# EPR Dosimetry of Chernobyl Liquidators

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**Abstract**

The paper is devoted to review of development and application of EPR dosimetry with teeth in Ukraine. It deals with specific features of the EPR dosimetry protocol, which was developed and is practically used in SCRM for retrospective dosimetry of clean-up workers (liquidators). Extensive methodological research was conducted in SCRM in order to develop an original version of EPR dosimetric protocol as well as to investigate the effects caused by confounding factors and develop approaches to their account and mitigation. The proposed EPR dosimetric protocol addresses the demand for high accuracy and reproducibility, low sensitivity threshold as well as high throughput of the technique. High qualities of SCRM version of EPR protocol were proven in the course of elaborate quality assurance program, which included a series of international intercomparisons. Creation and continuous operation of the nationwide tooth acquisition network is another key to the success of EPR dosimetry in Ukraine.

Particular attention in the paper is paid to definition of the most optimal way of application of EPR dosimetry for dosimetric support of the post-Chernobyl medical follow-up. The main applications of EPR dosimetry in Ukraine are both routine high precision reconstruction of doses to Chernobyl clean-up workers and the use of EPR dose estimates as a reference dose for validation of other retrospective dosimetry techniques. The latter proved to be the most efficient application of EPR dosimetry in the post-Chernobyl situation. EPR dosimetry was used for testing such methods of retrospective dosimetry as FISH, ADR, SEAD and RADRUE. Nowadays EPR dosimetry plays inevitable role in dosimetric support of the post-Chernobyl medical follow-up studies.

## Introduction

The Chernobyl accident and obvious failure of routine dosimetric monitoring of clean-up workers (liquidators) had stimulated significant development of various methods of retrospective dosimetry. Among those methods one of the most adequate proved to be an EPR dosimetry with teeth. Over last decade EPR dosimetry made all way from unique experimental technique to the tool of routine dose reconstruction. Many different applications are known for EPR dosimetry with teeth. It was used for determination of doses received in course of radiotherapy [1], dose reconstruction for atomic workers [2] as well as in several cases of accidental exposure [3-7]. In recent years, several review papers [8-11] and one book [12] were published dealing with various aspects of EPR dosimetry. Notable role in the process of development and implementation of this method belongs to the research performed in Scientific Center for Radiation Medicine (SCRM) AMS Ukraine, in particular to the work performed in collaboration with leading laboratories worldwide [8, 13-21].

This paper is dealing with some specific features of the EPR dosimetry protocol which was developed and is practically used in SCRM, briefly touches results of investigations performed in this institute, and concentrates to a larger extent on practical applications, which EPR dosimetry had found in Ukraine. Particular attention in the paper is paid to definition of the most optimal way of application of EPR dosimetry for dosimetric support of the post-Chernobyl medical follow-up.

## 1. Methodological aspects of EPR dosimetry with teeth

### 1.1. EPR dosimetric protocol, SCRM version

In general, any version of EPR dosimetric technique comprises several distinctive steps or stages. This includes collection of samples, sample preparation, recording and decomposition of EPR spectra, determination of cumulative dose and assessment of accidental exposure component, and assessment of uncertainty. It should be stressed that presently no single standard EPR technique exists. Combination of particular solutions concerning each element of this technique determines unique protocols, which are practiced in each individual laboratory. Herewith we will briefly discuss an EPR dosimetric protocol, which was developed and is being routinely used in SCRM AMS Ukraine. This protocol in more details is described elsewhere [13]. The aforementioned sequence of steps as well as peculiar features of the SCRM protocol are schematically presented at Fig.1. In may be seen, that quite significant modification were introduced into the generic scheme of EPR dosimetry with teeth. In our presentation we will follow the logical scheme as presented at Fig.1.

**Collection of samples.** Sample collection is an inevitable element of EPR dosimetry with teeth. Obviously, due to ethical considerations, extraction of teeth solely for dosimetric purposes is impossible. Therefore, only teeth, which are being extracted by medical prescriptions in the course of routine dental practice, may be collected and used for retrospective dosimetry. This consideration substantially reduces possibility to obtain dosimetric bioporobes (teeth) from the subjects, which are significant from the point of view of follow-up and thus dose reconstruction. Moreover, it should be taken into account that even sound molar contains only about 300-500 mg of enamel, while in practice significantly damaged teeth are extracted, having, respectively, much less enamel.

Obviously, teeth of Chernobyl clan-up workers are the unique and unrecoverable resource. The problem may be solved by organizing and operation of a widespread network for collection of teeth (desirably - all!), which are extracted by medical prescriptions from the liquidators. In order to secure collection of teeth from maximum number of exposed individuals, tooth collection network branches were established in 7 oblasts (regions) of Ukraine, which have the highest liquidator population. The structure of this network and respective flow-chart are presented at Fig.2. The teeth collected in various dentistry clinics within the given oblasts are collected in the regional hub and then, periodically, are forwarded to

