investigations revealed that it is the tyrosine (Tyr) radical (shown in Fig. 3) (Svistunenko et al.,1997a,b, 2002, 2004; Svistunenko, 2005).

4.1.3 Radiation-induced changes in the bovine Hb EPR spectra

The EPR spectrum of 743 Gy gamma irradiated sample is shown in Fig. 2; from the figure it is clear that no new radicals have emerged, and no remarkable changes in the intensity of the first two signals were recorded. The unchanged intensity of the first signal (with all the irradiation doses) suggests no net change in MetHb, which may be explained as follows: The manipulated sample is in powder form, so any enzymatic reaction that can lead to change in MetHb content is excluded. The presence of oxygen is mandatory for MetHb production by other pathways such as the oxidation of heme iron by the electron transfer from Fe(II) to O2 creating Fe(III) and superoxide radicals (O_2^-) (Misra and Fridovich, 1972) During irradiation, wrapped samples were prevented from molecular oxygen in air. So, MetHb production through the second pathway is prevented; while the first pathway may be blocked by the removal of oxygen molecules from the bovine Hb sample during preparation in its powder form. The non-significant change in intensity of S2 by irradiation (Fig. 1), reflects the stability of non-heme iron content as radiation doses increase up to 743 Gy. It is clear from

Fig. 1 that S3 suffered apparent significant decrease upon irradiation; which ensures the decrease of the net amount of hemichromes and reflects the crosslinking processes following Hb irradiation at high doses. Results showed that the most obvious radiation-induced change in bovine Hb EPR spectrum is the significant increase in S4 even for very low dose (4.95 Gy). This may be due to the increase in the production of free radicals in Hb protein (peroxyl and tyrosyl radicals) and reflects the high sensitivity of Hb protein to irradiation.

4.2 Chitosan

Chitosan is a natural polysaccharide, that can be prepared on an industrial scale by deacetylation of much more abundant chitin and its chemical structure is a copolymer of β-(1-4)-D-glucosamine and N-acetyl- β-(1-4)-D-glucosamine (Jaroslaw, M., et al., 2005). Due to unique biophysical and chemical properties of polysaccharides, such as biocompatibility, biodegradability, nontoxicity and nonantigenicity (Bin Kang, et al., 2007), a broad spectrum of applications has been emerged in different modern fields: water treatment (Kurmaev E.Z. et al., 2002), chromatography, additives for cosmetics, textile treatment for antimicrobial activity (Le Hai et al., 2003), novel fibers for textiles, photographic papers, biodegradable films, biomedical devices, and microcapsule implants for controlled release in drug delivery. Also, its nano-ordered hydrogel is a potential responsive material for biochips and sensors for the development of PC- controlled biochips, and is used also in some attempts as a gene delivery system for curing of some hereditary diseases (IAEA, 2004). Tissue engineering and adsorption of metal ions as well as dyes removal are some of the many applications of chitosan (Jayakumar, R., et al., 2005).

4.2.1 Chitosan EPR spectral features

Figure (3) represents the EPR spectrum of chitosan-A. There are two overlapped singlet signals, the first signal (S_1) is of g-factor = 2.00725 ± 0.00018 with peak-to-peak line width

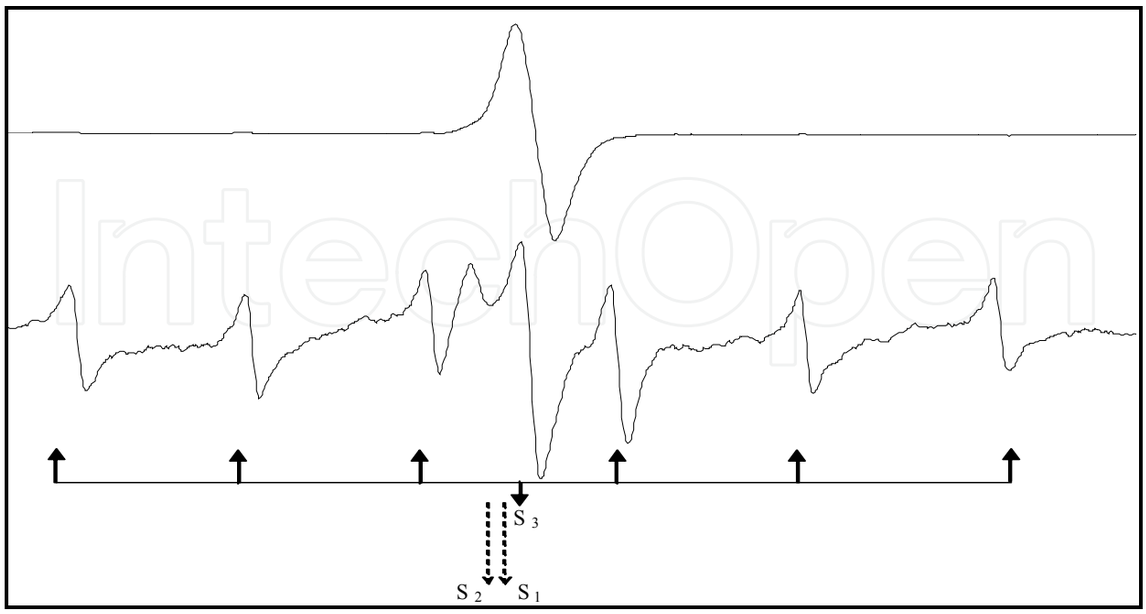


Fig. 3. EPR spectra of chitosan: lower represents the unirradiated sample spectrum, and the upper represents 30 kGy irradiated sample spectrum.

(W_{PP}) = 1.08 ± 0.072 mT, while the second signal (S_2) is of g-factor = 2.00966 ± 0.00073, while its W_{PP} = 5.70 ± 0.139 mT. EPR lines of Mn^{2+} (I = 5/2), ions are well recognized signal (S_3) with sextet hyperfine structure were observed (g_{iso}=2.01147±0.0002, a_{av}=9.06±0.35 mT). This signal is attributed to the presence of Mn^{2+} in crab shells from which chitosan-A was extracted (Maghraby, A., 2007). No new radicals have been emerged after irradiation up to 30 kGy, while some slight broadening in line width values for S_1 was noticed.

5. EPR radiation dosimetry

Radiation dosimetry using EPR utilizes the produced radicals as a result of the passage of ionizing radiation through matter, as extent of those radicals proportionate directly to the amount of ionizing radiation. Radiation dosimetry using EPR possesses some advantages which enabled the use of EPR in different fields of ionizing radiation dosimetry.

5.1 Industrial applications

5.1.1 Food irradiation

Food irradiation is a means of microbiological contamination reductions through which, food in packages or in bulk are exposed to a high radiation dose which is enough to destroy microbiological contents (Maghraby, A., 2007, Miyagusku, L., et al., 2007). The aim of food irradiation is sterilization and preservation of food during food transfer from region to another or to increase its quality locally before use (IAEA, 1978). The use of irradiation alone as a preservation technique can play an important role in cutting losses and reducing the dependence on chemical pesticides. Each year a few hundred thousand tones of food products and ingredients are irradiated worldwide. International food stuff trade especially seafood is growing up which increases the risk of the transfer of some diseases; this led the World Health Organization to legalize radiation treatment of food (WHO, 1988, 1994). International health and safety authorities have endorsed the safety of irradiation for all foods up to a dose level of 10 kGy, however, recent evaluation of an international expert study group appointed by FAO, IAEA, and WHO showed that food treated according to good manufacturing practices (GMPs) at any dose above 10kGy is also safe for consumption(ICGFI, 1999).

Irradiated food could be identified using different methods such as Gas chromatography, mass spectrometry, thermoluminescence (Schreiber, G., et al., 1993a, Schreiber , G., et al., 1993b, Schreiber , G., et al., 1993 c, Ziegelmann, K., et al., 1999, Parlato, A. et al., 2007, D'Oca, M. C. et al., 2008), and Electron paramagnetic resonance (EPR) spectroscopy (Desrosiers, M., 1989, Sünnetcioğlu, M., et al., 1999) which is characterized by its non-destructive detection of radiation-induced radicals, hence, it is a major technique for the investigation of irradiated food and the determination of the dose delivered accurately, which results in accepting or refusing of food transfer.

Mineral nutrients and Irradiated vegetables were identified using EPR (Lakshmi Prasuna, C.P, 2008, Maghraby, A., and Maha Anwar Ali. 2007), EPR spectral investigations have been carried out on some vegetable samples and the presence of various paramagnetic metal ions in various oxidation states is indicated. In almost all the fibrous vegetable samples, the free radical signal corresponding to cellulose radical is observed. However, in some vegetables like carrot, though the free radical signal cannot be distinguished, the free radical assignments are made depending on the organic radicals. The reason is that, the organic free radicals are generated due to CO group in the organic radicals (Lakshmi Prasuna, C.P,2008).

