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EPR Dose Reconstruction with Teeth: *in situ* Measurements, Determination of Organ Doses, and Application at Mayak (DOSREC)

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Final report
(summary)

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1. Objectives

The general objectives of the project were:

- to further develop the methodology of reconstruction of external radiation exposure by electron paramagnetic resonance (EPR) of tooth enamel and its application to an improvement of the dosimetry for the cohort of Mayak workers, and
- the exploration of implications of improved estimates of external doses on the cancer radiation risk per unit dose among the cohort.

To attain these objectives, four work packages were designed with the following main contents:

- exploration of the basic concepts of an EPR device for *in situ* dosimetry (work package 1);
- determination of the dependence of absorbed dose in teeth in a full-scale head phantom on energy and angular characteristics of a photon field to which the phantom is exposed and derivation of absorbed doses in other organs under these exposure conditions (work package 2);
- application of the method to workers of Mayak and derivation of conversion factors from absorbed dose in tooth enamel to organ doses for specified work areas (work package 3); and
- analysis of mortality among the Mayak worker cohort due to cancer in organs with dominantly external exposures (work package 4).

2. Research performed

The conventional method of dose reconstruction by EPR spectrometry of teeth requires the extraction of teeth prior to the measurement. In work package 1 the basic concepts and the potential of EPR spectrometry for *in situ* dosimetry of teeth were explored. First investigations were performed to provide the fundamentals for the development of an *in situ* EPR spectrometer for the measurement of human teeth. It was envisaged to achieve a lower detection limit for absorbed dose in teeth of 300 mGy. Conventional X-band EPR spectrometers can not be applied for *in situ* dosimetry because X-band microwaves are absorbed by the water in the living teeth and inside the mouth. The use of a modified EPR spectrometer operating at a lower microwave frequency in the L-band was investigated. The following tasks had been worked out before EPR spectrometry could be used in *in situ* dosimetry:

- development of procedures to evaluate the dosimetric signal from the L-band EPR spectrum of teeth and determination of the spectrum contributions by absorbed dose in enamel and in dentine, and assessment of an EPR dose response curve for tooth enamel;
- application of EPR spectrometry to rats with *in situ* irradiated teeth to explore influences of the living object to EPR measurement results;
- exploration, selection and testing of special microwave resonators for use inside the mouth and magnetic systems which can be located inside or very close to the human mouth.

In radiation dosimetry for nuclear workers the impact of neutron contribution to the total radiation dose should be known. Experiments were performed to evaluate the sensitivity of tooth enamel to neutrons. Enamel powder and whole teeth in tissue like phantoms were irradiated and measured either intact by L-band spectroscopy or as enamel powder samples by X-band.

In 1993 a series of *International Intercomparisons on EPR Tooth Dosimetry* was started in the framework of research projects of the European Commission and in cooperation with the IAEA. In the 2nd international intercomparison a tendency of different EPR dose evaluation methods was shown to overestimate the dose below 300 mGy. In view of these results the 3rd intercomparison was organized in order to evaluate the performance of laboratories conducting EPR tooth enamel dosimetry below 300 mGy.

Tooth enamel is the most stable fraction of the tooth without any remodelling during adult ages. Enamel is preferably used for retrospective EPR dosimetry because it is detecting radiation exposures without fading and independently of the time of occurrence. The assessment of radiation risk requires the conversion of measured absorbed dose in enamel to the dose in other specific organs of interest. In work package 2 corresponding conversion factors were derived in dependence on the photon energy spectrum and the geometry of the radiation field. This was achieved by conducting the following tasks:

- determination of the absorbed dose in enamel in a full-scale head phantom in dependence on energy and angle characteristics of photon fields by Monte Carlo simulation and its verification by comparison with EPR measurements, and
- development of a software package for calculation of conversion factors of enamel dose to doses to other organs under given exposure conditions.

