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ELECTRON PARAMAGNETIC RESONANCE FOR ACCUMULATED DOSE MEASUREMENT

Ph.D. Thesis SUMMARY

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Riga, 2006

IMPORTANCE OF WORK

There are about several tenths thousand inhabitants (6500 from Latvia) involved in clean-up activities after the Chernobyl Nuclear Power Plant (NPP) accident in 1986. Nowadays they represent group of chronically ill people with diseases prevalence of digestive, musculoskeletal and nervous systems. The officially documented doses ranged from 0.01 to 0.25 Gy documented only for part of the cohort having low probability of stochastic effects and excluding deterministic. However, the official doses having large part for criticisms because include only external photon exposure measured by individual dosimeters. The internal exposure, irradiations by incorporated nuclides were not taken into consideration. This deals with absence of reliable measurements of the doses. The work is devoted to develop new technique to access the real individual doses in reason to facilitate treatment and rehabilitation of clean-up workers.

THE AIM OF THE WORK

The work is aimed to develop electron paramagnetic resonance (EPR) dosimetry to measure accumulated doses of ionising radiation absorbed by individuals.

To reach the goal the following main tasks should be performed:

1. Exploration of influence of specimen preparation on EPR measurements and select the best technology;
2. Exploration of influence of EPR measurements modes on detected signals;
3. Estimation of the uncertainties budget of EPR dosimetry;
4. Analyses of EPR dosimetry system response factor;
5. Verification of EPR dosimetry in respect with the international

standard; 6. Demonstration of EPR capabilities for individual retrospective dose assessment (for the Chernobyl NPP accident clean-up workers).

SCIENTIFIC NOVELTY

The following results have been achieved for the first time:

- Dosimetry based on EPR signal by human tooth enamel to measure accumulated doses of ionising radiation absorbed by individuals,
- Influence of specimen preparation on EPR measurements; the conditions assuring the highest signal to noise (S/N) ratio and minimizing background signal. The recommendations on the best specimen preparation technology has been developed;
- Dependence of detected EPR signal on:
    - modes of EPR measurements from tooth enamel;
    - optimum of microwave power,
    - registration temperature,
    - procedure for spectra processing;
- Uncertainties budget of EPR dosimetry on human tooth enamel: standard uncertainty of EPR method is below 30% in dose region 100-500 mGy;
- Internationally verified EPR dosimetry on human tooth enamel.

VERIFIABILITY

The developed technique has been verified at the international standard level, owing to comparison achieved calibrated dosimetric data with 30 laboratories around the World.

APPLICATION

The developed technique has been applied for the medical research performed in the Center of Occupational and Radiological Medicine. Doses measured by EPR have been used to choose proper treatment and rehabilitation procedures of Chernobyl NPP accident clean-up workers. Based on the EPR dosimetry data two Medical Doctor thesis have been promulgated

MAIN PUBLICATIONS

1. A. Pavlenko, E. Pakers, N. Mironova-Ulmane, U. Ulmanis, M. Zakaria. Some problem of radiation protection in Latvia. Proc. of Conference of Applied Physics, Kaunas (2000) pp.75-78

2. A. Pavlenko, N. Mironova-Ulmane, M. Zakaria. Status and Technology of Personnel Dosimetry in Latvia. Latvian Journal of Technical Science. N5 (2000) pp.65-74

3. N. Mironova-Ulmane, A. Pavlenko, T. Zvagule, T. Karner, R. Bruvere, A. Volarte. Retrospective dosimetry for Latvian workers at Chernobyl. Radiation Protection Dosimetry, Nuclear Technology Publishing. Vol. 96 (1-3) 2001 pp. 237 -240

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5. N. Mironova-Ulmane, A. Pavlenko, M. Eglite, E. Curbakova, T. Zvagule, N. Kurjane. Chernobyl clean-up workers: 17 years of

follow-up in Latvia. Recent Advances in Multidisciplinary Applied Physics, pp.9-19,Elsvier Sceince 2005 (ISBN 0 08 0444 696-5)

APPROBATION

1. European Workshop on Individual Monitoring of External Radiation, Helsinki, Finland 4-6 September, 2000.

2. IRPA Regional Congress on Radiation Protection in Central Europe, Dubrovnik, Croatia, May 20-25, 2001.

3. European Medical and Biological Engineering Conference, EMBEC-2002, Vienna, Austria, 4 -8 December.

4. International Conference on Applied Physics, APHYS-2003, Badajoz, Spain, 13-18 October 2003.

PH.D. THESIS STRUCTURE

The work consists of introduction, 8 chapters, 42 figures, 9 tables and conclusion. The work is written on 111 pages with 180 references.