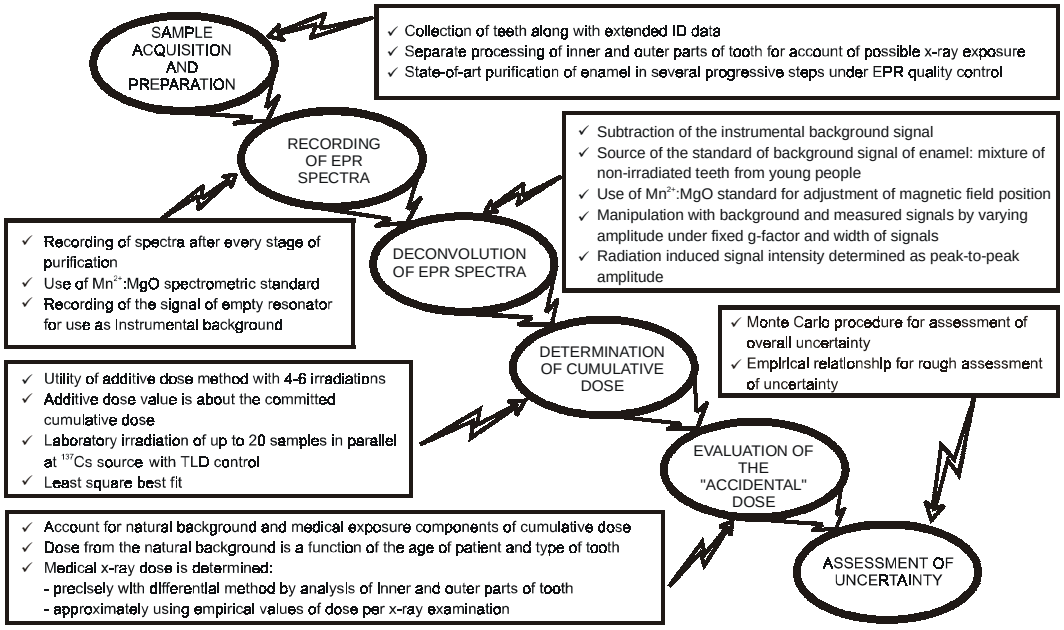



**Fig.1. SCRM version of EPR dosimetric protocol**.

Kiev to the central bioprobe bank. Here the collected teeth are registered and logged into a database, and, after input inspection and estimation of quality, are placed into the bank for long-term storage. Later, upon specific request, some samples are retrieved from the storage and are used for dose reconstruction. The results of EPR dosimetry are used in a number of occasions - more detailed discussion of application areas for EPR dosimetry is given below. In principle, as depicted in Fig.2, routine dose reconstruction could be performed in several accredited EPR laboratories. However, so far such routine dose reconstruction is performed in only one institution, namely Scientific Center for Radiation Medicine AMS Ukraine.

Since reconstruction of individual doses is concerned, some personal data need to be acquired in the course of tooth collection. This is achieved by filling out a special ID form, so called "Tooth passport". This form consists of three main sections. First of all, contact and personal data is registered, allowing to identify the tooth donor and, if needed, reestablish personal contact with him. Respectively, the first section includes the name of the clinics where the tooth was extracted and registration number of a person, full name, year of birth and year of clean-up work in Chernobyl as well as contact telephone number(s). In the second section of the tooth ID form all instances of lifetime exposure, both occupational and medical are recorded. The third section contains characteristics of the extracted tooth, in particular its position in a mouth and reason of extraction (diagnosis). Passport of tooth is filled out by a dentist prior to extraction of tooth and it accompanies the sample until it arrives into the central bioprobe bank and passes check-in to the respective database. In the course of practical collection of teeth the tooth ID form was substantially modified, being reduced only to the most essential entries. It was demonstrated that any additional information could be acquired, if needed, by the secondary contact with liquidator.

Although legal grounds for establishment of the tooth acquisition network were laid in 1997, this effort came to active phase in 1999, when appropriate funding was put in place. In 2001 the network was expanded, incorporating two more oblasts of Ukraine, increasing their count to seven. In total, since the beginning of operation of the tooth acquisition network, about 4000 teeth were collected and checked into

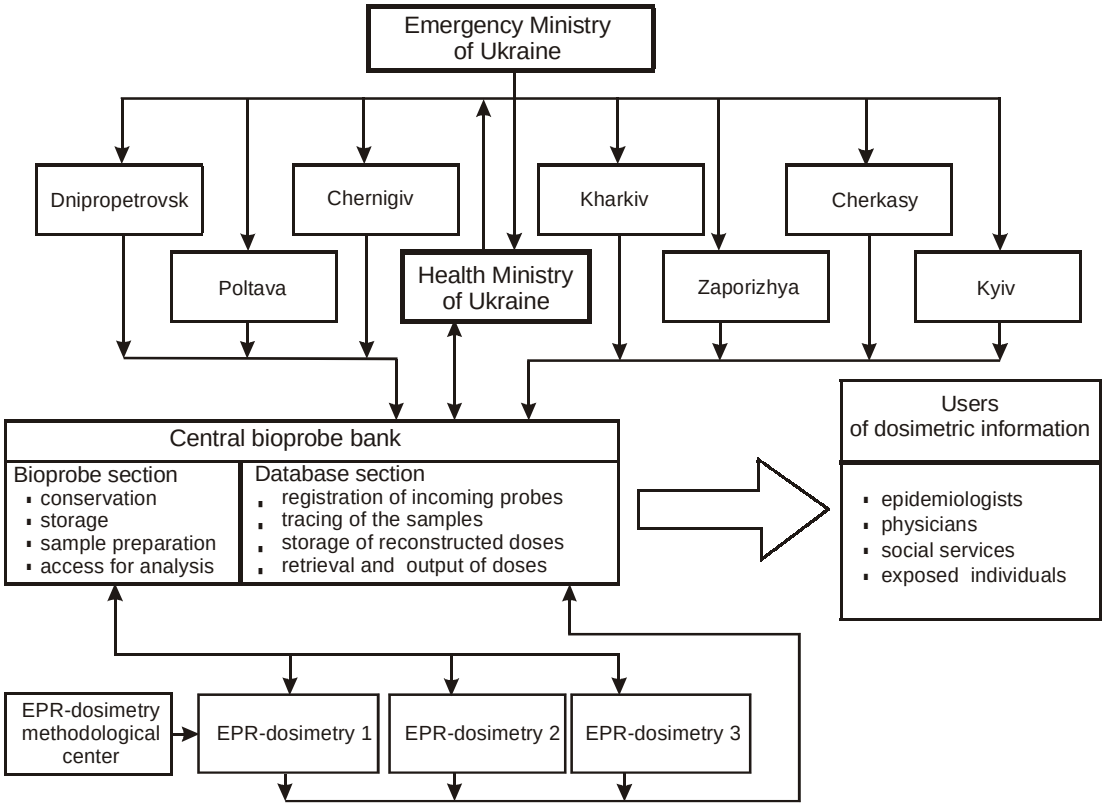



**Fig.2. Structure and operation flowchart of the tooth acquisition network in Ukraine.**

**Table 1. Quality grades of teeth and percentage in the pool of collected samples.**

| Grade | Characteristics of a tooth | Applicability for EPR dosimetry | Percentage in the pool of collected teeth |
|---|---|---|---|
| 1 | Tooth roots (including fragments), enamel is absent | Not applicable | 24 |
| 2 | Insufficient amount of enamel (10-20%), teeth under metal crown | Practically not applicable | 11 |
| 3 | Incisors, canines | Practically not applicable | 17 |
| 4 | Molars and premolars with 20-50% of enamel | Applicable if dose is high | 10 |
| 5 | Molars and premolars with more than 50% of enamel | Applicable, could be limitation in terms of separate buccal and lingual part analysis | 21 |
| 6 | Intact crown and root | Unlimited applicability | 17 |

the bioprobe bank.

Intermediate and long-term preservation and storage of teeth is a separate issue. Study of various storage media (ethanol, formaldehyde, Nikiforov's mixture - 50% alcohol+50% ether) had revealed that from the point of view of biological decontamination, pre-treatment of enamel and absence of destructive effect on EPR spectra, the most appropriate medium is Nikiforov's mixture. However, from the practical point of view, use of liquid storage media is quite difficult, requiring supply of robust vials, ready solutions and complicated transportation of the collected samples. Therefore for operation of the widespread tooth acquisition network the simplified pre-storage protocol was proposed. According to this protocol, extracted tooth is washed and disinfected in formaldehyde, rinsed in large amount of tap water, and then dried at room temperature and sealed in a paper envelope with the tooth ID form being stapled to it. It was demonstrated that a sample processed in such manner is being dried to the appropriate degree on the way to the central bioprobe bank. According to Ukrainian legislation, extracted teeth are not considered as human organs or sources of biological hazard - this significantly simplifies the legal aspects of the described procedures.

