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In vivo ASSESSMENT OF RADIATION EXPOSURE

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***Abstract*—Three workers at a San Salvador ^{60}Co irradiation facility were victims of a radiation accident, resulting in the amputation of a leg from two workers. The absorbed dose to bone was successfully assessed by electron paramagnetic resonance (EPR) quantitation of radiation-induced hydroxyapatite centers.**

INTRODUCTION

CONSIDERING the total number of worldwide operations involving radioactive sources, radiation accidents resulting in severe health consequences to individuals have been rare (Nenot 1990). Immediately following such incidents, timely and appropriate medical treatment for the victims would aid their recovery. The development of emergency biological radiation dose-equivalent indicators that could facilitate triage would benefit both victims and medical personnel.

Electron paramagnetic resonance (EPR) spectroscopy is used routinely to detect and quantify paramagnetic centers in a variety of materials. The potential of EPR as a dose assessment method has been realized and implemented for applications ranging from detection of radiation-processed foods (Dodd et al. 1988; Desrosiers 1990) to archeological dating (Ikeya 1988). Previously, EPR spectrometry of bone tissue from a radiation accident victim suggested that the mineralized component may be useful as an "*in vivo* dosimeter" (Brady et al. 1968). Long-lived radiation-induced paramagnetic centers in the hydroxyapatite matrix of bone tissue are specific to ionizing radiation and are indicators of ionizing radiation exposure. Moreover, for these centers the EPR signal intensity is proportional to the absorbed dose.

The use of EPR as a retrospective dose assessment technique was recently demonstrated for persons near the Chernobyl accident site. The levels of dose equivalent were estimated by EPR analysis of paramagnetic centers in tooth enamel hydroxyapatite (Ishii et al. 1990). A limited, but severe, radiation accident in El Salvador occurred in 1989 (IAEA 1990). This paper describes EPR measurements on bone tissue that provided dose estimates for the victims of the accident.

METHOD

Sections of bone tissue from each amputated leg were provided by the Radiation Emergency Assistance Center and Training Site (REAC/TS) based in Oak Ridge, TN. To assess the absorbed dose to parts of the leg of each patient, a fragment (approximately 3 × 15 mm) was cut from each bone sample. The first-derivative EPR spectrum of each bone fragment was recorded. The peak-to-peak amplitude of the EPR signal ($g_\perp$) derived from radiation-induced paramagnetic centers in the mineralized bone tissue was used as a measure of the bone dose response. Additive doses of ^{60}Co radiation were given to these fragments, and the EPR spectra were measured at each dose increment. A mathematical fit to the EPR dose response was then extrapolated to the negative dose axis (abscissa) to obtain an estimate of the initial absorbed dose, as described previously (Desrosiers 1990).

RESULTS AND DISCUSSION

On 5 February 1989, an accident occurred at a San Salvador industrial irradiation facility (IAEA 1990). Three workers received significant radiation exposures when they entered a room containing a raised pool-type ^{60}Co radiation source, under the mistaken impression that the "radiation had dissipated." This incident resulted in severe radiation sickness and the amputation of a leg from two workers (referred to as Patients A and B). At a later date, experts from REAC/TS were invited to assist the medical team treating the patients. At the request of REAC/TS, bone samples from the amputated leg of each patient were examined to assess the absorbed dose and map its distribution.

EPR spectra of bone fragments from the femur, tibia, and proximal phalange of the second toe for Patient A revealed detectable levels of the radiation-induced hydroxyapatite center, identified by the characteristic $g_\perp$ and $g_\parallel$ spectroscopic splitting factors (Fig. 1); similar spectra were obtained for the tibia and femur of Patient B. The