Introduction

Since the discovery of X-rays and radioactivity more than 100 years ago, human being benefits applying ionising radiation. On the other hand radiation harm to the individual became evident that demand limitation of radiation exposure or dose. In occupational radiation protection dose is usually derived from monitoring of personal dosimeters. In cases of uncertain or unavailable personal dosimetry and under conditions of suspected overexposure accidental dosimetry is used. The solid state methods of TLD and EPR provide powerful tools for dose assessment. These methods allow to measure integrated absorbed dose in many years after the accident and make dose reconstruction for places and people where this assessment has not been done timely [1]. There are about 6500 clean up workers from Latvia participated in work in Chernobyl region during 1986-1991. Nowadays they represent group of chronically ill people [2] with progressive diseases like diseases of bones, muscles and connective tissues, diseases of digestive and respiratory systems, as well as diseases of nervous system and sensory organs.

According to documents their doses ranges from 10 to 250 mGy. These doses correspond to annual limits recommended by International Atomic Energy Agency (IAEA) [3], International Commission on Radiological Protection (ICRP) [4] and fixed in the local regulations [5], as a limit below which no any radiation induced effects could exist. However, given doses correspond only to external exposure and registered only for 1/3 of the cohort.

The pilot study on dose estimation by EPR for Latvian clean-up workers has been made in 1997. It demonstrated underestimation of official doses by factor of 2-4.

Tests done by Instrumental Neutron Activation Analysis (INAA) showed elevated concentration of Sr in extracted teeth. It gives an assumption that half of absorbed dose, and in some cases even more could caused by ^{90}Sr and some other fission products, ^{137}Cs for instance [6].

The results of the work could be implemented for treatment and rehabilitation of Chernobyl liquidators and provide additional contribution to radiological studies. Application of EPR method could have reasonable benefit for treatment planning and retrospective individual dose estimation for Nuclear Medicine and Radiotherapy patients.

1. Ionising radiation and its biological effects

The basics concepts of protection against exposure from ionising radiation are reviewed including physical and biological interaction of radiation, deterministic and stochastic effects.

2. Radiological protection and dosimetry of individuals

The existing methods of dose assessment are listed including external and internal dosimetry methods as well as individual dose estimation from environmental monitoring data. Mainly this chapter is focusing on EPR technology for dose assessment. The EPR method has been compared to the other retrospective methods and selected for existing studies on individual dose estimation. The well developed TLD method is used like verification tool for EPR dosimetry results.

3. EPR instrumentation

EPR measurements on teeth enamel have been made at room temperature by an X-band cavity PE-1306 spectrometer operated at 9.4 GHz. The technology of EPR dosimetry schematically presented on Fig. 1.

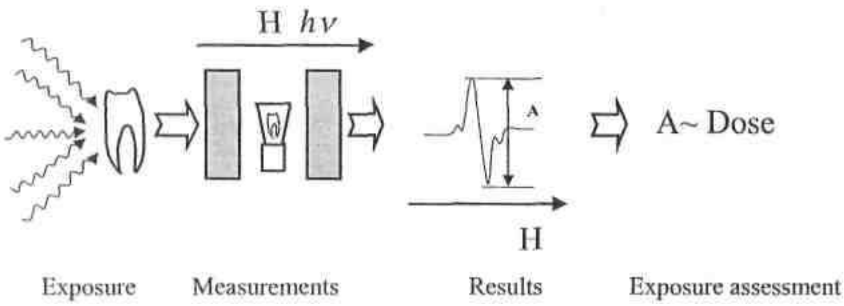

Fig. 1. Technology of EPR dosimetry.

The radicals created by ionizing radiation in enamel could be measured by inserting the enamel in magnetic field and additionally exposing by high frequency electro magnetic radiation [7]. At the specific magnetic field value the electro magnetic radiation absorption is occurred. The EPR spectrometer register the first deviation from absorption curve and amplitude of this deviation is proportional to amount of inserted radicals. The later is proportional to absorbed dose. To improve the signal/noise ratio given EPR spectrometer employs high-frequency magnetic field modulation in combination with phase-sensitive detection. This arrangement produces S/N ratios that are orders of magnitude larger than would be possible without it. Operation of the EPR spectrometer is achieved by optimizing sets of technical parameters chosen through its microwave power, magnetic field and signal channel components.