Obviously, there are certain aspects, which are significant from the point of view of dose reconstruction, in particular amount of available enamel or position of tooth (front teeth are not usable for dose reconstruction due to large and uncontrollable contribution of solar UV exposure into dosimetric signal. In order to formalize qualitative evaluation of incoming teeth and facilitated retrieval of appropriate samples from the bioprobe bank, a ranking system was designed in SCRM. All teeth are assigned with certain grades according to their status. The ranking criteria as well as distribution of the collected samples by the quality grades are presented in Table 1. One may see that only about half of collected samples have grades-4 to -6 and thus are appropriate for dose reconstruction; the highest grade - 6 have only about 17% of collected teeth and therefore only these samples are good for high precision dose reconstruction using two halves of a tooth and detection of lifetime x-ray irradiation.

Upon incoming registration, each of the samples is examined and the grade is assigned. This information is recorded in the database, significantly facilitating subsequent use of the collected material. For instance, in the course of high precision dose reconstruction needed for provision of reference quality dose estimates, only teeth having grade-6 are pulled from the bioprobe bank and used for EPR dosimetry. In general, the system of formalized quality assessment of the collected samples proved to be very efficient instrument for management of the bioprobe bank and sensible use of collected teeth.

**Sample preparation.** If reconstruction of low doses (below 0.5 Gy) is concerned, sample preparation plays the key role. As shown in Fig.3, for doses below 0.5 Gy dosimetric signal appears as quite small

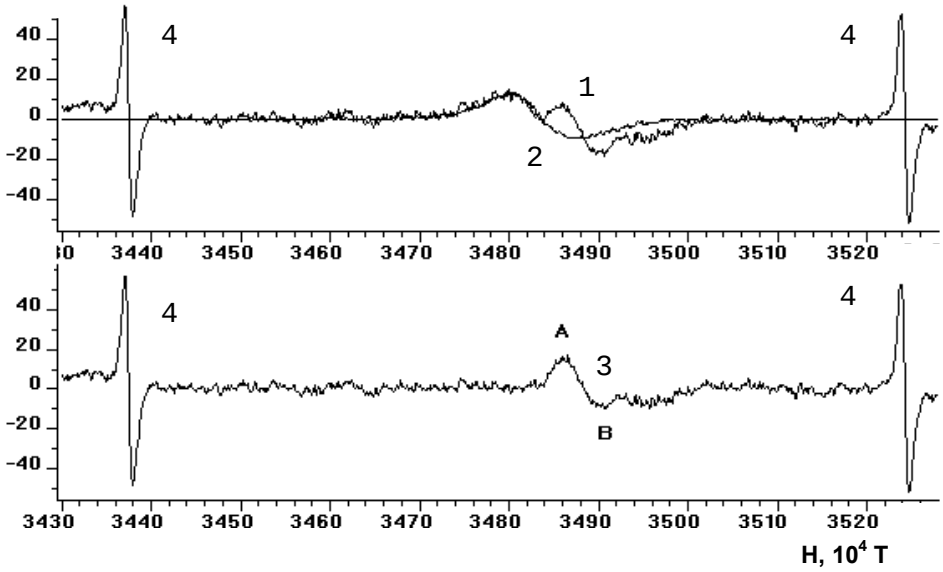



**Fig.3. Typical EPR spectrum of tooth enamel exposed to dose 0.8 Gy.**

1 - recorded (original) spectrum
2 - standard signal of native (background) signal
3 - dosimetric signal (difference of 1 and 2)
4 - lines of $Mn^{2+}$:MgO spectrometric standard, used for calibration of g-factor and intensity of EPR signals
A - first maximum of dosimetric signal
B - first minimum of dosimetric signal

addition to the more intense background (native) signal. Obviously, improvement of this "signal to noise" ratio is an effective way of enhancement of the sensitivity of the method. Basically, this may be achieved by purification of the sample and reduction of the background signal

It is known that dosimetric signal is associated with mineral component of tooth, while native signals are usually associated with organic component of tooth. In fact, the ratio of mineral to organic components in enamel and dentine is 95:5 and 70:30, respectively. Therefore, rigorous separation of enamel from dentine is one of the key issues in the sample preparation process. The most straightforward method is mechanical removal of softer dentine from the tooth crown using hard alloy dental drill. Although this approach is widely used [22-25], it is not perfect. First of all, this method is extremely labor intensive and has relatively low throughput. High skills of operator are required for efficient removal of dentine from the curvatures of inner surface of dental crown. In addition, one should be aware of possible artifacts which could be introduced by local overheating of enamel due do high speed drilling or generation of unwanted EPR signals if UV illumination is used for visualization of dentine inclusions [26-28]. After all, the resulting purification of the sample depends of the skills of an operator, complicating thus standartization of sample preparation procedure.

Alternative approach to the purification of enamel is based on chemical treatment of the samples. This approach was perfected and brought to the state-of-the-art level in SCRM [13]. The flow chart of this procedure is presented in Fig.4. Essentially this is multi-stage technique; each progressive step is used if the previous operation failed to provide the desired quality of the sample. The quality of purification achieved after each individual step (Fig.4) is objectively controlled by means of EPR spectroscopy - if EPR spectrum demonstrates presence of the signals from impurities, the sample is subjected to the next step (degree) of processing. It should be mentioned that chemical processing with alkali solution (KOH or