5.1.2 Drugs and medical products irradiation

Use of ionizing radiation in sterilization of medicinal products, such as catheters, syringes, drug and drug raw materials, is a new technology alternative to heat and gas exposure sterilization (Jacobs, 1995; Reid, 1995; Tilquin and Rollmann, 1996; Boess and Bőgl, 1996). The advantages of sterilization by irradiation include high penetrating power, low measurable residues, small temperature rise and the fact that there are fewer variables to control (Fauconnet et al., 1996; Basly et al., 1997). Thus, sterilization can be carried out on the finally packaged product and is applicable to heat-sensitive drugs.

The regulations of radiosterilization differ among countries. In other radiation sources such as X-rays, fast electrons and UV illumination. Irradiation produces new radiolytic products. To prove the safety of radiosterilization, it is important to determine physical and chemical features of the radiolytic products and elucidate the mechanism of radiolysis. Thus, it is desirable to establish a method to discriminate between irradiated and unirradiated drugs. Electron spin resonance (ESR) spectroscopy appears to be well suited for determination of free radical concentrations in complex media and so, it can be used to detect and distinguish between irradiated drugs from unirradiated ones (Gibella et al., 1993; Signoretti et al., 1994; Miyazaki et al., 1994; Onori et al., 1996).

As a cephalosporin antibiotic, duricef is used in the treatment of nose, throat, urinary tract and skin infection that are caused by specific bacteria, including staph strep and E. coli, effects of gamma radiation on cephalosporins with various substitutive groups have been reported in different papers (Miyazaki et al., 1994; Onori et al., 1996; Jacobs, 1983; Yũrũs and Korkmaz, 2005; Gibella et al., 2000), but low-and high-temperature kinetic features, structure and activation energies of the radical species involved in the formation of their ESR spectra were investigated in none of these papers, except of few published work (Yũrũs, S and Korkmaz, M., 2005). Eleven of the studied cephalosporins with various substitutive groups have been shown to exhibit, interestingly ESR spectra of unresolved doublet appearence (Onori et al., 1996; Yũrũs and Korkmaz, 2005). This conlusion was considered as an indication relevant to the origin of radicalic species produced in irradiated cephalosporins. Species originating from substitutive groups and cephem ring are expected to be responsible from ESR spectra of irradiated cephalosporins, but the ultimate patterns of the latter are believed to be determined by the relative weights of those species. Thiamphinicol sterilization using irradiation to doses up to 25 kGy was investigated using EPR spectroscopy, and it was found that standard dose used for sterilization (25 Gy) did not produce any detectable changes in the physico-chemichal properties of Thiamfinicol.

5.1.3 Other applications

An electron paramagnetic resonance (EPR) investigation of a series of glasses irradiated at room temperature with β or X radiation sources has been made in order to predict the long term behavior of glasses used in the nuclear waste disposal, in particular, no paramagnetic defects associated with aluminum ions are detected in these irradiated glasses (Bruno Boizot, et al., 1998).

Applications in polymer research and industries are numerous, for example, Poly (vinyl chloride) is one of the most used thermoplastic polymers, thanks to its low production cost, easy processing, excellent mechanical properties, high compatibility with additives and possibility to be recycled. Particularly interesting is its employment in vital single use medical devices such as catheters, cannulae, urological products and flexible tubes for

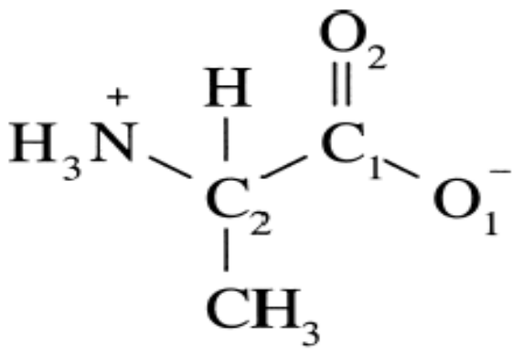
extracorporeal connections. The sterilization of these products is performed by electron beam or γ irradiations, a termination step, in which the active centers are deactivated. At 25 and 50 kGy oxygen appears to saturate all radicals and the EPR spectrum shows only one component, associated with peroxyl radicals. At the 100 and 150 kGy irradiation doses the EPR spectrum shows more structure and it comprises overlapping signals from the peroxyl and polyenyl radicals not yet oxidized (Baccaro, S. et al., 2003, Costa, L. et al., 2004).

5.2 Medical applications

5.2.1 Alanine dosimetry

5.2.1.1 Introduction

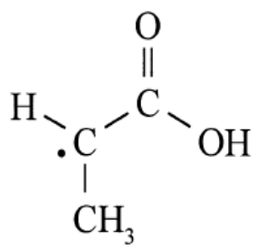
The natural amino acid L-α-alanine (see Figure (4)) has attracted considerable interest for use in radiation dosimetry (Bradshaw, W., etal., 1962, Regulla, D., and Deffiner, U., 1982, Nam, J., and Regulla, D., 1989, Ciesielski, B., and Wielopolski, L., 1994) and has been formally accepted as a secondary standard for high-dose and transfer dosimetry (Nett, H., ate al., 1993). The EPR powder spectrum from amorphous alanine pellets or other types of disordered alanine samples has been used for this purpose. The peak-to-peak amplitude of the central line of this powder spectrum is commonly used for monitoring the radiation dose (Eirik Malinen, et al., 2003a).



L-α-alanine

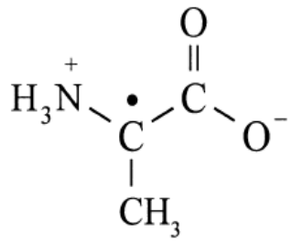
Fig. 4. Molecular structure of L-α- alanine.

It was found that at least three different radicals are formed and stabilized in alanine after X irradiation at room temperature as shown in Figure (5), (Sagstuen, E., et al., 1997a, Sagstuen, E., et al., 1997b, Mojgan Z. Heydari, et al., 2002). Two of these, the R1 radical (Structure 1) and a species formed by net hydrogen abstraction from the central carbon atom (radical R2, Structure 2), appear to occur in comparable relative amounts (55–60 and 30–35%, respectively) (Mojgan Z. Heydari, et al., 2002). The third species (denoted R3) is a minority species (5–10%), and an unambiguous structure assignment has not been made (Sagstuen, E., et al., 1997b). Structure 3 below, was suggested as a possible candidate for R3 (Eirik Malinen, et al., 2003b).



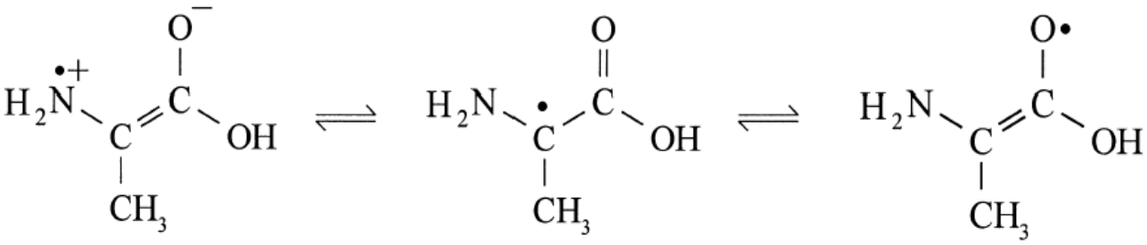
Structure 1

R1 (SAR)



Structure 2

R2



Structure 3

R3

Fig. 5. Three structures of alanine radicals, R1 or (SAR) is the Stable Alanine Radical, R2, and R3 in its three forms (Eirik Malinen, et al., 2003a and Eirik Malinen, et al., 2003b).

5.2.1.2 Dosimeters structure and shape

Alanine dosimeters often are composed of a binder and the alanine itself, the ratio and the binder type differs from type to type. The pellets are now in routine use as dosimeters for medical applications because of their robustness they are used as reference dosimeters sent by mail as a service offered by many laboratories (Maghraby, A., 2003).

Transfer alanine dosimeters which are distributed by the IAEA for intercomparison purposes were made of 70% per weight DL-α-alanine + 30% per weight polystyrene (Mehta, K., and Girzikowsky, R., 2000).

There are a lot of variations in alanine dosimeter shapes, varies according to different reasons, like the purpose of use, resolution required, and achievable sensitivity.

5.2.1.3 Applications

Experimental procedures of the use of alanine as dosimeter for brachytherapy purposes was described by De Angeles, C., et al., 1999. Also, a device for in vivo measurements of the rectal dose in radiotherapy for prostate cancer was developed (Daniela Wagner, et al., 2008) as shown in Figure (6). It was possible to insert this device without clinical complications

and without additional rectal discomfort for the patients. For irradiations of alanine dosimeter probes under reference conditions, deviations of less than 1% in reference to the national German standard were achieved. In the absence of metallic implants, the relative deviations between measured and applied dose values at the anterior rectal wall are less than or equal to 1.5% for the in vivo measurements.