4. Samples their irradiation and influence on EPR

The following technique was applied for sample preparation, Fig.2. This procedure was described in [8] and with significant modifications applied for the given experiments. The criteria for sample preparation technology were separation of dosimetric signal from background one and increasing S/N ratio.

Teeth were extracted form patient during medical treatment in the clinic. The crown was separated from the root mechanically. The dentine was removed with a hard alloy dental drill. Care was taken to prevent over heating of samples avoiding fading of dosimetric signal and producing additional radicals not related to dosimetry.

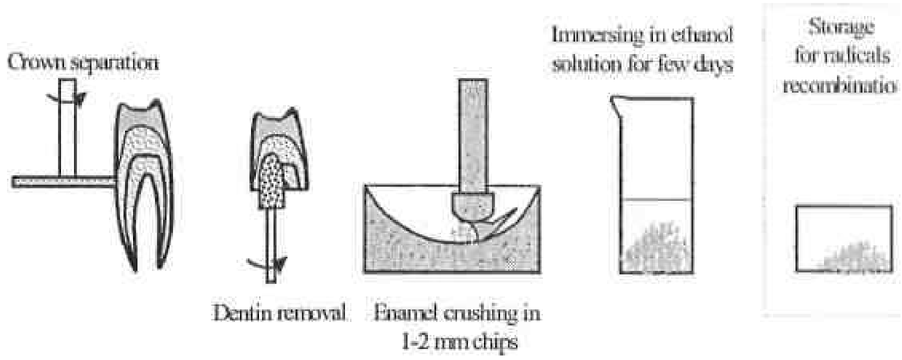

Fig.2. Sample preparation procedure.

The enamel was crushed into pieces 1-2 mm using agate mortar and pestle. The samples were kept in an alcohol-ethyl mixture for several days for degreasing and drying.

The samples were then stored for a few more days to allow recombination of the mechanically induced radicals. Before measurements samples were stored in essicator containing annealed silicagel for future drying.

Following such processing, the amplitude of the native signal was reduced and the S/N ratio optimised. The grounded enamel was weighed on an analytical balance and placed in quartz ampoules for EPR spectroscopy. The optimum weight of sample for measurement was around 100 mg.

Irradiation of samples has been performed at Gamma-Contour installed at Latvian Nuclear Research Center (LNRC) by gamma photons with average energy 1.12 MeV. Teeth enamel samples have been packed in paper and inserted in plastic contained for irradiation. There are the following factors affecting EPR signal discussed in the given chapter:

- Environmental factors;
- Metabolic modification;
- Energy dependence.

All these factors have significant influence on the EPR spectra and therefore on dose estimated. The ways of the influencing factors reduction is proposed.

5. EPR detection modes

The spectral measurement parameters were optimized between maximum sensitivity and time saving, on the one hand, and obtaining as much information as possible, on the other.

EPR signals increase as the square root of the microwave power until saturation slows and then reduces the signal intensity. The microwave power variation allows separating dosimetric and background signal and increasing S/N ratio. As microwave power increases, "dosimetric signal/background signal" ratio increases, while

S/N ratio decreases. The compromise value of microwave power was found 6.2 mW having the highest S/N ratio, Fig. 3.

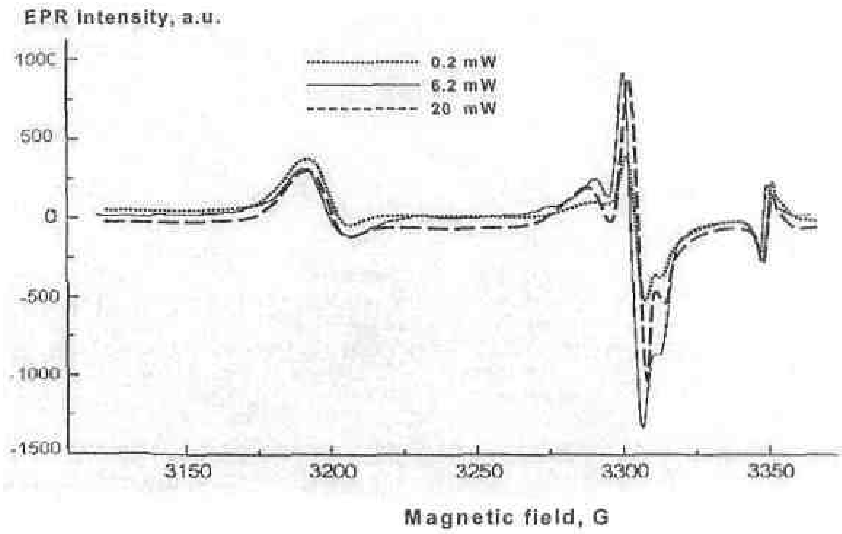

Fig.3. Influence of microwave power on EPR

The EPR resolution usually increases at low temperatures and allows to identify the fine structure of EPR spectra. For given studies effect of low temperatures on EPR spectra of tooth enamel was studied for optimization of measurement condition.