EPR spectrometry with tooth enamel has a large potential to determine retrospectively exposures to external radiation that occurred several decades ago. It was the task of work package 3 to contribute to an improvement of the dosimetry for external exposures for the cohort of Mayak workers and to apply the software developed in work package 2 by the following steps:

- evaluation of photon energy spectra of exposure fields at working places of Mayak, and taking it into account in the further steps;
- EPR determination of absorbed dose in enamel for workers who received more than 50 % of their occupational doses before 1954, the time in which an old type of film dosimeter without energy compensation filtering was used for the occupational dose monitoring;
- EPR determination of absorbed dose in enamel for workers who received more than 50 % of their occupational doses after 1961, the time in which a modern type of film dosimeter with energy compensation filtering was used for the occupational dose monitoring;
- calculation of organ dose to absorbed dose in enamel conversion factors in dependence on the Mayak worker tooth donors working area; and
- comparative analysis of EPR dosimetry with tooth enamel and occupational dose monitoring by film dosimetry for Mayak workers.

The aim of work package 4 was to analyse mortality among the Mayak worker cohort due to cancer in organs with dominantly external exposures. The analyses were intended to be based on external exposures which were validated in the first three work packages of the project. Candidates for the study organs were bladder, colon, kidney, pancreas, rectum and stomach. The aim was to analyse the data with the two-step clonal expansion (TSCE) model of carcinogenesis. Influences of uncertainties of dose estimates on risk assessments with the TSCE model were to be analysed.

Work package 4 comprised the cohort selection and verification of causes of deaths and diagnoses of cancers selected for the study and the evaluation of consequences of dose uncertainties in the TSCE model. Research with the objective of analysis of the available cancer mortality data using film badge doses was performed. Mortality data for selected cancers on the basis of improved dose estimates and uncertainties in dose estimates were analysed. A methodology was developed on how to group different organs for future common analyses of the cancer mortality among Mayak workers with the TSCE model.

3. Main achievements

In this project a number of new techniques and instrumentation has been introduced that significantly improves and enlarges the application of retrospective EPR dosimetry with tooth enamel. Methodologies were developed that allow assessment of external individual doses on the bases of results EPR measurement of tooth enamel and occupational film badge monitoring. The application of the new methodologies results in an improved assessment of external individual doses for the Mayak worker cohort.

– Investigations with L-band EPR spectroscopy were performed providing the fundamentals for *in situ* EPR dosimetry. Procedures for measurement and analyses of L-band EPR spectra of teeth were developed and the dose response function was determined. The detection threshold with the current system set-up was 0.5 mGy. The background radicals in tooth enamel were identified as radiosensitive but they are not stable over long time. The experiments with rats demonstrated that there is only little influence of rat movement on EPR measurement, which is required for *in situ* measurements. The surface loop-type resonator was identified as the resonator of choice for *in situ* dosimetry. Small permanent magnets which can be inserted into the mouth were found to be principally applicable in *in situ* dosimetry, but require further development.

– The sensitivity of tooth enamel to neutrons was investigated by X- and L-band EPR spectrometry. The results obtained with both methods are consistent and all show that tooth enamel is weakly sensitive to neutrons. The sensitivity is dependent on neutron energy and is up to 10 % of the gamma sensitivity. The neutron spectra at the reactor plant and at the radiochemical plant at Mayak were calculated. In both cases the n/γ relative sensitivity was negligible and therefore it is likely that the neutron contribution to the total dose can be ignored in the tooth dosimetry of Mayak workers.

– The dose response of tooth enamel inside an anthropomorphic human voxel phantom (Golem) in dependence on photon energy in the range 0.01-10 MeV and angle characteristics of photon fields were evaluated by Monte Carlo simulation. The simulation algorithm was validated by comparison with EPR measurements for teeth irradiated in a full-scale head Plexiglas phantom with A80 X-rays and ^{60}Co. A software package was developed that allows calculation of air kerma, effective dose and organ dose per absorbed dose in tooth enamel conversion factors in dependence on tooth position, radiation field photon spectrum and irradiation geometry.

– The *3rd International Intercompaison on EPR Tooth Dosimetry* was implemented to provide an overview of the current state of EPR tooth enamel dosimetry and to evaluation of possible additional radiation exposures of samples. Fourteen laboratories participated; two could not demonstrate suitability of their method for measurement of low doses. The other 12 laboratories demonstrated consistency of EPR dose reconstruction. A considerable improvement in accuracy was demonstrated since the last intercomparison in 2000. In the analysis of the unirradiated tooth samples, 8 % of them were identified as outliers with additional absorbed dose above background dose.