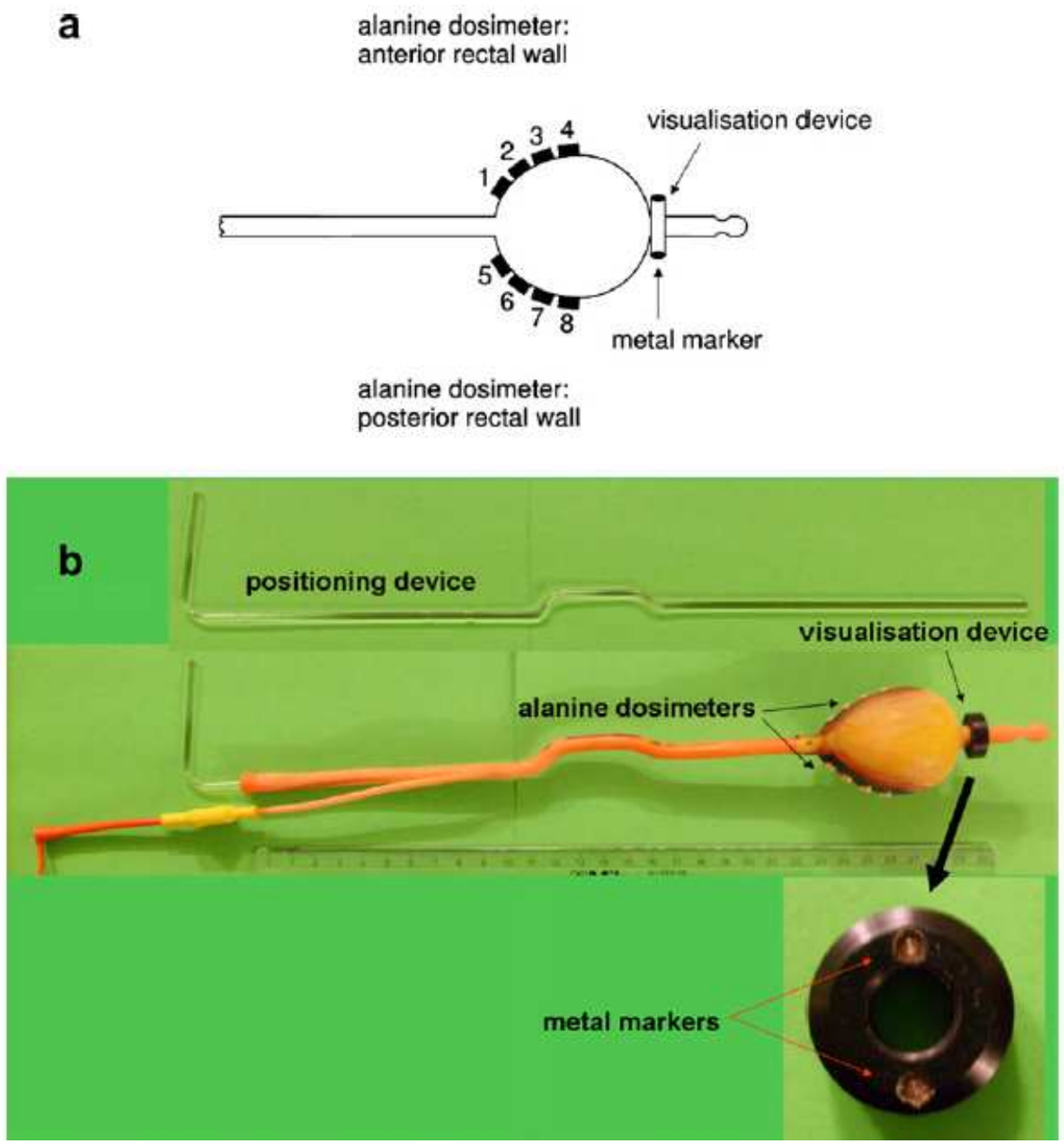


Fig. 6. (a) Sketch of the used rectal balloon equipped with alanine dosimeters. Four alanine dosimeter probes were placed at the anterior rectal wall (1–4) and: four alanine dosimeters at the posterior rectal wall (5–8). Note the visualization device on top of the balloon consisting of two metal markers. (b) Picture of one rectal balloon equipped with alanine dosimeters. For illustration, the positioning device was inserted. At the top of the rectal balloon, the visualization device with metal markers was added (Daniela Wagner, et al., 2008).

At the posterior rectal wall, relative deviations of up to 3.5% may occur. The dominant contribution to the overall uncertainty for the in vivo measurements was the positioning of the dosimeter probes in the patient's body and their corresponding localization in the Computed Tomography (CT) data. Therefore it is expected that improving the probe positioning in the patient's body (e.g. by an increased visibility in the radiographic images) will lead to more accurate results.

The method presented in this study turned out to be useful for in vivo quality control of the irradiations. The relative deviation between the dose determined by the ESR measurements and the planned dose determined by the treatment planning systems (TPS) was shown to be within the 5% limit recommended by the ICRU (ICRU, 1976) for doses above 0.7 Gy (Daniela Wagner, et al., 2008).

Alanine was used also for the in-phantom dose mapping in neutron capture therapy (NCT) (Baccaro, S., et al., 2004), Recoil proton dose can be measured by means of alanine detectors, after subtraction of gamma dose contribution as evaluated from the dose measured with TLD-300. To this purpose, it is necessary to study the sensitivity of alanine to proton recoils and the coefficient for converting the recoil proton dose in alanine to that in tissue.

5.2.1.4 Influencing factors

Time passes before starting measurements after irradiation of alanine dosimeters is a key factor for acquiring reliable measurements, it was found that there is complex dependence on the time conjugated with the received dose range (Nagy, V., and Desrseirs, M. 1996). However in one of recent studies (Anton, M., 2008), the postirradiation behavior is highly dependent on the dosimeter structure and constituents.

In addition to the time dependence, extensive studies on ambient environmental conditions effects on the alanine dosimeters sensitivity and response were performed (Nagy, V. et al., 2000, Sleptchonok, O.F., et al., 2000, Anton, M., 2005). It was found that the effect of storage conditions is dependent on the type of the dosimeter. Effect of higher temperatures also was studied (Maltar-Strmečkia, N. and Rakvin. B. 2005). Same studied parameters (relative humidity and postirradiation behavior) were carried out for a new alanine film dosimeters (Ruth M.D. Garciaa, et al., 2004).

Some other influencing factors were studied: the angular response of alanine dosimeters either in the form of pellets or powder (Jean-Michel Dolo, and Tristan Garcia. 2007), and the grain size (Tristan Garcia and Jean-Michel Dolo. 2007).

5.2.1.5 Energy dependence

Energy dependence of alanine dosimeters were investigated (Eva Stabell Bergstrand, 2003). It was found that the alanine response is 0.8% lower for high energy X-rays than for Co-60 gamma rays, this result indicates a small energy dependence in the alanine response for the high-energy photons relative to Co-60 which may be significant. Another recent study has been performed to reveal the response of alanine dosimeters to high energy photons 8 and 16 MV relative to the response of alanine dosimeter irradiated to the reference beam quality (Co-60), a confirmation of these results was made using EGSnrc package (Anton, M., et al., 2008). Additional study of energy dependence of Dl-alanine to 10 MV high energy photons has revealed the decrease in alanine response with respect to the Co-60 reference beam quality (Borgonove, A.F., et al., 2007).

5.2.1.6 Alanine derivatives

Some researchers tried to use different alanine substitute in order to take the advantages of alanine as solid-state dosimeter with minimum drawbacks, however, the positive results are not mandatory, for example: Polycrystalline phenyl-alanine and perdeuterated L-a-alanine (L-a-alanine-d4) were studied as potential high-energy radiation-sensitive materials (RSM) for solid state/EPR dosimetry. It was found that phenyl-alanine exhibits a linear dose response in the dose region 0.1–17 kGy. However, phenyl-alanine is about 10 times less sensitive to γ-irradiation than standard L-a-alanine irradiated at the same doses. Moreover, the EPR response from phenyl-alanine is unstable and, independent of the absorbed dose, decreases by about 50% within 20 days after irradiation upon storage at room temperature. γ-irradiated polycrystalline perdeuterated L-a-alanine (CD3CD(NH2)COOH) has been studied at room temperature by EPR spectroscopy. By spectrum simulations, the presence of at least two radiation induced free radicals, R1 (CH3C*(H)COOH) and R2 ($H3N^+$-C*(CH3)COO^-), was confirmed very clearly. Both these radicals were suggested previously from EPR and ENDOR studies of standard alanine crystals (Veselka Ganchevaa et al., 2006).
Also, Minidosimeters of 2-methylalanine (2MA) were prepared and tested as potential candidates for small radiation field dosimetry (Bruno T. Rossi, et al., 2005). To quantify the free radicals created by radiation, a K-Band (24 GHz) EPR spectrometer was used. X-rays provided by a 6 MV clinical linear accelerator were used to irradiate the minidosimeters in the dose range of 0.5–30 Gy. The dose–response curves for both radiation sensitive materials displayed a good linear behavior in the dose range indicated with 2MA being more radiation sensitive than L-alanine. Moreover, 2MA showed a smaller LLD (Lower Limit of Detection) value. The proposed system minidosimeter/K-Band spectrometer was able to detect 10 Gy EPR spectra with good signal-to-noise ratio (S/N). The overall uncertainty indicates that this system shows a good performance for the detection of dose values of 20 Gy and above, which are dose values typically used in radiosurgery treatments (Chen,F., et al., 2007).
Alanine-in-glass dosimeters were prepared by packing pure polycrystalline L-*a*-alanine directly as supplied by the manufacturer in glass tubes. These dosimeters exhibited a linear dose response in the dose range from 0.1 to 20 Gy. These positive properties favor the polycrystalline alanine-in-glass tube as a radiation dosimeter (Anan M. Al-Karmi, and M.A. Morsy, 2008).
A new generation of self-calibrated alanine dosimeters were developed, and a regular international intercomparison is held for evaluation of radiation dos using these dosimeters (Gancheva, V. et al., 2008), these dosimeters are consists of RSM (α-alanine, sugar, other ones), Mn^{2+}/MgO as internal EPR intensity standard (IES) and a binder. Necessity to assurance of very good homogeneity of dosimeter material; and the cost of IES present in the amount of some percent in each self-calibrated dosimeter are of the main shortcomings of this technique. Also, it was found that addition of gadolinium to the alanine dosimeters in definite amounts helps to improve the Linear Energy Transfer (LET) sensitivity for γ photons (because of its high atomic number, Z = 64) and thermal neutrons as well (because of its high thermal neutron cross section) (Marrale, M., et al., 2007).