It was found that amplitude of the main dosimetric signal close to g = 2.0 is not temperature dependent. At low temperatures close to 4.2 K it shows some fine structure but determination of EPR radicals structure was outside task for the given work. For the given studies only amplitude of the dosimetric signal was important because is directly connected to absorbed dose in teeth enamel. Mathematical simulation of the background and dosimetric signals has been performed to approximate the EPR spectrum of tooth enamel in reason to separate then from each other. The method used the combination of Gaussian functions both for background and dosimetric signals. Latter it was found that such approximation produce big overall uncertainty of EPR measurement due to individual shape of background signal for every enamel sample. Therefore it was decided to use additional irradiation method for dose estimation.

6. Uncertainties budget

For estimation of EPR dose reconstruction uncertainties concept similar to one presented in the ISO [9] recommendations and discussed in [10] was used. The following uncertainties are related to the measurement of absorbed dose in tooth enamel and need to be considered for the estimation of uncertainty of an individual dose [11], $U_{EPRDOSE}$:

- — Sample preparation uncertainty *(U_{sam});*
- — Fading uncertainty *(U_{fad});*
- — Uncertainty of measurement *(U_{EPR});*
- — Uncertainty of natural background dose *(U_{back});*
- — Uncertainty of EPR dose calculation method *(U_{cal});*
- — Uncertainty of enamel metabolic modification *(U_{met}).*

These uncertainties could be grouped

$$U_{EPRDOSE} = (U^2_{sam} + U^2_{fad} + U^2_{EPR} + U^2_{back} + U^2_{cal} + U^2_{met})^{1/2}, \qquad (1)$$

based on assumption that all individual uncertainties are uncorrelated.

Sample preparation

It was experimentally found that average uncertainty of given sample preparation technology presented on Fig.2 *(U_{sam})* was around 10%.

Fading

There is no evidence that fading contributes to the combined standard uncertainty of EPR dose reconstruction with tooth enamel. Therefore $U_{fad} = 0$.

EPR measurements

The EPR measurement uncertainty (U_{EPR}) is a combination of uncertainties from spectrometer noise (U_{noise}), sample positioning in resonant cavity (U_{pos}) and spectrometer stability (U_{stab}):

$$U_{EPR} = (U^2_{noise} + U^2_{pos} + U^2_{stab})^{1/2} \qquad (2)$$

The intensity of the tooth enamel EPR dosimetry signal is overlaid by noise in the spectrum from two sources, high frequency and low frequency noise. For future calculation it was accepted spectral noise level U_{noise} = 12% for the given amplitudes of analyzed signals.

The EPR signal intensity is influenced by sample positioning variations. The uncertainty U_{pos} was determined experimentally and it is usually about 2%.

The spectrometer sensitivity is one of the most important parameters affecting accuracy of EPR measurements. The spectrometer stability has been proved by MgO: Mn^{2+}, Cr^{3+} standard crystal inserted in resonator together with sample. This allows to decrease uncertainty of spectrometer stability close to 7%.

The total uncertainty of EPR measurements (U_{EPR}) including the (U_{noise}), $(U_{pos}$, (U_{stab}) is 14% for given amplitude of EPR signal.

Contribution of natural background radiation

The typical value of natural background dose for Latvian inhabitants is equal to 1 mGy per year. This value has been verified by

TLD dosimeters and calculated assuming average terrestrial exposure 100 nGy/hour. *(U_{back})* is assumed around 3%.

Uncertainty of EPR dose calculation method

The additive dose method used in the given studies one need to obtain the dependence of the EPR dosimetric signal on the irradiation dose. A linear dependence was assumed and least square fitting was used. The other procedure of dose reconstruction or background spectrum subtraction method was eliminated from future studies by experimental fact of high dependence of background signal on individual. Overall standard uncertainty of dose reconstruction by given procedure sometimes overcome 80%, therefore for uncertainty reduction it was decide to use additive dose method.

Tooth enamel samples were irradiated in Gamma Contour, Latvian Nuclear Research Centre (LNRC).

In this case the overall uncertainty could be estimated as follows.

The uncertainty of air kerma dose rate summaries uncertainty of positioning *(U_p)* and combined uncertainty of source *(U_{source})*. Uncertainty of sample position *(U_p)* and for the given set up is estimated 2 %.