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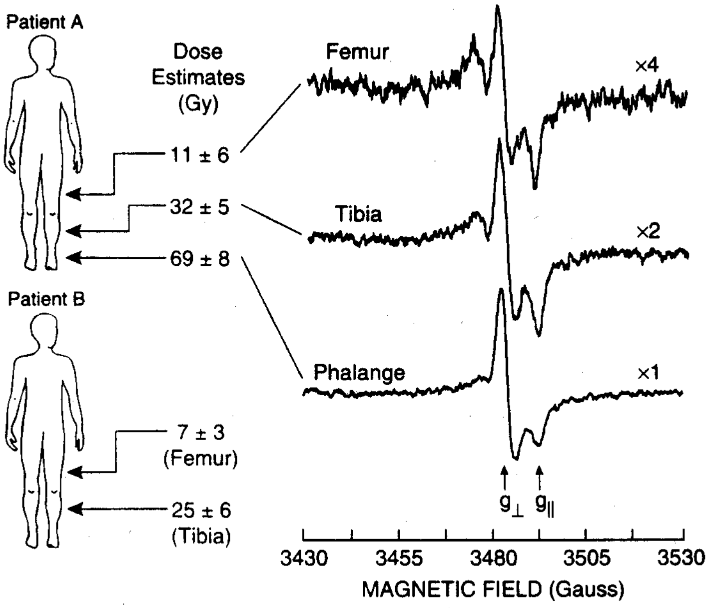

Fig. 1. Shown are the first-derivative EPR spectra of bone fragments from the femur, tibia, and proximal phalange of the second toe for Patient A. The dose estimates for Patients A and B, obtained by the EPR method, are summarized in the accompanying diagram. The estimated uncertainties are expressed at the 95% confidence level.

doses estimated by EPR were highest at the extremities and greater for Patient A than for Patient B. These data are consistent with the details of the accident: Patient A was the closest to the ^{60}Co source, and the top of the source was at foot level on a platform above the storage pool surface. Initial absorbed dose levels were estimated visually from the degree and extent of epidermal damage (Patient A: lower leg > 30 Gy, upper leg 10–15 Gy; Patient B: lower leg > 30 Gy, upper leg 3–15 Gy) (IAEA 1990). The EPR dose estimates are in accordance with the visual estimates and are clearly a better indicator of the extent of exposure to the lower leg. Furthermore, the estimated uncertainties for the EPR dose evaluations are significantly smaller than the clinical estimates.

Although the absorbed dose to bone is measured with better precision using the EPR method, the accuracy of the EPR estimates is clouded by lack of information on the metabolic *in vivo* persistence of the radiation-induced paramagnetic centers in the mineralized tissue. The hydroxyapatite paramagnetic center is stable for years once the bone ceases to become living tissue; however, there have been conflicting reports on the *in vivo* lifetime of the paramagnetic center (Slager et al. 1964; Swartz 1965).

A recent study by M. J. McCreery, A. E. Lunsford, and J. J. Conklin has attempted to clarify this issue. Mouse femurs, removed, irradiated, and reimplanted under conditions simulating normal metabolism, have shown that though some radiation-induced centers are initially lost, a majority (>50%) of the centers remain and approach a constant number after 6 mo. These data suggest that, although some centers decaying via an unknown metabolic pathway are lost, others are apparently deep centers that may persist for long periods. The rate of metabolic decay for the hydroxyapatite centers should vary with the turnover rate for the bone type, e.g., trabecular vs. cortical (compact) bone.

The EPR dose estimates measured here are derived from cortical bone samples likely to have the greatest number of surviving centers. Since the metabolic decay rates for the bones of Patients A and B are unknown, and a number of days passed before the legs were amputated (Patient A, 132 d; Patient B, 161 d), these estimates should be regarded as lower limits of the exposure.

CONCLUSION

Since the availability of bone tissue is rare, development of a less invasive approach to accident dosimetry is desirable. Although tooth enamel would offer greater sensitivity and not be subject to metabolic deactivation of hydroxyapatite paramagnetic centers, the question of sample availability remains. However, a program to refine and standardize the EPR method for biological dosimetry would benefit long-term follow-up dosimetry for large-scale radiation accidents, especially those involving the general populace (e.g., Chernobyl), using bone and tooth samples as they became available.

Notably, clinical radiation therapy could also benefit from EPR dosimetry. The measured doses for Patients A and B are of the magnitude administered in clinical applications (1–20 Gy); the EPR method could validate and map absorbed radiation dose for clinical applications. In fact, the EPR method has been demonstrated to be sensitive to radiation delivered by bone-seeking radiopharmaceuticals (Desrosiers et al. 1991) and offers the first direct quantitative *in-vivo* assay of dose for this type of treatment.

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