5.2.2 Other organics

The search for new EPR dosimeter is non stopping, the search for organic dosimeter ensures the minimum energy dependence at least at 0.5 MeV and higher photon energies, and hence

tissue equivalency of the dosimeter (Maghraby, A., and Tarek, E., 2006), for example: sulfanilic acid possesses several good features of the good dosimeter and is characterized by its simple spectrum. Although its sensitivity is less than that of alanine, it could be pressed into pellets purely without need to a binder, and hence more homogeneity could be achieved. Sulfanilic acid is nearly tissue equivalent which enables its use in radiation therapy dosimetry, also it is isotropic and its detection limit is about 100±30 mGy. Sulfanilic acid EPR signal intensity shows noticeable stability for a sufficient time, which enables its use as a transfer dosimeter. Sulfanilic acid deserves further studies in order to be established as a common radiation dosimeter using EPR (Maghraby, A., and Tarek, E., 2006).
One of the most promising organic dosimeters ever since the discovery of alanine at 1962 (Bradshaw, W., et al., 1962), is the Lithium format (Gustafsson, H., et al., 2008). It is characterized by its simple spectrum (one narrow peak spectrum) and its high sensitivity (six times more than alanine), beside its obvious stability. Lithium formate also possesses tissue equivalency more than that of alanine, with suitable microwave dependence and modulation amplitude dependence (Tor Arne Vestad, et al., 2004). Lithium formate may replace alanine in the near future specially for its clinical uses.

5.3 Inorganic dosimeters

A wide variety of inorganic dosimeters were investigated, some of these dosimeters processed higher sensitivity than alanine with reasonable stability, and some examples are following:

5.3.1 Combined TL and EPR dosimeters

Beryllium oxide ceramics was investigated for TL and EPR dosimetry. Ceramics were doped with lithium and neodymium ions. TL and EPR signals associated with Li centers whose amplitude is proportional to the absorbed dose are observed. A complete anneal of the EPR signal takes place in the temperature range of the TL recordings (Kortov, V., et al., 1993b).
Onori, S., et al., have used the well known thermoluminescent material; calcium sulphate: Dy, for EPR high dose assessment (Onori, S., et al., 1998). Three EPR signals are detectable for $CaSO_4$: Dy phosphor, two out of the three signals were studied for high dose applications since one of them showed saturation at about 1 kGy. The concentration of both centers, $(SO_3)^-$ and Ca-vacancy, increases with dose at least up to 10^7 Gy or more. In both cases, the dose-effect relationship is not linear, being supralinear for $(SO_3)^-$ center and sub-linear for $(Ca)^{2-}$ center. $(Ca)^{2-}$ center is very stable over time independently of dose, while $(SO_3)^-$ center is not stable over time and can be used for a first dose estimation soon after irradiation.
The effect of grinding on powder form of clear fused quartz was studied by EPR and TL techniques. The minimum detectable dose (MDD) for using EPR was about 2 Gy for the clear fused quartz in powder form, which is 2 times greater than the bulk form. The EPR signal for of background varied inversely with particle size and was quite high for sizes lower than 38 μm, while for a Co-60 irradiated samples (about 22 Gy), the EPR intensity of the coarse powder varied directly with particle size. Thus, the intensity of a particle size of 20-38 μm was very low (Ranjbar, A., et al., 1999).
Feasibility of reading LiF thermoluminescence dosimeters by EPR was studied by Breen, S., (Breen, S., and Battista, J., 1999). EPR signals can be observed in irradiated polycrystalline LiF rods, but only near liquid nitrogen temperatures. The magnitude of this signal was

measured by two methods: direct measurement of the radiation-induced signal, and curve fitting. The direct measurement showed that the radiation-induced signal increased linearly with dose; however, the technique suffered from low sensitivity; at low doses (below 20 Gy) the signal was barely discernible above the noise in the spectrum.
The curve-fitting method isolated three peaks in the EPR spectra of TLD-100. One component increased linearly with dose, although the spectrum of unirradiated TLD-100 possessed a large contribution from this component. This behavior is similar to that observed in the peak isolated by direct measurement. A second component was uncorrelated with dose. The third component decreased with dose, although this part of the spectrum was modeled poorly, perhaps due to the presence of another (fourth) signal in the spectrum. Due to the experimental difficulty in interpreting these spectra, and the low sensitivity of the application, EPR is not recommended as a substitute for thermoluminescent dosimetry of polycrystalline LiF.

5.3.2 Other inorganic compounds

Sulfamic acid possesses high-sensitivity to gamma radiation and is able to detect radiation doses below 5.0 Gy which would be advantageous for a possible use in medical applications, beside other good dosimetric properties like almost energy independence, narrow line and simple spectrum of well-defined radicals, also predictable decay kinetics which enable its use as a transfer dosimeter (Maghraby, A., 2007).
Ferrous ammonium sulfate was used as a high dose dosimeter in the range from 33.5 to 546 kGy (Juárez-Calderón, J. et al., 2007). Also, Sulphur trioxide anion in $K_2CH_2(SO_3)_2$ and carbon dioxide anion in irradiated sodium formate ($NaHCO_2$) were suggested as inorganic alternatives to the EPR/alanine dosimeter by Keizer, P.N., (Keizer, P.N., et al. 1991). These two systems have a four-fold sensitivity advantage over alanine. The radicals sulphur trioxide anion and carbon dioxide anion are, moreover, found in a wide variety of matrices, and it may be possible to find one in which they are even stronger. Sulphur trioxide anion was found to be completely stable over time, while carbon dioxide anion was not so stable against decay as sulphur trioxide, for example the signal decayed by 30 % over the first six weeks when irradiated to 10 kGy. The main drawback in inorganic dosimeters is their non-water equivalence.
Dosimetric properties of magnesium sulphate were investigated (Morton, J., et al., 1993). On irradiation with Co-60 γ rays, the stable SO_3^- is produced whose EPR signal amplitude increases linearly with dose up to about 10^5 Gy Advantages and disadvantages of the SO_3^- radical system were compared with α-alanine. The studied dose range was between 0.25 Gy and 50 Gy, focusing on the region below 10 Gy. Storage as well as measurement of the encapsulated samples was at room temperature, sample spectra are reproducible several weeks later. It was seen that the signal enhancement for magnesium sulphate is about 80%, quite significant for the lower dose range.
Magnesium oxide was suggested as a combined thermostimulated luminescence TSL-EPR detector for ionizing and ultraviolet (UV) radiations (Kortov, V., et al., 1993a).
Dose dependence of the EPR signal intensity caused by Fe^{+3} ions impurities is linear from 1 to 10^4 Gy for X irradiation. Temperature range of measurements for the EPR signal is expanded, allowing measurements of radiation dose at higher temperatures.
In Physikalisch-Technische Bundesanstalt (PTB), Schneider, C., (Schneider, C., 1994), tested the SO_3^- radical in an anhydrous $MgSO_4$ matrix, it shows a three times stronger EPR signal

than the alanine radical at the same dose. Because the SO_3^- spectrum has negligible high frequency noise components, the pattern recognition of the derivative spectral shape out of the noise background is better. Peak-to-peak evaluation at low doses (<10 Gy) is therefore more accurate for this simple single line spectrum. Discussion of EPR dosimeter materials cannot circumvent the problem of water equivalence. At low energies (<50 keV) the photon response of a martial is proportional to Z^4 up to Z^5, so, for instance, with sulphur nuclei instead of oxygen in a dosimeter, the response will differ by a factor of more than 16. In practice, the mass collision stopping power (the quotient energy loss over beam pathlength, ($\Delta E/\Delta l$) of alanine is about 3% lower than that of water in the electron energy range 0.1-1.0 MeV, whereas for $MgSO_4$ it is about 17% lower. Therefore, in the search for alternative EPR dosimeter materials, it is desirable that a matrix be found which combines spectral advantages (as shown by the SO_3^- radical for example) with a low Z value for its constituent nuclei.