The combined uncertainty of source *(U_{source})* includes additional factors having an influence on the dose delivered to the enamel. It includes variation in air temperature, humidity, pressure and variation in spontaneous disintegration of the source. For given irradiation set up contribution of all these factors is around 10 %. Uncertainty of irradiation time *(U_t)* was estimated around 5 %.

The correction factor k is estimated based on Monte Carlo simulation of the electron transport in tooth enamel. The value k was taken from [12] and uncertainty assumed to be below 3%.

Because of using the additive dose method for EPR dose estimation where the absorbed dose is not measured directly from the value of EPR amplitude but extrapolated from the dose measured by TLD method. Therefore it is need to include TLD measurement uncertainly (U_{TLD}) that was previously estimated 16%. Additionally it needs to be included uncertainty of linear regression approximation (U_{app}) that was estimated about 3%.

The uncertainty of EPR dose calculation includes all above mentioned uncertainties. Assuming that these uncertainties are not related to each other one can get:

$$U_{cal} = (U^2_p + U^2_t + U^2_k + U^2_{source} + U^2_{TLD} + U^2_{app})^{1/2} \qquad (3)$$

The uncertainty EPR dose calculation (U_{cal}) was calculated equal to

0.201 and for future estimation accepted 20%.

Uncertainty of teeth enamel metabolism

Teeth enamel metabolism has notable contribution to EPR signal and it strongly individual dependent. In these studies the contribution of metabolism to overall uncertainty budget was accepted 10% and possessed assuming no caries affected parts of teeth in the studies.

Estimation of the combined standard uncertainty of EPR dose reconstruction

Based on the estimations given above for different contributions and formula (1), the overall uncertainty of EPR dose reconstruction results in a combined standard uncertainty *($U_{EPRDOSE}$* 28.3%) or below 30% for the dose interval 100 mGy - 500 mGy based on assumption that uncertainties *(U_{sam}), (U_{EPR}), (U_{back},), (U_{met}), (U_{fad})* and *(U_{cal})* do not correlated to each other. This uncertainty is only valid for photon exposures with energies above 300 keV. The given estimation of combined uncertainty could be characterized like an ideal case where additional contributing factors are not included.

6. Verification of EPR measurements by TLD method

The existing method of TLD dosimetry used in Latvia is described including materials, technique and factors affecting including own calibration of TLD method.

Uncertainty and performance evaluation of TLD method

Dose *D* estimation on TLD dosimeters is performed by following formula

$$D = (\frac{1}{S_i}(TL_{meas} - TL_{bgr})) \cdot K_{cal} \cdot K_E \cdot K_F \cdot K_A, \qquad (4)$$

where Si - individual sensitivity of Thermoluminescence (TL) detector, *TLmeas* - measured TL output from the detector, *TLbgr* -background TL signal from the detector, *Kcal* - TLD reader calibration coefficient showing relationship between measured TL current and absorbed dose in Sv; K_E - energy dependency of TL detector; K_F - fading correction coefficient; K_A- correction of angular dependence of TL detector.

The formula for estimating the dose given in equation could be rewritten as:

$$D = (C_{meas} - C_{bgr}).K_{cal} \, . \, K_E \, . \, K_F, \quad (5)$$

where $$C_{meas} = (TL_{meas} - TL_{instr})/S_i \, . \quad (6)$$

For estimation of combined standard uncertainty all uncertainties could be treated as not correlated input quantities and estimated according to formula

$$u(D) = (u_{Cmeas}{}^2 + u_{Cbgr}{}^2 + u_{Kcal}{}^2 + u_{KE}{}^2 + u_{KF}{}^2 + u_{KA}{}^2)^{1/2}, \quad (7)$$

where U_i is the standard uncertainty of every input quantity or contributor to the dose.

The examples of estimation of the standard uncertainty of dose D according to [7] for the dose $D = 10\ mSv$ is presented below.

The standard uncertainty values $U(C_{meas})$ and $U(C_{bgr})$ are estimated according to Poisson statistics of random physical process of particles emission and counting. In this case the $U(C_{meas})$ and $U(C_{bgr})$ are calculated as root mean square from the measured value and for C_{meas} = 70000 counts and $C_{bgr} = 10$ counts the $U(C_{meas}) = 1\%$ and $U(C_{bgr}) = 3\%$.

Uncertainty $U(K_{cal})$ is estimated based on calibration factor of the TLD system. The $U(K_{cal})$ value includes uncertainty of irradiation in standard laboratory and statistical variation in dosimeters reading and estimated to be is not more then 5%.