– Working places of the Mayak workers tooth donors of this project were registered. The simulated exposure fields of these working places were partly taken from the American-Russian Project 2.4 and were calculated in this project. For the work places dose conversion factors were calculated with the assumption of AP exposure geometry, for air kerma, effective dose, and 6 organs that are important for cancer risk analysis. EPR measurements were performed for 74 tooth samples of Mayak workers with main occupational dose before 1954 and after 1961, and 71 samples of Ozyorsk residents. The absorbed background dose in tooth enamel of Ozyorsk residents was in average 91 ± 61 mGy. For 26 % of the samples from Mayak workers, the difference between results of EPR and film dosimetry was bigger than a factor of 2. The differences are partly caused by strontium burden of the teeth, but further investigation is required to resolve the discrepancy completely. With exclusion of these cases, results of EPR and film dosimetry with consideration of the photon fields at working places are in good agreement. For workers with main occupational dose before 1954 and after 1961 differences between EPR and film dosimetry were in average less than 15 %.

– Data selection for the Mayak worker cohort and the classification of tumour sites with respect to the importance of ^{239}Pu dose was performed. A data set with 18 833 workers (14 079 of them male) was selected. For 54 workers, the given information is incomplete and is not used. The neutron dose is not negligible compared to the gamma dose. 633 workers were identified with recorded zero occupational external dose, but should have been monitored according to their occupational history. Their inclusion turned out to have influence on the results of risk modelling. Modelling of carcinogenesis included calculations using the TSCE model, mostly aiming at feasibility. All solid tumours (except lung, liver, bone and soft tissue) were selected. There are 798 cases among males. A methodology has been derived to take into account dose uncertainties in the analysis of epidemiological cohort data with the two-stage clonal expansion (TSCE) model of carcinogenesis. It was shown that exposure uncertainty does affect the parameters of the biologically motivated two-stage clonal

expansion (TSCE) model, but can be corrected when the distribution of the uncertainties is taken into account.

– Preliminary analysis of cancer mortality of Mayak workers indicated a non-negligible contribution of incorporated plutonium to the exposure of bladder, kidney, pancreas and stomach. A sub-cohort of 7 479 workers was studied who either worked only in the reactor (no plutonium exposure), or for whom measurements of the plutonium concentration in the urine was measured and the plutonium dose estimated. The analysis showed that the equivalent dose due to plutonium is exceeding the external dose for 15 % of the workers in bladder, pancreas and stomach, and for more than 20 % of the workers in the kidneys. The plutonium doses of the 7 479 workers are not correlated with the external doses, which implies that a risk analysis for the cohort has to differentiate between the two exposure types. Taking the two results together it became obvious that the initial plan of the project to analyse the cancer mortality in organs that are predominantly exposed by external radiation – and that this analysis can be based on estimates of external exposures alone – had to be abandoned. Unless there is not a major change in estimates of organ doses due to plutonium exposures, future analyses have to take into account plutonium exposures explicitly. Two characteristics were chosen as criteria for pooling of organs. An agreement in the two chosen criteria is not intended to imply that there are general similarities in the characteristics of the cancer types of the organs. Pooled organs are chosen only in a way that their mortality rates among the Mayak workers agree in two main characteristics of their TSCE-model description. Lung and stomach have specific characteristics and enough cases to allow for separate analyses. Among the other organs, three groups of pooled organs can be considered, within which the estimates of the clonal expansion rates agree within half a standard deviation and the mortality ratios within one standard deviation. These are: (a) colon, liver and pancreas (103 cases), (b) colon, kidneys and pancreas (103 cases), and (c) kidneys, pancreas and rectum (98 cases)

4. Dissemination

At the time of writing this report the investigations conducted in the project have been disseminated in research papers published in 8 peer-reviewed international scientific journals; additionally 7 papers have been submitted or are in preparation for publication. The results have been presented at 12 national and international conferences.