Electron paramagnetic resonance (EPR) studies have been made on lithium metaitanate (Li_2TiO_3) ceramics irradiated by gamma rays of Co-60 source at ambient and Liquid Nitrogen Temperatures (LNT). The EPR spectra have been found strongly dependent on irradiation dose and temperature. The radiation defects induced by gamma irradiation at LNT were found to disappear almost completely by heating up to 255 k. in contrast to this, the radiation defects produced by irradiation at ambient temperature showed tolerance of elevated temperatures up to about 600 k (Grišmanovs, V., et al., 2000).

The sulphur trioxide anion looks interesting, so, new inorganic dosimeters based on barium and strontium dithionates ($BaS_2O_6.2H_2O$ and $SrS_2O_6.4H_2O$) were developed by Bogushevich, S., (Bogushevich, S., and Ugolev, I., 2000). The minimum detection limit was found to be 0.05 Gy at the measurements uncertainty of ± 30%. The dependence for γ irradiated dosimeters was linear up to 50 kGy for barium dithionates, and 80 kGy for strontium dithionates. Radical ions SO^-_3 in barium and strontium dithioniates are stable at 20^{o}C. Studies have shown that, at temperatures below 35^{o}C, the signal is stable within ± 5% for at least two years. Similarly, Barium sulphate (BaSO4) was irradiated by γ-rays and analyzed with electron spin resonance (ESR) to study radiation induced radicals for materials as radiation dosimeter (Sharaf, M.A. and Gamal M. Hassan. 2004).

Ammonium dithionate has been investigated as a potential dosimeter material (Danilczuk, M., et al., 2008). The radical signal in irradiated polycrystalline samples is a structureless narrow line. Ammonium dithionate was found to be more sensitive an l-α-alanine by a factor of seven at he same spectrometer settings. The results indicate that the ammonium dithionate can be applied as a dosimeter for situations when a material more sensitive than l-α-alanine is needed.

5.4 Retrospective and emergency dosimetry

5.4.1 Teeth enamel dosimetry

The EPR spectrum of irradiated tooth enamel (Shin Toyoda, et al., 2008) contains a multitude of signals that can be divided into two categories, radiation-induced and radiation insensitive signals (Figure (7)). This approach is an approximation because the intensity of the so-called non-radiation sensitive EPR spectral components from tooth enamel are also slightly affected by irradiation, which is evident after irradiation with doses above one hundred Gray. However, these EPR spectral components can be considered as radiation insensitive in the application range of retrospective dosimetry.

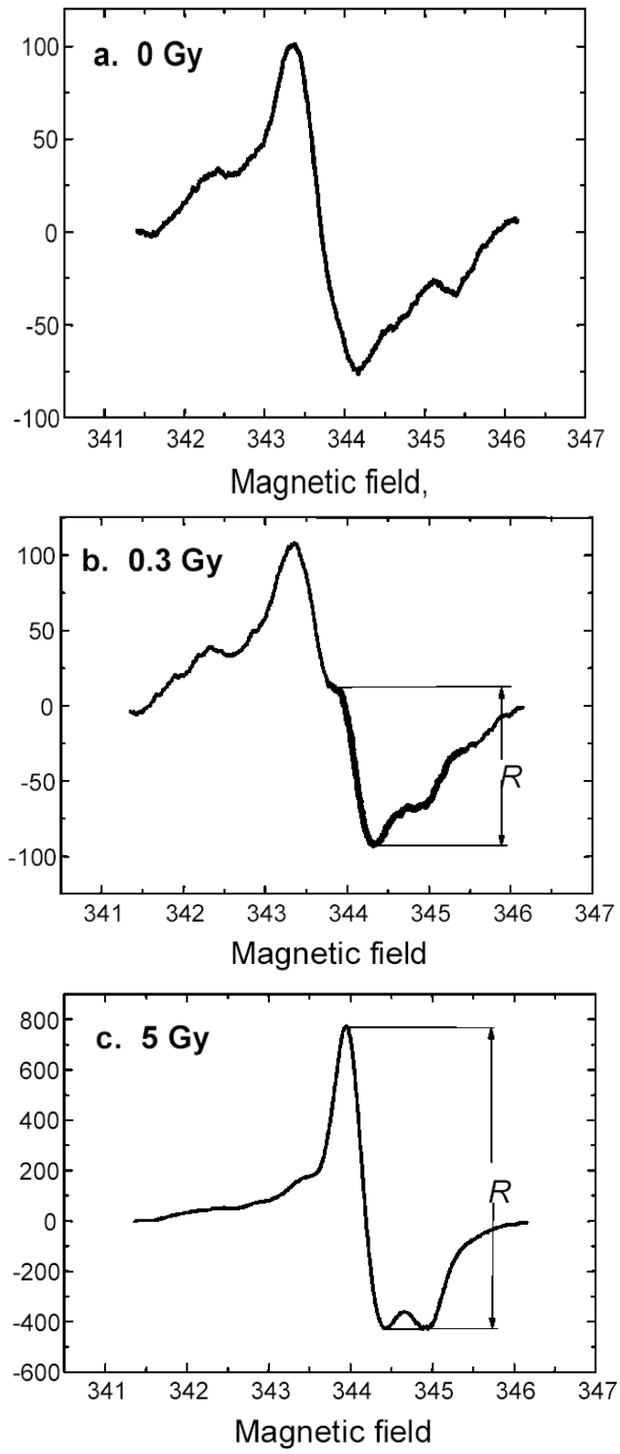


Fig. 7. EPR spectra of tooth enamel after irradiation with different doses: a- 0 Gy; b- 0.3 Gy; c- 5 Gy. The dosimetric component of the spectrum after irradiation with 0.3 Gy (in the middle – b) is in dark. R is the peak-to-peak amplitude used for EPR reconstruction (IAEA, 2002).

The majority of radiation-induced radicals in tooth enamel are carbonate derived, i.e.,CO_2^-, $CO3^-$, CO^-, $CO3^{3-}$, but also radicals derived from phosphate, i.e., $PO4^{2-}$, and oxygen, i.e.,O^- and O^{3-} were identified. The identification of radicals was based on EPR and ENDOR (Electron Nuclear Double Resonance) measurements of irradiated synthetic hydroxyapatite doped with ^{13}C (Callens, F., et al., 1998). Not all radiation-induced radicals are thermally stable, e.g., the CO3-radical, with g-value of the EPR signal ranging from 2.0060 to 2.0122, decays completely at room temperature during the first two weeks after irradiation (Callens, F., et al., 1998, Cevc, P., et al., 1972, Romanyukha, A., et al., 1996). For dose reconstruction the asymmetric EPR signal with $g_{\perp}$=2.0018 and g||=1.9971 (signal maximum at g=2.0032 and minimum at g=1.9971) is used. The signal is predominantly derived from stable CO_2^- radical (IAEA, 2002).
Two methods have been used to assess the absorbed dose of irradiated enamel by EPR: additive re-irradiation and the use of calibration curve, in the additive re-irradiation method: the sample is incrementally irradiated to construct a response curve specific to the sample in question (Pavlenko, A et al., 2007) as shown in Figure (8). The other method uses a universal calibration curve (EPR signal Intensity versus absorbed dose) generated using a large blended sample pool of enamel material designed to average the sample-to-sample variances. For doses greater than a few hundred mGy, the variation in EPR signal intensity from sample to sample for tooth enamel is about 10%, however, dose reconstruction using the universal calibration curve method is much less time-consuming and is non destructive (Desrosiers, M., and Schauer, D.A., 2001). Some other techniques are not widely used (Lanjanian, H., et al., 2008). Some consideration to be taken into account, such as the internal irradiation of human body by radioactive cesium isotopes (Borysheva, N., et al., 2007), many other influencing parameters have been investigated (El-Faramawy, N., 2008).