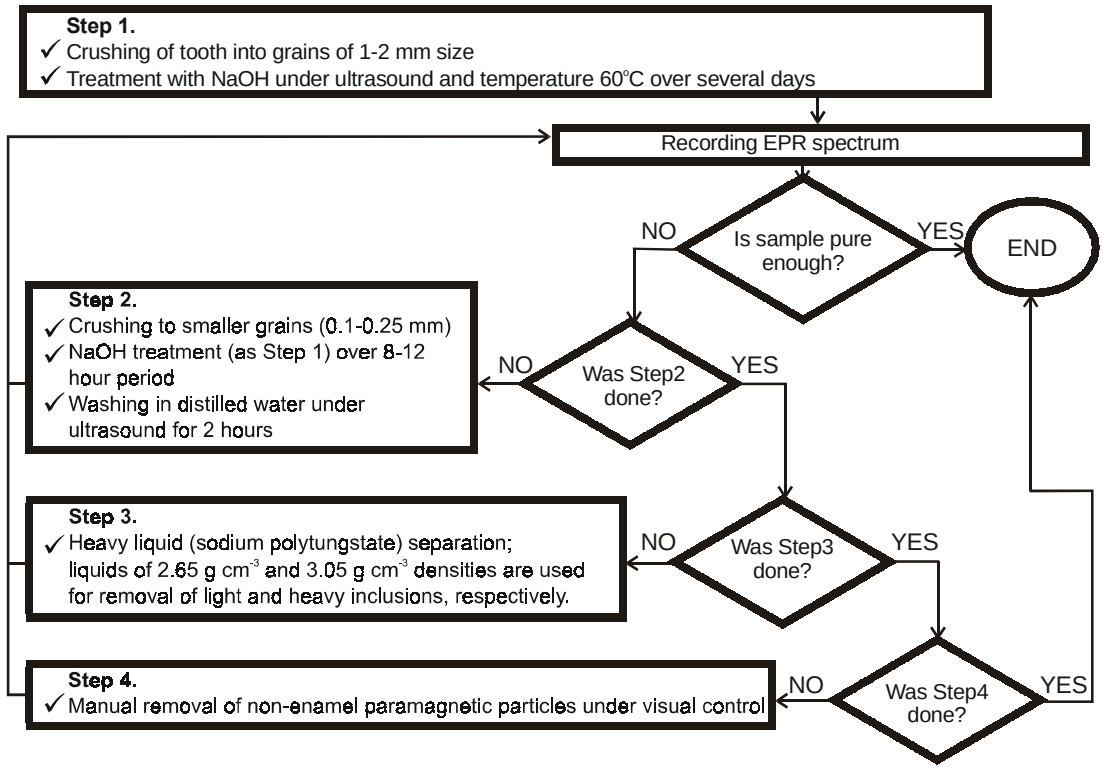


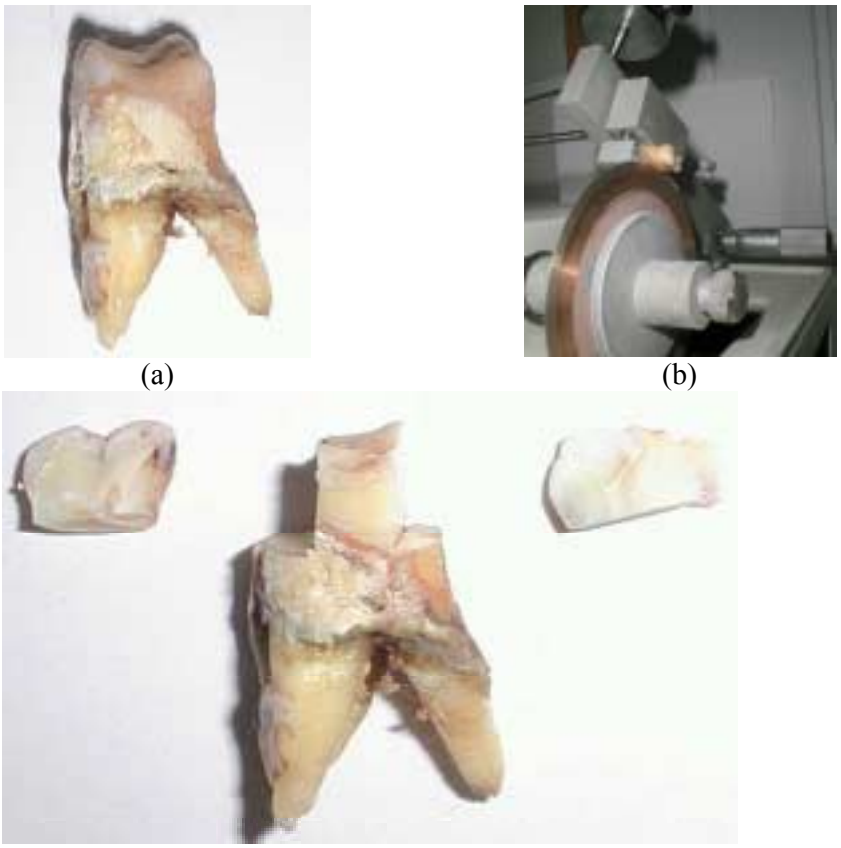

**Fig.4. Flowchart of the SCRM sample preparation procedure.**

NaOH) is conducted with ultrasound and enhanced temperature ($60^o$ C) applied to a solution. Simultaneous processing of many samples using the same ultrasonic bath as well as extremely low labor intensity are the strong sides of this operation. The process of chemical separation may last up to several days; alkali solution in the tubes is changed several times over duration of the treatment until no white sediment is created anymore. As a variant, big pieces of enamel after mechanical removal of dentine may be subjected to this treatment. In case if steps 1 and 2 (Fig.4) turn to be inefficient, heavy liquid separation of non-enamel inclusions should be applied. This process makes use of difference in specific weight of enamel (2.9-3.05 g $cm^{-3}$) and foreign inclusions. In our practice we use non-toxic water solution of sodium polytungstate ($Na_6(H_2W_{12}O_{40})\cdot H_2O$), which is quite flexible in terms of variation of a specific weight. In some (in fact, very rare) cases when all three stages of sample purification are not successful, manual removal of inclusions could be performed under visual control.

The described procedure of sample preparation has high throughput and possesses high degree of standardization - both features are extremely important when bulky dose reconstruction is concerned. In fact, low labor intensity and high throughput are achieved due to parallel processing of a large number (several dozens) of samples and multistage protocol, while higher stages of purification are applied to some samples only when needed.

It also should be mentioned that, in the latest version of the SCRM dosimetric protocol, buccal and lingual parts of a tooth are prepared and measured separately in order to allow determination and account of possible lifetime x-ray exposures. With low speed diamond saw the buccal and lingual planar pieces are cut from the tooth crown (Fig.5). The following purification of enamel from these plates is performed according to the above-described procedure. As a result, it is possible to perform dose reconstruction separately for buccal and lingual parts of tooth and subsequently evaluate the contribution of x-ray irradiation.

**Registration of EPR spectra.** This step of the EPR dosimetric protocol (see Fig.1) is performed using X-band spectrometer BRUKER ECS-106 with registration parameters which are de facto standard in EPR



(a) (b)

(c)

**Fig.5. Cutting of a tooth to buccal and lingual parts using low speed diamond saw.**

a - original sample
b - process of cutting
c - result of cutting

dosimetry with teeth [21]. The unique feature of the SCRM protocol is a use of programmable goniometer, which proved to be extremely efficient tool for elimination of sample anisotropy [29]. In order to secure reproducibility of the results, spectrometric standard $Mn^{2+}$:MgO is used for both calibration of g-factor and intensity of EPR signal.