The uncertainty $U(K_E)$ is estimated on energy dependence of TLD response. For given uncertainty analysis it is accepted to set $U(K_E) = 10\%$.

The uncertainty $U(K_F)$ is assumed on monthly monitoring interval and to be less then 3%.

The uncertainty $U(K_A)$ represent uncertainty of angular dependence of TLD detectors. For future calculation the $U(K_A)$ value is set to 10%. Using equation (7) one can get the estimated uncertainty of TLD measurement is 16 % for dose 10 mSv. With higher doses is possible to decrease overall uncertainty of measurement but the angular and the energy dependence continuing to be the main contributors of uncertainty.

Performance of TLD

The performance of TLD system has been evaluated according to internationally existing standard procedure.

In 1999 TLD laboratory was taking part in International Intercomparison Procedure for Radiological Purposes organized by IAEA.

This process includes several steps: sending of dosimeters to IAEA, irradiating at laboratory, returning back to the participants, where doses were measured.

Fifteen dosimeters were sent to IAEA, where nine were irradiated in (Physikalische-Technische Bundesanstalt, Germany) and six were used for background radiation controlling. Irradiation was made on 420 kV X-ray unit using slab 300x300x150 mm water phantom. The selected radiation includes 0° incidence as a basis data and simulating of work place by changing angle of incidence between +80° and -80°. The nominal distance and the angle of incidence were measured with resolution 0.1 mm and 0.1° respectively. Standard uncertainty was in the range 2 ÷ 2.5%. Doses delivered to dosimeters ranges from 5 to 30 mSv. Results of dosimeters measurements made in Latvian TLD laboratory reported as corrected response of dosimeter Q

$$Q = \frac{Hp(10)_{std}}{HP(10)_{mes}} \tag{8}$$

where $Hp(10)_{std}$ is personal dose equivalent reported by standard irradiation laboratory and $Hp(10)_{mes}$ is value measured in the laboratory.

According to international regulations Q value should lie between lower and upper uncertainty limits (-33% ÷ +50%) for doses more then 10 mSv.

The results of Intercomparison show that the values measured by Latvian TLD laboratory are placed into internationally acceptable limits.

Verification of EPR

Teeth enamel samples were irradiated by gamma rays delivered by Gamma-Contour installed at Latvian Nuclear Research Center. An average energy of gamma photons was 1.12 Me V. TLD dosimetry method has been applied as a calibration method for EPR dose measurement. TLD pellets have been used during an additional irradiation of enamel as reference dosimeter of absorbed dose. Enamel from non exposed individuals together with reference TLD has been packed in one plastic container to achieve secondary electron equilibrium. Container was located on the working table assuring equal distance from the irradiator to enamel and reference TLD, Fig. 4.

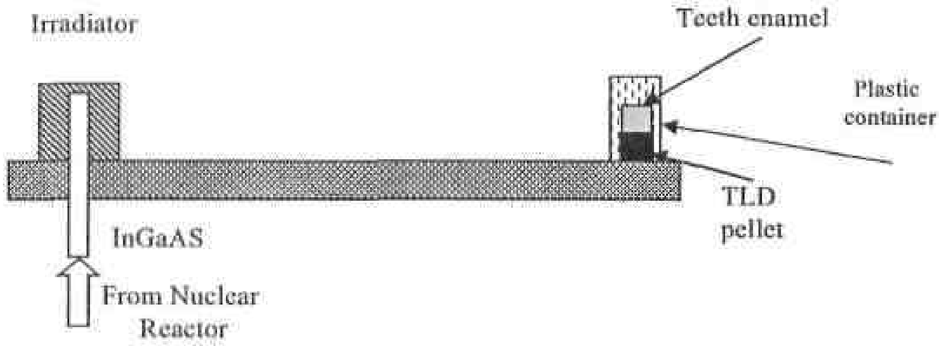

Fig.4. EPR signal amplitude calibration by TLD method.

Using given irradiation procedure it was assumed that dose absorbed by TLD is equal to dose absorbed by teeth enamel. Time of exposure has been varied from 1 to 10 minutes, controlled by chronograph. Latter, the dose absorbed by TLD detector was measured by TLD system that gives reference dose value for teeth enamel. The calibration curve of EPR signal is presented on Fig. 5.