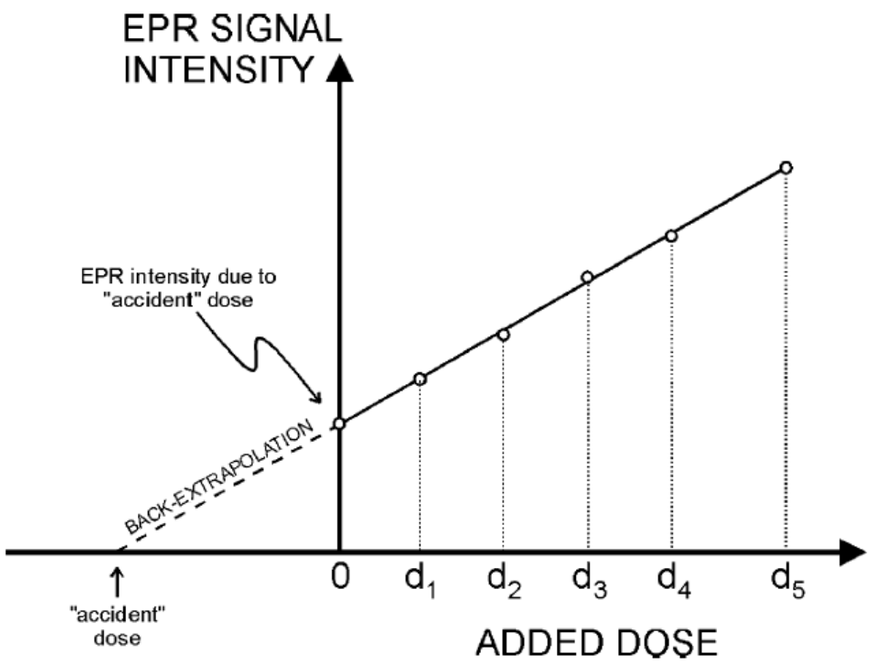


Fig. 8. The additive dose method for dose reconstruction is based on the re-irradiation (d_1 – d_5) of a tooth sample to obtain a sample-specific dose response curve, which is used to back extrapolate to the absorbed dose value (Desrosiers, M., and Schauer, D.A., 2001).

The dosimetric response of neutron irradiated human tooth enamel has been investigated (Khailov, Artem; et al., 2008). The neutron sensitivity (/Gy-100 mg) of human tooth enamel remained constant for various mean neutron energies ranging from 167 to 450 keV. Similarly, the EPR signal intensity remained independent of the neutron dose rate variation from 0.5 to 2.4 Gy/h (Rao F.H. Khan, et. al., 2004), other studies on the use of deciduous teeth have been performed (El-Faramawy, N.A., 2005, El-Faramawy, N., and Wieser, A., 2006).

5.4.2 Emergency dosimetry

There is growing awareness of the need for methodologies that can be used retrospectively to provide the dosimetry needed to carry out triage immediately after an event in which large numbers of people have potentially received clinically significant doses of ionizing radiation (Trompier François, et al., 2008b, Trompier François, et al., 2007a). Although some very promising approaches are being developed using biologically based parameters there also is recognition that such measurements have the potential to be confounded by other physiological and pathophysiological factors that are likely to be present in such event (Nicolalde, Roberto J; et al., 2008).

In contrast, the EPR measurements are based on physical changes in tissues whose magnitudes are not affected by the factors that can confound biologically based assessments. The EPR methods are based on the generation of stable free radicals, whose magnitude is proportional to the total dose of radiation received by the tissue, thereby allowing these tissues to be used as endogenous physical dosimeters (Nicolalde, Roberto J; et al., 2008).

5.4.2.1 Human subjects

5.4.2.1.1 In vivo EPR measurements of teeth

In vivo measurements of radiation-induced EPR signals in teeth is a safe technique (Ann Barry Flood, et al., 2007) and currently it utilizes a large permanent magnet (40 mT) and, in principle, this system could be deployed in the .field using a small vehicle (Dong, Ruhong; et al., 2008). While clones of this system (see Figure (9)) would be an effective component of large deployment teams, a smaller magnet system would facilitate wider distribution of this capability. The feasibility of such magnet systems has been demonstrated (Swartz et al., 2007). These are in a form that could be incorporated into a helmet-like structure that would fit over the head. An intraoral magnet is also being developed. It is anticipated that within several years, the technology will be advanced to a point where it may be possible to obtain sufficient sensitivity with lower frequencies and thus lower the requirements for the magnetic field (Benjamin B. et al., 2008). This would further decrease the size of the magnet that is needed.

A current laboratory-based system (Benjamin B.Williams, et al., 2007) can make measurements comfortably in human subjects with a 5-min acquisition time providing dose resolution of ±0.75 Gy (1 SD) and a threshold of not more than 2.0 Gy, with the result being immediately available. There are a number of areas in which improvements should be feasible within 1–2 years. Improvements that are in process include: increasing the sensitivity of the existing types of resonators and the number of teeth in which the measurement is made by changing the size and/or shape of the resonator (see Figure (10)), improving data analysis (Demidenko, E., et al., 2007), increasing microwave power, and reducing sources of noise. Dose resolution can be improved immediately by extending the time for the measurement, with the increase being proportional to the square root of the

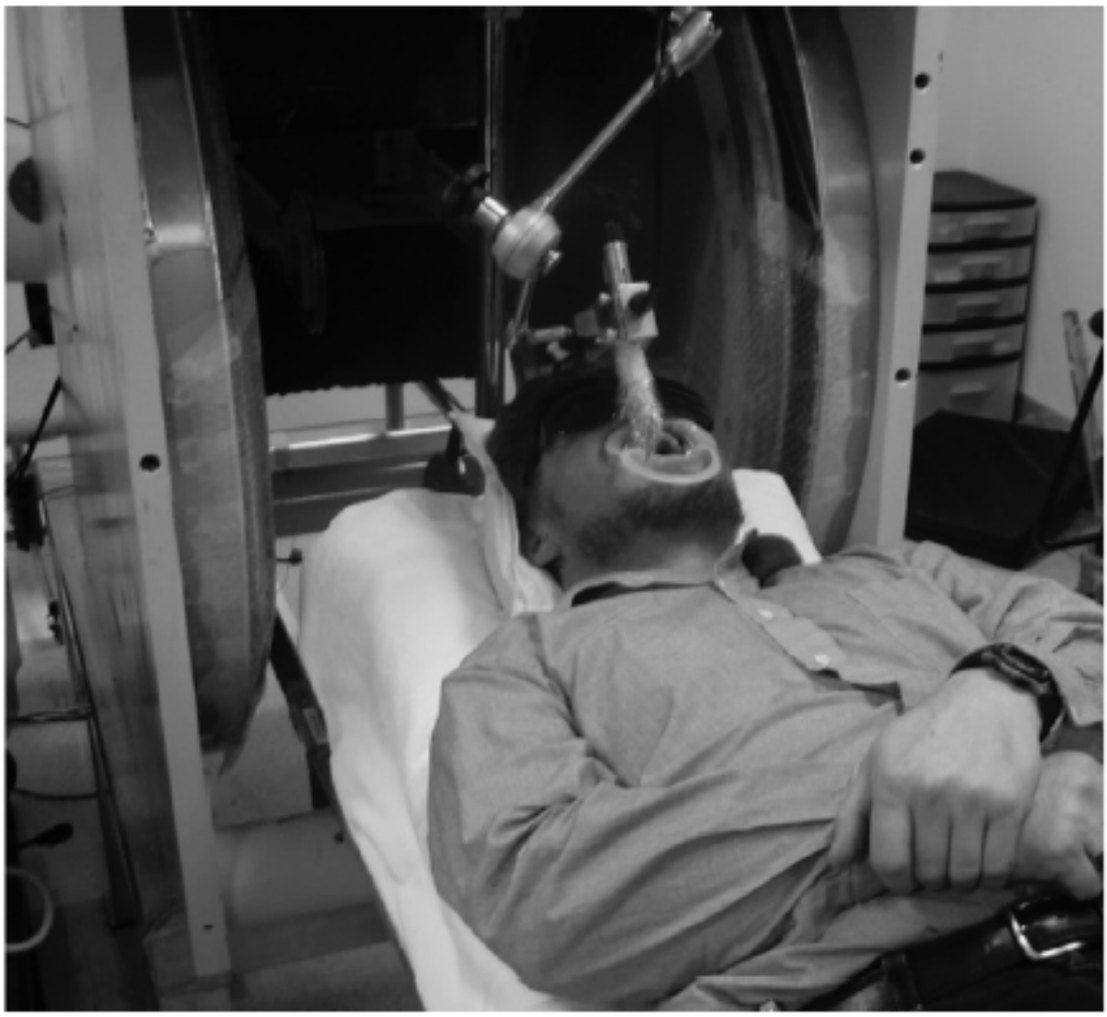


Fig. 9. Clinical spectrometer with a volunteer in it (Harold Swartz et al., 2007).

time of the measurements (i.e. increasing acquisition time from 5 to 20 min would increase the resolution by a factor of two) and by making the measurements in more than one tooth simultaneously. While the threshold, sensitivity, and accuracy can be improved further, there are some caveats that pertain to this method regardless of such improvements. The measured quantity is absorbed dose to teeth, not the critical organs of interest in radiation protection. This is not a problem if the exposure is homogeneous. In the event of an asymmetric exposure it may be feasible to utilize the Monte Carlo simulations of doses to human teeth from photon sources of eight standard irradiation geometries that have been performed and a set of dose conversion coefficients (DCCs) were calculated for 30 different tooth cells (Ulanovsky et al., 2005). DCCs were determined as ratios of tooth absorbed dose to air kerma for monoenergetic photon sources. To facilitate handling of the data set a software utility has been developed. The utility plots the DCC and computes conversion factors from enamel dose to air kerma and from enamel dose to organ dose for user-supplied discrete and continuous photon spectra.