**Spectra deconvolution.** The spectra deconvolution (see Fig.1) is performed according to the spectrum subtraction method in which the EPR spectrum of a non-irradiated reference sample is subtracted from the spectrum of the irradiated sample [24, 30-33]. In case of SCRM protocol, the reference sample is prepared from homogenized enamel material collected from teeth of several young adults [13, 30]. In addition, a spectrum of empty tube is subtracted in order to minimize the effect of low frequency noise signals and enhance thus the accuracy and reproducibility of low dose measurements. The "classical" version of SCRM protocol [13] included manual spectra manipulation and subtraction. Recently an automated procedure for spectra decomposition was developed and implemented. The result of spectrum decomposition step of the protocol (Fig.1) is the amplitude of the dosimetric signal in tooth enamel.

**Evaluation of cumulative dose.** The next stage of the technique is evaluation of the cumulative dose received by the tooth (enamel). This procedure makes use of the fact that in a wide range of exposures, intensity of the dosimetric signal linearly depends on the absorbed dose. However, the slope of calibration curve (i.e. dependence "dosimetric signal vs. dose") and, sometimes, its shape depend on individual properties of the particular sample. According to our experience based on analysis of several hundreds teeth, individual variability of radiation sensitivity is about 15%. Moreover, about 5% of the samples demonstrate non-linearity of calibration curve in the low dose range. Lack of account of the latter effect

may lead to significant under- or overestimation of dose. Therefore, in the SCRM dosimetric protocol individual calibration of radiation sensitivity is performed using the additive dose technique [12, 34]. Additional irradiation of the samples is performed using calibrated $^{137}$Cs source with accuracy not worse than 3%.

In fact, application of the additive dose method has certain pros and cons comparing to the method of universal calibration coefficient (application of single coefficient for all samples) [20, 21, 24]. The strong sides of the additive dose method are discussed above, while its shortcomings are attributed to higher labor intensity caused by the need for repetitive irradiation sessions and EPR spectrum recording. Another disadvantage is caused by destructive nature of the additive dose method - dosimetric information in the enamel is altered after additional irradiation and the sample cannot be reevaluated in later time. In the practice of SCRM, higher labor intensity is deliberately accepted for the sake of much higher precision of dose reconstruction. From the point of view of destructive nature of additive dose method, a compromise may be achieved by calibration using only small part of the available sample [35]. According to this approach, a small piece (several mg) of enamel is exposed to high dose (about 10 Gy) in order to assess the slope of calibration line. Therefore, this method allows to address the problem of variation of radiosensitivity of individual samples at the cost of moderate additional labor. At the same time, one need to keep in mind that this simplified additive dose method does not address the question of possible non-linearity of dose response curves. In routine dose reconstruction of doses in SCRM we use universal calibration coefficient during screening of incoming samples and then one of the discussed versions of the additive dose technique is used for precision dose reconstruction.

If the additive dose method in concerned, quite important issues are related to the choice of irradiator and the mode of additional irradiation: number of irradiations and dose increment.

Due to significant energy dependence of EPR response (at low energies the intensity of dosimetric signal may be up to seven-fold to the respective signal caused by high energy exposure with the same dose), additional irradiation should be performed by the source with the energy similar to the energy of the concerned accidental exposure. In case of Chernobyl exposure, average energy of gamma exposure was about 500 keV [36] and, therefore, $^{137}$Cs source (662 keV) is optimal for additional irradiation of the studied samples. In order to provide the balance of secondary electrons, irradiation should be performed behind the layer of a build-up material. In our practice we use 8 mm PMMA plate; special investigation had revealed that under such conditions the balance of secondary electrons is achieved while attenuation of incident beam is still small. The irradiation protocol [37] assumes 4-6 additional irradiations with variable increment of dose in order to obtain sufficient number of points in the region of possible non-linearity of dose response curve. One of the options is to start irradiation with dose about the expected accidental dose, doubling dose increment for each following irradiation.

In order to assess the uncertainty of cumulative dose evaluation, the stochastic modeling [38] is used, allowing to account the uncertainties of dosimetric signal evaluation and the accuracy of the dose of additional irradiation. Specialized software was developed for this purpose in SCRM [37].

**Evaluation of accidental dose and its uncertainty.** Once the cumulative dose is determined, the next step (Fig.1) is expressed in evaluation of the accidental dose - a component of cumulative dose caused by the concerned event of accidental or occupational exposure. One should remember that the cumulative dose is also formed by the components related to the natural background exposure, medical x-ray exposure and solar UV exposure. The first component could be easily assessed knowing the age of extracted permanent tooth (which is less than the age of the person and varies for different kinds of teeth). Two latter components are less definitive and act as confounding factors in EPR dosimetry with teeth (see Section 1.2). One of the most serious problems in EPR dosimetry is related to the effect of medical x-ray exposure. Development of approaches to its account and mitigation became possible after fulfillment of large cycle of a research, which is briefly discussed in Section 1.2. The problem of UV exposure is

addressed now by exclusion of the front teeth (incisors and canines) from consideration. Although this measure reduces the pool of available samples, lack of this consideration may result in severe distortion of dose assessments.

Comprehensive discussion of different sources of uncertainty and approaches to their evaluation is given elsewhere [39]. Here we will limit the discussion to a statement that, in general, overall uncertainty of SCRM technique depends on possible contribution from x-ray diagnostics. In the case, when x-ray component of dose is not present in the tooth, uncertainty ($2\sigma$) is ca.30-40 mGy. In the case when x-ray component is present, uncertainty could be as high as 60-80 mGy.

### 1.2. Study of confounding factors

A good deal of research was devoted to the study of confounding factors and development of approaches to their account and mitigation. Limited volume of this paper does not allow us to present these results in depth. We just mention that among those studies were investigations of the effect of crushing enamel and grain sizes [17], UV exposure [18] and, in particular, medical x-ray exposure [19, 40]. The last included a large cycle of both theoretical and experimental studies. Among others we did Monte Carlo simulations of depth dose profiles for idealized enamel slabs, whole isolated teeth [40] and teeth placed in the head of mathematical phantom. Experimental research was concentrated on reproduction of geometries and conditions of exposures, which were modeled mathematically. In addition various types of x-ray examination (both dental and thorax) were simulated using ALDERSON type heterogenic antropomorphic phantom (Fig.6). It was demonstrated that x-ray examination of a torso has negligible contribution to the dose to teeth (not more than 0.2 mGy), while dental x-ray examination may lead to high doses (up to 70 mGy) in enamel. It was shown that doses to teeth strongly depend on the type of examination (local vs. panoramic) and the hardware used for this examination. At the same time, in all cases pronounced depth profiles were observed in the studied teeth. These observations suggested


(a) (b)

**Fig.6. Geometry of simulation of local dental x-ray examination:**

a - exterior view of the ALDERSON type phantom head

b - section of phantom at jaw level with whole teeth placed in 6-8 positions.

rejection of our original approach to account of x-ray dose (assessed as a product of number of examinations and dose per examination) and transfer to the approach based on separate analysis of buccal and lingual parts of a tooth and observation of dose gradient. The modern version of the SCRM EPR protocol requires the use of such separate analysis of two parts of a tooth in order to evaluate medical x-ray dose based on the results of this analysis.