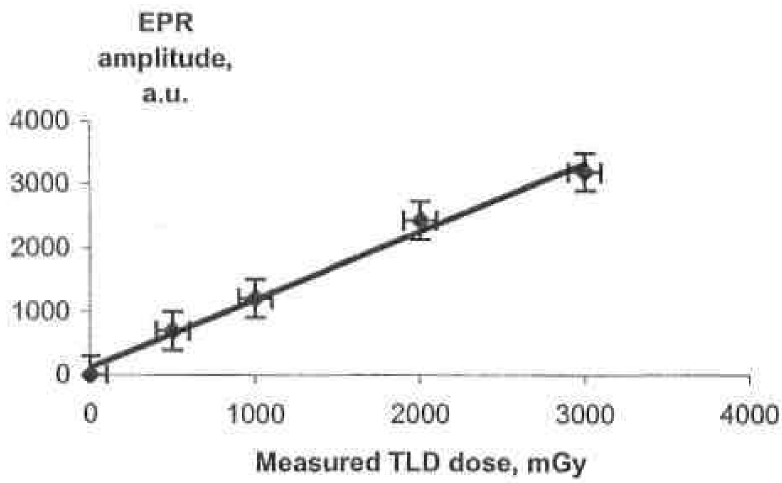

Fig.5. EPR signal amplitude dependence on absorbed dose.

There one initial and four additional irradiation points were used for calibration curve assuming linear regression between absorbed dose and EPR signal.

8. Application

Medical status of clean-up workers

The clinical studies were conducted in the Center of Occupational and Radiological Medicine, P. Stradins Clinical Hospital.

The results of medical investigations have been compared with a control group of 237 employees of Ministry of Internal Affairs of corresponding age having no occupational radiation exposure. For more detailed medical tests the control group was subdivided according to profession, duration of service, individual habits. In the structure of the diseases (1992-2000) diseases of bones, muscles and connective tissues, diseases of digestive and respiratory organs occur as well as diseases of nervous system and sensory organs [13]. The disease rate of clean-up workers is much higher that in the age matched population group. It gradually increases even 10-15 years after the work in Chernobyl area [14]. Diseases of nervous, digestive, circulatory system, mental disorders and diseases of muscles and connective tissue are the most frequent in the clean-up workers group. Studies of immune systems have shown the incidence of good ability of leukocytes to produce interferons is 2-3 times lower for Chernobyl NPP accident clean-up workers than that for controls ($p<0.001$) [15, 16]. According to these results, most of the Chernobyl clean-up workers have endogenous interferon deficiency leading to depression of immune system.

Measured absorbed dose in tooth enamel

As the result of the work the dose absorbed by teeth enamel for group of clean-up workers has been measured. It indicates difference between the official doses and doses measured by EPR, Fig. 6. Generally EPR doses are several times higher then official doses.

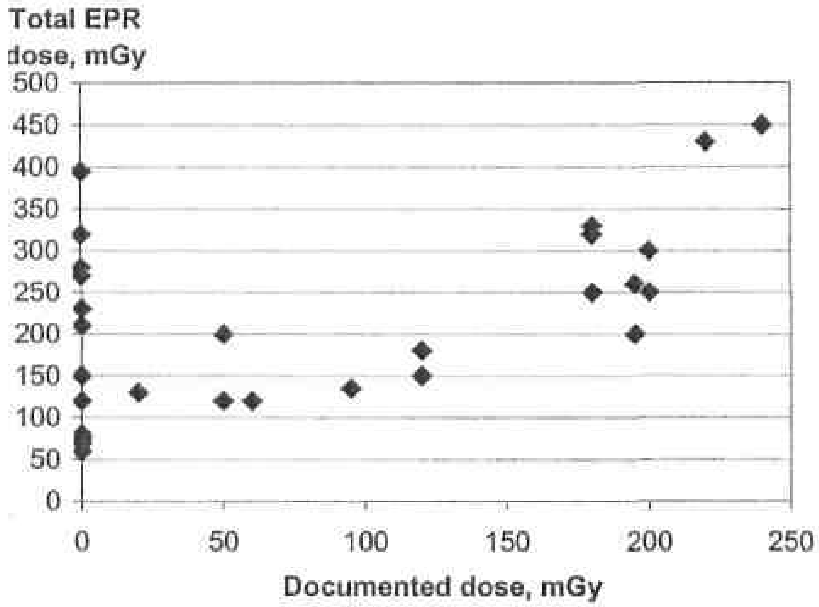

Fig.6. Officially documented doses and doses measured by EPR.

It was observed that EPR doses more then 50 mGy have been measured for people who officially were classified as not exposed. Additionally, EPR doses indicated individuals with exposure more then 250 mGy (limit for occupational exposure during emergency situation in former USSR).