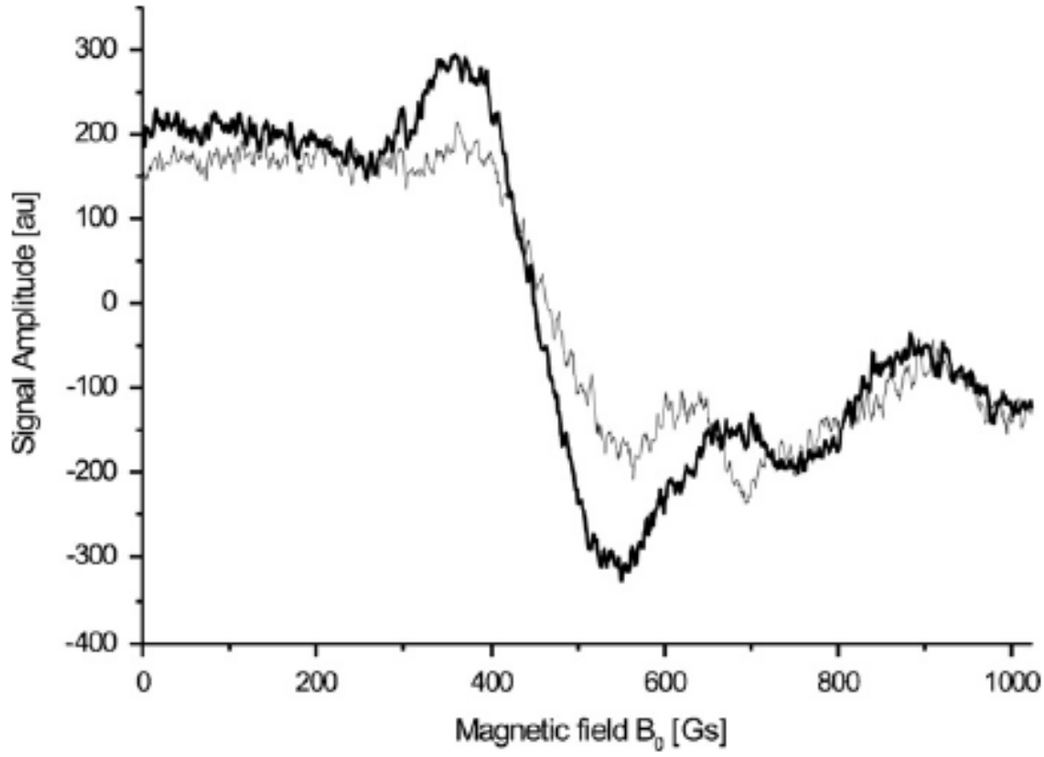


Fig. 10. Spectra from measuring two teeth (upper and lower) simultaneously (Harold Swartz et al., 2007).

The utility of EPR measurements for decision-making will depend on the homogeneity of the exposure and the type of radiation. The latter is noted because neutrons contribute very little to the EPR signal in teeth due to the low amount of hydrogen atoms in the enamel (Zdravkova et al., 2003; Trompier et al., 2004). If the dose has a major contribution from ingested or inhaled radionuclides, the dose delivered to the teeth may not closely reflect the dose to critical tissues (George A. Alexander et al., 2007).

5.4.2.1.2 Measurements in .fingernails (or toenails)

Although it was suggested as early as 1968 (Brady et al., 1968) that fingernails might be useful for after-the-fact dosimetry, only recently have the necessary studies been carried out to demonstrate convincingly that this approach has potential for use in the field for triage and perhaps even fairly precise determination of dose (Hongbin Li, et al., 2008). Preliminary results indicate that using simple cuttings from fingernails and X-band (9500 MHz) for the measurements, absorbed doses as of 1Gy with an uncertainty of ±0.50 Gy (1 SD) can be obtained with currently available techniques and instruments (Romanyukha et al., 2007; Trompier François et al., 2007b). If the use of fingernails for field dosimetry continues to develop, there should be no difficulty in constructing a field-deployable 9500MHz spectrometer for this purpose, which would be lightweight and automated for use by minimally trained individuals. The radiation-induced signals in fingernails are stable for at least several days (and much longer if the samples are collected within a few hours after the

event and stored at low temperature). Because the measurements would be made in vitro, it should be possible to calibrate the radiation response of each sample by a simple procedure in which radiation is added to the sample. A potential advantage of measurements in fingernails, especially if combined with in vivo EPR dosimetry of teeth, include obtaining the measurement from a different location on the body (thereby providing a means to assess if there was an heterogeneous exposure).

Potential limitations to this approach may be overcome by simple modification of the collection process. For example, cutting of the fingernail can create a mechanically induced signal (MIS) that overlaps with the radiation-induced signal (RIS). However, the MIS decays rapidly and the decay is greatly accelerated by simple chemical treatment as shown in Figure (11), (Xiaoming He, et al., 2008, Dean Wilcox, et al., 2008). The influence of this MIS also can be removed by appropriate data processing because the shape is different from the RIS (Swarts Steven, et al., 2008). As is the case with any technique that requires removal of a sample from the subject, there is a potential for mislabeling the sample. This problem can be reduced by the development of automated procedures to rapidly remove any MIS and, if necessary, to calibrate the individual sample. Because only minimal manipulation of the sample is required and the measurement can be made within 5 min, it is feasible to determine the absorbed dose while the subject is still present. Finally, this method may not be applicable in children where nail volume is low (George A. Alexander, et al., 2007). Recently, doses in the range of 0.4 Gy could be detected using more sensitive EPR spectrometer with a resonator of high quality factor (Hirosuke Suzuki, 2008).

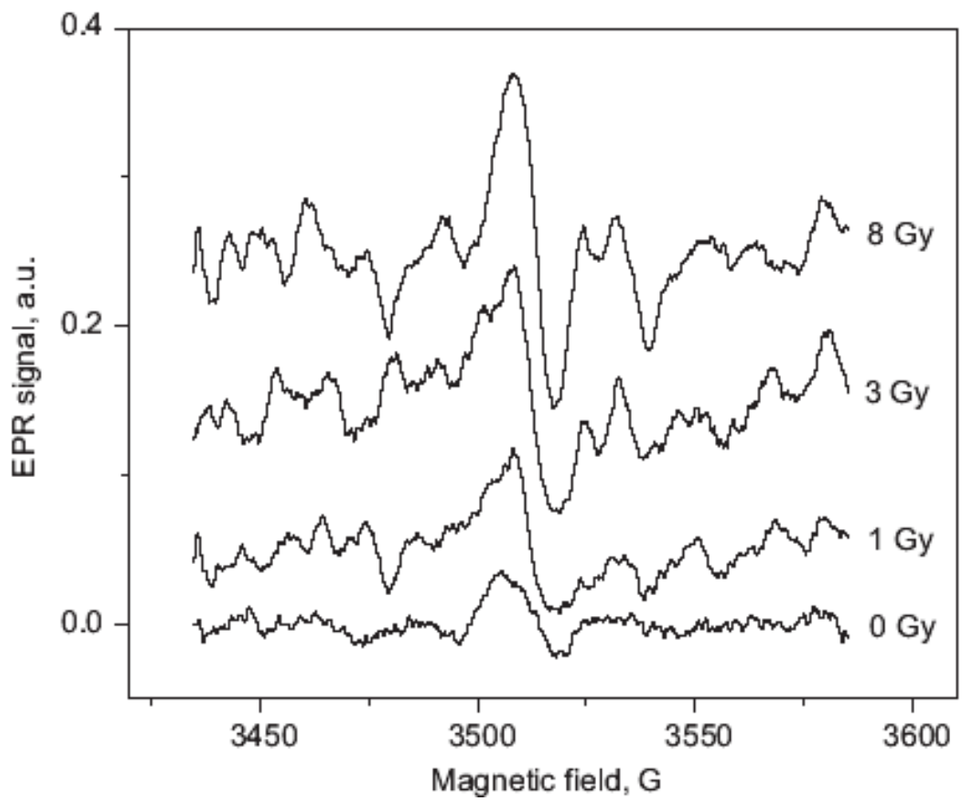


Fig. 11. EPR Spectra of fingernails treated with dithiothritol for 20 min after receiving different radiation doses (Romanyukha , a., et al., 2007).

5.4.2.1.3 Hai

Hair is composed mainly of alpha keratin same like fingernails, however its use as accidental dosimeter is limited because of the melanin pigments (Trivedi, A., and Grenstock, C., 1993). Some attempts were performed to study different hair types, with different pigments, but it was found that hair EPR signal exhibit some complexities that limit its use in dose evaluation. On the other hand, recently, melanin itself (in hair) was used to indicate the presence of radiation-induced radicals (Thomas Herrling et al., 2008).