### 1.3. Quality assurance program

Since EPR dosimetry is a relatively new method, which is still in the phase of establishment, particular attention needs to be paid to quality assurance of the results and check of reliability of the method. In order to ensure high quality of the results obtained in SCRM, an elaborate quality assurance program was developed and implemented. Besides regular internal tests and verification of calibrator source (the calibrator is traceable to IAEA laboratory of secondary standard in Siebersdorf), SCRM took part in a series of bilateral and multilateral intercomparisons. It is generally accepted that intercomparison is the most efficient mechanism for straightforward evaluation of quality of a radiation measurement method.

From the point of view of its design, all intercomparisons fall into three groups:

- intercalibration on the average samples of tooth enamel with uniform properties; 1st International Intercomparison [20] including 9 laboratories from 6 countries was performed according to this plan;
- intercomparison using whole teeth exposed *in vitro*; the 2nd International Intercomparison [21] with 20 participants and two bilateral intercomparisons were performed in this way [41];
- intercomparison using whole teeth exposed *in vivo*; one bilateral test was performed with Center of Applied Dosimetry of Utah University (USA), in which the actual teeth from liquidators were used [42].

All intercomparisons were performed as blind tests, e.g. nominal dose values were not known to the participants.

Fig.7 depicts the results of SCRM lab, which were demonstrated in the most recent intercomparison (bilateral test using whole teeth irradiated *in vitro*). One may see that in the whole range of doses, SCRM EPR dosimetry protocol [13] performs very well, providing accurate dose estimates. Average deviation from nominal doses was about 30 mGy, relative deviation - less than 14%.

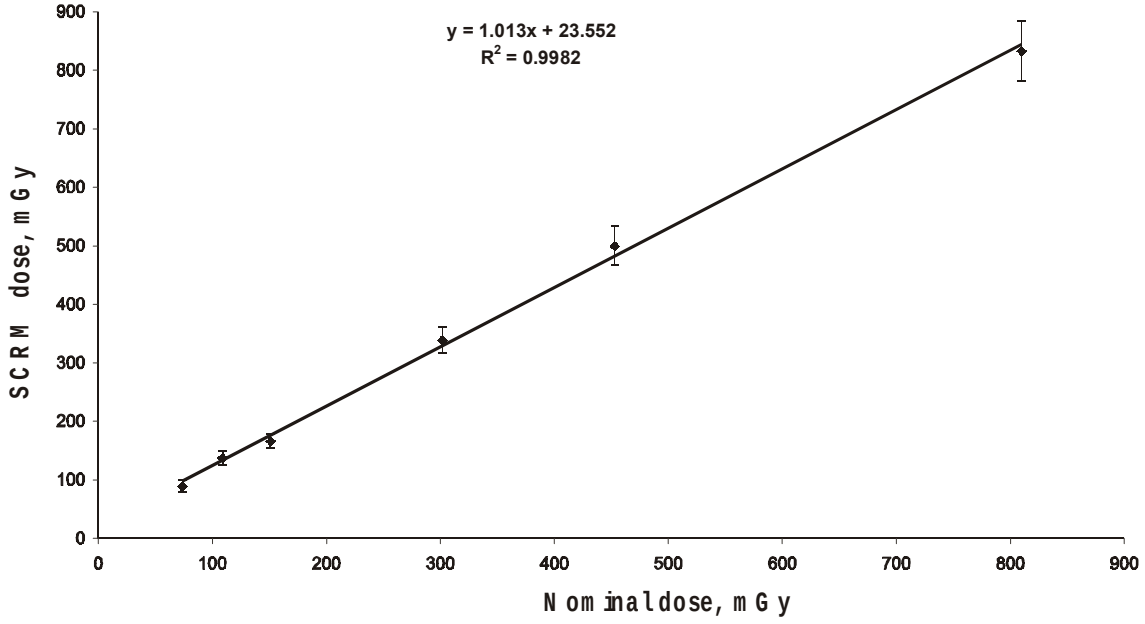



**Fig.7. SCRM results in the most recent international intercalibration of EPR dosimetry with teeth (bilateral intecomparison with CAD).**


**Fig.8. Geography of tooth acquisition in Poltava oblast of Ukraine.**

## 2. Application of EPR dosimetry in Ukraine

### 2.1 Acquisition of teeth in the national scale

As mentioned in Section 1.1 of this paper, the nationwide tooth acquisition network was established in Ukraine. In 1997 a joint order of the Ministry of Health and Academy of Medical Sciences came to effect, establishing the legal basis for collection of teeth from Chernobyl clean-up workers, which reside in 5 oblasts of Ukraine. In 2001 two more oblasts were incorporated into this network. The central bioprobe bank was established in SCRM AMS Ukraine with the function of accumulation and long term storage of the collected samples. The modern structure of the tooth acquisition network is shown at Fig.2. This network has hubs in each of the concerned oblasts, as a rule a principal dentist (officer of the Ministry of Health) is assigned to be a person responsible for operation of the regional branch of the network. As a rule, each regional hub receives collected teeth from a number of dental clinics spread over the oblast. Collection of teeth from liquidators is organized in the specialized hospitals or dental clinics, which provide medical service to Chernobyl clean-up workers. As an example, the geographical structure of tooth acquisition in Poltava oblast is presented in Fig.8.