The dose measured by EPR includes exposure from different kind of radiation. It includes medical, external and internal exposure, natural background radiation and etc.

Dose estimation from incorporated Sr in calcified tissues

The difference by factor 2-5 between officially documented doses and measured by EPR has been found. It was proposed that large part of exposure comes from internal irradiation. There are several conceptually distinct methods to assess internal dose [17]. One of the approaches used for internal dose estimation is approximate calculation of absorbed dose for beta-emitted nuclides based on activity measurement at the given organ. The method calculates the dose rate from the specific organ using the average energy of beta emitted nuclide and its activity in the organ. The dose rate in mGy/day is estimated by formula [18]

$$P(t) = C_0 \cdot 1.38 \cdot 10^{-2} \cdot E_\beta \cdot k \qquad (9)$$

where C_0- specific activity of the teeth enamel (Bq/g);

E_β - average activity of β emitted $^{90}Sr/^{90}Y$, 1.09 MeV;

k - part of β -radiation energy absorbed directly in the teeth enamel, 0.9.

Activity of ^{90}Sr measured on tooth enamel in 1997 for Chernobyl clean-up workers ranges from 20 Bq/g to 350 Bq /g [6, 19].

Using the formula (9) the absorbed dose rate to the teeth estimated for Chernobyl clean-up workers ranging from 0.27 mGy/day to 4.7 mGy/day.

Taking into account density of soft tissues (~1 g/cm^3) and bone (~3 g/cm^3) the maximum range in soft tissues is equal to 3 mm and in bones 1.2 mm. Therefore it could be assumed that incorporated

$^{90}Sr/^{90}Y$ irradiating bones and surrounding organs as bone surface and red and yellow bone marrows.

^{90}Sr has very long physical and biological half life and continues to irradiate human organism in many years after intake. Therefore contribution to the EPR dose from this factor only increases with time. The nature of critical organs and it dense ionization by beta particles could provide significant impact on the health of clean-up workers that has been demonstrated by clinical studies [13, 14, 15, 16].

THE MAIN RESULTS OF THE WORK

The following results have been achieved:

- Dosimetry based on EPR signal by human tooth enamel has been developed to measure accumulated doses of ionising radiation absorbed by individuals,

- Influence of specimen preparation on EPR measurements has been explored selecting the technology assuring the highest signal to noise ratio and minimising background signal. The recommendations on the best specimen preparation technology has been developed;

- Influence of EPR measurements modes on detected signals by tooth enamel has been explored, of microwave power, registration temperature and procedure for spectra processing have being optimised;

- Uncertainties budget of EPR dosimetry for human tooth enamel has been assessed; standard uncertainty of EPR method is below 30% in dose region 100-500 mGy;

- EPR dosimetry on human tooth enamel has been verified in respect to the international standard. The calibration of the TLD system has been performed; uncertainty of the method is in the range -30% + +50%; combined standard uncertainty of TLD method has been estimated and is 18% for dose 10 mSv.

1. The individual doses measured by EPR varied in the range 60 -800 mGy. External exposure corresponds to officially documented occupational dose. Internal irradiation represent from 40 to 50% of the total body dose;

2. Dose rate from incorporated nuclide ^{90}Sr has been estimated and is in the range 0.27 mGy/day - 4.7 mGy/day.

ACKNOWLEDGEMENTS

I am deeply indebted to my supervisor Ms. Nina Mironova-Ulmane and scientific advisor Mr. Yuri Dekhtyar. Thank you for optimism, thank you for support, thank you for the knowledge you gave to me.

I sincerely pleased to all my family and especially for my wife for motivation and strong moral support. Thank you Dears for your understanding.

Special thanks to Mr. Konstantin Bogucharskis for friendship and possibility to interpret his data presented on Fig. 36, 37 and for assistance on TLD uncertainty estimation.

Huge thanks to all collective of BIN Institute and especially to Mr. Alexei Katashev, Ms. Tatyana Bogucharska, Mr. Aldis Balodis for fruitful discussion, friendship, and moral support.

Warm thanks to Ms. Vineta Zemite for help, translation assistance and friendship.

Special gratitude to Mr. Genadi Sagalovich for his support and realistic view of life.

I would like to thank Mr. Uldis Ulmanis for his assistance and personal example as experience, wisdom and intelligence.

And finally thanks to all colleagues in the IAEA and specifically to Mr. Sergey Fesenko, Mr. Stanislav Vatnitsky and Mr. Gustavo Massera for high level of professionalism.

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