5.4.2.1.4 Measurements in "biopsies" of teeth using 9500 MHz EPR

Many studies have demonstrated that retrospective measurements of dose by examination of isolated teeth with higher frequency EPR can provide very accurate estimates of dose at times ranging from immediately after the exposure to archeologically relevant times (Desrosiers and Schauer, 2001). The practical problem with this approach for acute dosimetry is the need to remove the tooth from the mouth. It now appears feasible, however, to obtain small samples from teeth rapidly and in a cosmetically acceptable manner. Small amounts can be used because of the increased sensitivity of higher frequency EPR and, there may be advantages in using frequencies even higher than 9500 MHz. Such a process could be very useful for triage and early assessment of dose to help in the determination of therapeutic intervention. Even if the technique of tooth biopsy does not fully meet the expectations, there may be situations where the value of the information that would be obtained would justify the removal of a tooth for in vitro measurement. The latter approach might be applicable in subjects for whom there are other indications of a potentially life-threatening dose and it is essential to verify the dose so that potentially risky therapies can be applied appropriately (George A. Alexander, et al., 2007).

5.4.2.1.5 Other tissues

Several reports in the literature have described the effects of radiation in workers who exposed their fingers to intense radioactive sources. The radiation injuries occurring after local exposure to a high dose (20 to 100 Gy) could lead to the need for amputation. It has been investigated the use of low-frequency EPR spectroscopy to evaluate non-invasively the absorbed dose. Low-frequency microwaves are indeed less absorbed by water and penetrate more deeply into living material (~10 mm in tissues using 1 GHz spectrometers). Preliminary results obtained with baboon and human fingers compared with human dry phalanxes placed inside a surface-coil resonator. The EPR signal increased linearly with the dose. The ratio of the slopes of the dry bone to whole finger linear regression lines was around 5. The detection limit achievable with the present spectrometer and resonator is around 60 Gy, which is well within the range of accidentally exposed fingers (Zdravkova, M. et Al., 2004).

5.4.2.2 Non-human subjects

This item may contain everything man uses: his food, clothes, tools, constructive materials, plastics (Trompier François; et al., 2008a) and so many things that can be found in the day life. These things around the man receive same (more or less) radiation dose in case of radiation accidents, hence evaluation of radiation doses using these objects may reflect to a close relation some details. Materials have been investigated by different techniques: sugar, wall bricks, roof tiles, plastics, watch glass, ruby present in watches, medicines carried by persons and shell button (Baffa, O. 1, et al., 2008). Sweeteners based on saccharine, cyclamate, stevia and aspartame may be used.

A preliminary study of EPR signals of watch glass carried out by Wu (Wu, K., et al., 1995) and Trompier François (Trompier François, et al., 2008c) had suggested that it was an appropriate dosimeter. A large number of watch glass and display windows of mobile phone with EPR techniques to study the variability of dosimetric properties among the different types of sample. Dose response, signal stability and effects of storage conditions was presented (Bassinet, Céline; et al., 2008).
Egg shell was used as accidental EPR dosimeter, as it contains Calcium carbonate $CaCO_3$ (Da Costa, Z.M., et al., 2007), dose response is linear from the range of 3 Gy to 1kGy, and no dose rate dependence was observed.

5.4.3 Environmental dosimetry

Concern regarding the possibility of criminal or terrorist use of nuclear materials has led to an interest in developing the capability to measure radiation dose in a variety of natural and man-made materials. One such novel EPR dosimeter is drywall, a common construction material composed largely of gypsum (calcium sulphate dihydrate). A radiosensitive EPR signal in drywall has been observed, and suitable dose measurement protocols have been developed (Thompson, Jeroen W. et al., 2008). In other study, investigation of radiation induced radicals in coral reefs revealed that microcrystalline aragonite radicals can be used for environmental dosimetry purposes (Sharaf, M.A. and Gamal M. Hassan. 2004). Some attempts to follow the changes in sealevel were performed via the $^{230}Th/^{234}U$–ESR combined analysis for corals (Bonnie A.B. et al., 2007).

6. Dating

ESR has increasingly contributed to interdisciplinary research, such as dating of geological and archaeological materials (Dobosz, B., and Krzyminiewski, R. et al., 2007). Geosciences benefit from the potential of ESR spectroscopy to date minerals (e.g. carbonate deposits, calcites, silica, phosphates, etc.) (Thompson, J. and Schwarcz, H.P. 2008), and fossils (e.g. shells, corals, bones, teeth) (Ikeya, 2002). Noticeable progress in dating has, for instance, recently been reported on ESR studies (Skinner, Anne R. 2008) of limestones from Cretaceous–Tertiary boundary on the extinction theory of the dinosaurs 65 million years ago (Griscom and Beltrán-Lopez, 2002), and on ESR dating of the most ancient human settlements in Europe by ESR spectroscopy of fossil herbivorous teeth, coupled with U-series measurements, to model the uptake of uranium (Falguéres et al., 2002). The very long lifetime of some signals allows ESR to provide information over the entire span of human evolution. A survey on the present state in geological dating using ESR is given by Skinner (2000) and Skinner et al. (2002) (Dieter F. Regulla, 2005).
Dating of megafauna can contribute to the better knowledge of megafauna presence in this region as well as to the events associated to the extinction of these species. In some cases ESR is an interesting possibility of dating, since no remains of compounds containing C-14 can be found (Oliveira, L., et al., 2008).
Also, dating of barnacles may reflect past sealevel and sea level changes (Skinner, Anne, et al., 2008). Knowing the dates of these changes can constrain the periods of regional hominid occupation and provide a better understanding of local and global environments. Also, dating of teeth may lead to the accurate determination of sedimentation rates, improving the age estimates for humids and other Paleolithic cultural deposits (Anne R. Skinner, et al., 2008).

7. Uncertainties

One of the problems in evaluation of uncertainty in EPR tooth dosimetry is that different factors that influence the total uncertainty cannot be separated. Another problem is that blank samples are absent resulting into a lack of calibration standards. Each tooth extracted for medical indications has its own age that starts from hydroxiapatite formation. Due to natural radiation exposure there are not any tooth enamel with zero dose. Therefore, each tooth accumulates some unknown dose doe to natural background (Shishkina E., et al., 2008).

For the reasons above, the accuracy of EPR dosimetry is not a trivial task. A new approach for estimation of the uncertainty using combination of physical and numerical (Monte Carlo simulation) experiments has been developed. The exp erimental basis of that work was the results of intercomparison of three EPR laboratories: GSF (Munich, Germany); ISS (Rome, Italy) and IMP (Ekaterinburg, Russia).

Results of the study show that EPR measurement uncertainty depends on both amplitude of signal and sample mass. Moreover, statistical modeling of EPR signal demonstrates the presence of not only a random error of signal evaluation but also a systematic bias of spectra processing that depend on amplitude (Shishkina E., et al., 2008).

For radiation therapy, a small uncertainty of the applied dose is required. The uncertainty budget for the alanine/ESR dosimetry system of the Physikalisch-Technische Bundesanstalt (PTB) was determined, which relies on the use of a reference sample. A method is also presented which allows a reduction of the influence of fading or other changes of the ESR amplitude of irradiated alanine probes with time. If certain conditions are met which are described in detail, a relative uncertainty of less than 0.5% can be reached for probes irradiated with ^{60}Co in the 5–25 Gy dose range, including the uncertainty of the primary standard (Krauss, A. 2006). First results for dose values between 2 Gy and 10 Gy are presented as well (Mathias Anton, 2006). More methods of evaluation of uncertainties of alanine dosimetry can be found elsewhere (Bartolotta, A., et al., 1993, Bergstrand, S., et al., 1998, Kojima, T., et al., 1999, Nagy, V., et al., 2002).

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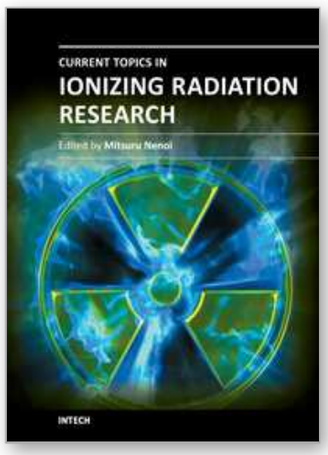

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Since the discovery of X rays by Roentgen in 1895, the ionizing radiation has been extensively utilized in a variety of medical and industrial applications. However people have shortly recognized its harmful aspects through inadvertent uses. Subsequently people experienced nuclear power plant accidents in Chernobyl and Fukushima, which taught us that the risk of ionizing radiation is closely and seriously involved in the modern society. In this circumstance, it becomes increasingly important that more scientists, engineers and students get familiar with ionizing radiation research regardless of the research field they are working. Based on this idea, the book "Current Topics in Ionizing Radiation Research" was designed to overview the recent achievements in ionizing radiation research including biological effects, medical uses and principles of radiation measurement.

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