Most general characteristics of the tooth acquisition network as well as the results of its operation are presented in Table 2. It may be seen from this table that the effectiveness of this work in different oblasts is not uniform. The best results were achieved in Kiev oblast, in which the pilot stage of this effort had began in 1992, and in Poltava oblast. The last case is worth separate discussion. In 2000 in the framework

**Table 2. Characteristics of infrastructure for collection of teeth from liquidators.**

| Oblast of Ukraine | Year of initiation | Number of dental clinics involved in collection of teeth | Number of dentists | Number of teeth collected in 1998-2001 |
|---|---|---|---|---|
| Dnipropetrivsk | 1998 | 30 | 40 | 152 |
| Zaporijja | 1998 | 12 | 18 | 75 |
| Kyiv | 1992 | 5 | 11 | 2096 |
| Poltava | 1998 | 57 | 94 | 1360 |
| Kharkiv | 1998 | 5 | 12 | 247 |
| Cherkasy | 2001 | 5 | 8 | 27 |
| Chernyhiv | 2001 | 2 | 5 | 24 |
| | TOTAL: | 116 | 188 | 3981 |

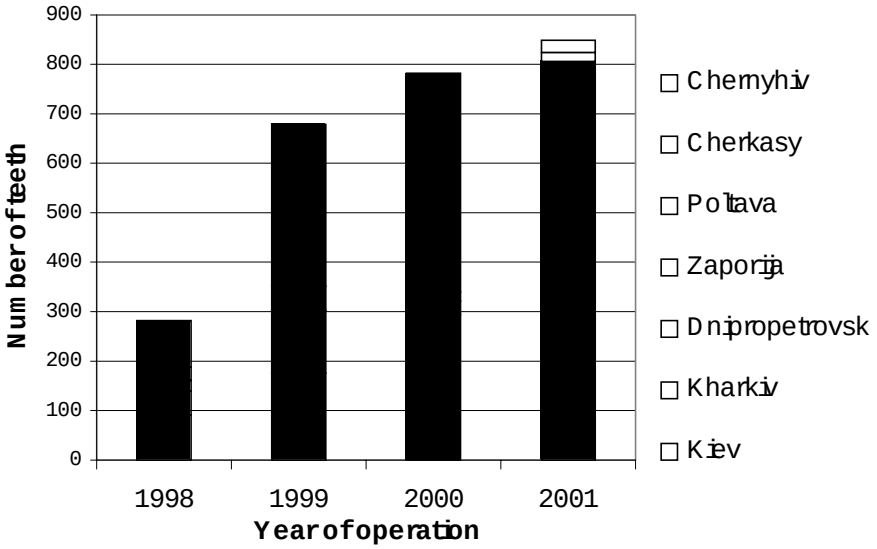



**Fig.9. Collection of teeth in 7 oblasts of Ukraine.**

of German-French Initiative "Chernobyl", one of the oblasts was selected for establishing "good practice" called to demonstrate the effectiveness of the tooth collection system under condition of appropriate supply. In this oblast (Poltava) the monetary incentive was provided at a sufficient level, suggesting fixed fee to the coordinator and "per sample" payment to dental practitioners and their assistants. This approach proved to be extremely efficient leading to significant expansion of the collection network (see Table 2 and Fig.8) as well to the increase of the number of collected samples (Fig.9). So the number of participating dentists increased from 11 in 1998 to 94 in 2001, annual influx of collected teeth grew more than twofold. In 2001 the logistics tested in Poltava oblast was applied in other regions covered by the tooth acquisition network.

Tooth collection is performed in the following manner. When the tooth is extracted by a dentist, the special form (see Section 1.1 for details) is filled out and the tooth is washed and placed into a paper envelope stapled to the form. Samples collected in local hospitals are forwarded to the regional hub and batches of teeth are periodically sent to Kiev to the central bioprobe bank. Upon arrival to Kiev, all samples are subjected to input control called to evaluate the state of a tooth and assign respective rank (see Table.1). Then all teeth are logged into the bioprobe bank and the information from the tooth ID form is entered into the database. Periodically (at least once per quarter) a detailed review of the quality of collected samples is prepared and sent to the oblast coordinator, providing thus a feedback to the regional level of the tooth acquisition network. Totally over the period of operation of the acquisition network (1992-2001) 3981 teeth were collected (see Table 2), and this number is increasing daily. In general, the pool of collected samples establishes a good basis for both routine dose reconstruction and, more important, for randomized selection of subjects for all kinds of validation tests (see Section 2.3 of this paper).

### 2.2. Reconstruction of individual doses

First time EPR dosimetry was used for reconstruction of individual doses Ukrainian liquidators in 1993. Since 1995, when the methodological guidelines [43] were adopted by the Ministry of Health, EPR dosimetry is being performed regularly. Till the end of 2001 465 individual doses were reconstructed, mostly using the whole scale SCRM protocol including individual calibration by the additive dose technique. However, all this time, our methodological research continues, finding its reflection in upgrades of the dose evaluation protocol. So, till 1999 doses were reconstructed using the whole teeth and

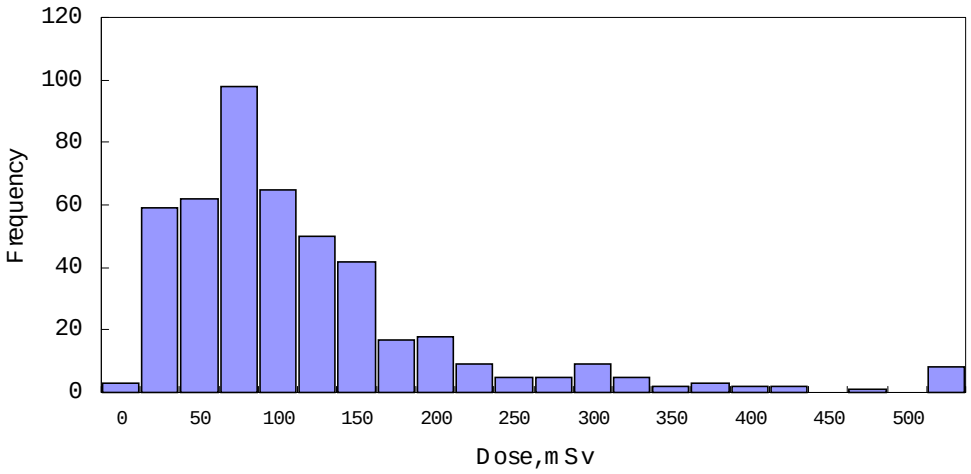



**Fig.10. Distribution of individual doses of liquidators 1986-1987 assessed by EPR dosimetry with teeth.**

the contribution of x-ray doses was assessed basing on the data from the tooth ID forms regarding the number of x-ray procedures and the empirical data on average doses per one examination. However, in the course of tests and comparisons we found that information from the ID forms is very unreliable and, therefore, the formerly used method of x-ray dose account is endowed with unacceptably high uncertainty. As a result, since mid 1999 we have switched to the more elaborate protocol comprising separate dose evaluation using lingual and buccal parts of teeth. All contemporary EPR analyses are performed using this approach, which allows to detect and quantify the possible contribution of dental x-ray exposure. Appearance of another confounding factor - UV exposure, which was first reported in 1996 [44], prompted the revision of all previously obtained results and withdrawal of dose estimates obtained with front teeth. Although a comprehensive study [18] of the effect of UV exposure suggested a clue to mitigation and evaluation of this effect, currently we do not use front teeth for EPR dosimetry.

Fig.10 presents the frequency distribution of individual doses of Chernobyl clean-up workers assessed by EPR. One may see that this distribution confirms the point that very high doses of liquidators were rather exception than a rule, and a mean dose of liquidators of 1986-1987 is 110 mSv.

It should be stressed that a wide scale application of high precision measurement protocol with individual calibration of each sample is a unique experience. In other cases a full scale EPR protocol was used for reconstruction up to several dozens of persons [4, 45], ans a wide scale EPR dosimetry [46] was applied using certainly less accurate technique based on the use of a single calibration coefficient. In fact, application of the elaborate protocol for reconstruction of several hundreds of individual doses in Ukraine allowed not only to conduct accurate dosimetry, but also to bring some qualitatively new results. So, the effect of non-linearity of dose response curves was discovered; as discussed above, this phenomenon may have significant effect on the accuracy of dose reconstruction using EPR dosimetry with teeth. In addition, application of the additive dose technique to all studied teeth allowed comparison of radiosensitivity of different types of teeth. It was shown (Fig.11) that radiosensitivity does not depend on type and location of a tooth. Another important result is presented in Fig.12 reflecting degree of inter-sample variation of individual radiosensitivity. It was shown that relative variation of calibration coefficient ($1\sigma$) is about 12%. Remarkably, these results provide quantitative measure of additional uncertainty, which is introduced into EPR dosimetry if a method of universal calibration coefficient is used for dose assessment. This estimate (12% additional error) is applicable for all types of teeth used for dose reconstruction (Fig.11).

The results of routine EPR dosimetry are used in Ukraine in the framework of several medical

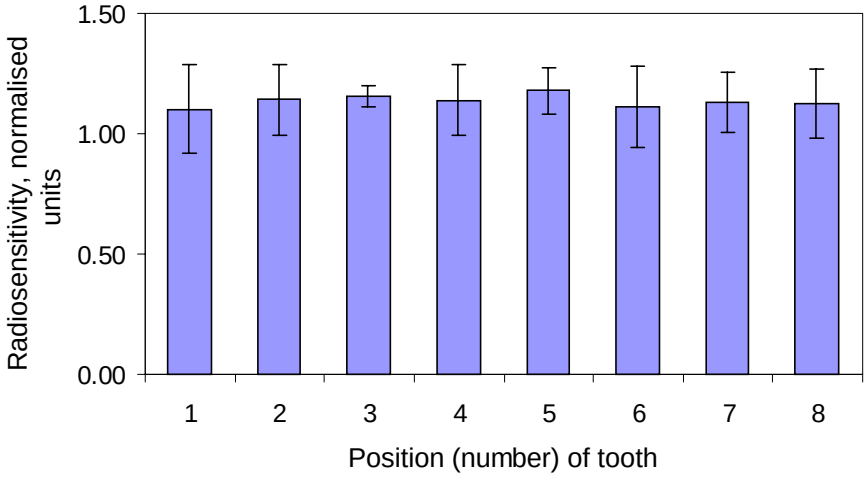



**Fig.11. Radiosensitivity of different types of teeth.**
Teeth nos.1-2 - incisors, 3 -canines, 4-5 premolars, 6-7 - molars, 8 - wisdom teeth.

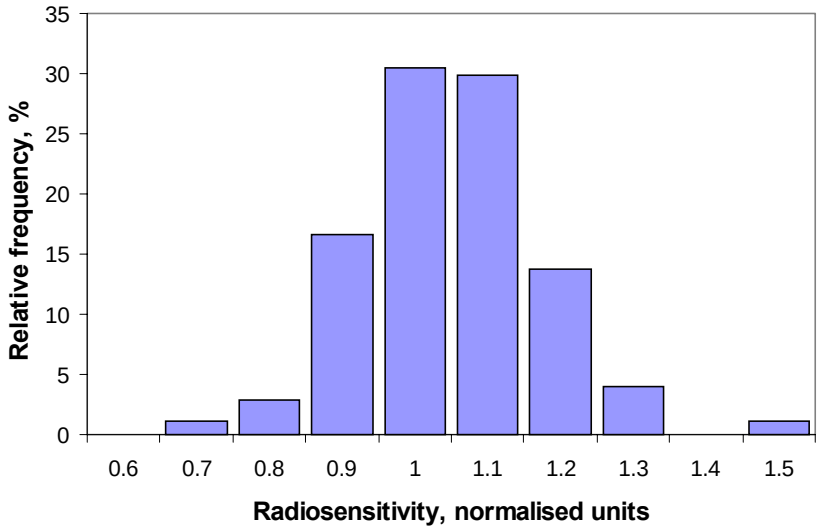



**Fig.12. Distribution of individual radiosensitivity of human teeth (Ukrainian population)**

studies as high precision assessments of individual doses received by liquidators. However, high cost and labor intensity of EPR dosimetry, as well as limited availability of samples, prevent this technique from being a routine dose assessment method for dosimetric support of a large-scale biomedical follow-up.

### 2.3. EPR dosimetry as a reference method for validation of other dose estimates

This unique application of EPR dosimetry was proposed and is effectively used in Ukraine. The matter is that prior to its application, any method of retrospective dosimetry needs to be validated by means of independent, presumably superior accuracy, "gold standard" method. From the discussion above, one may conclude that EPR dosimetry possesses unique qualities (high precision, possibility of dose reconstruction long time after exposure), which makes it an inevitable tool for calibration and validation of other methods of dosimetry. In terms of accuracy, internal consistency and overall quality, EPR dosimetry with teeth may be considered as a source of dose estimates of a reference quality. In fact, EPR dosimetry is the only retrospective dosimetry protocol, which comprises perfectly traceable elements; uncertainty of

each of them may be evaluated in rather straightforward manner. Overall performance of EPR dosimetry with teeth had been proven in the course of several blind intercomparisons (see discussion above - Section 1.3).

Therefore, on the basis of the described above results, a concept of utility of EPR dosimetry as a reference method for validation of the potent methods of retrospective dosimetry, was developed. According to this approach, the method under consideration is applied to the representative sample of subjects who have high quality (in particular, no x-ray dose) EPR dose estimates. Upon comparison of results provided by the method of concern with the "gold standard" EPR doses, the conclusion regarding the accuracy and general applicability of the given method can be derived. Not touching statistical aspects of the validation studies, here we should concentrate on the aspects related to application of EPR dosimetry.

Obviously, application of EPR as a reference method sets certain requirements for selection of subjects and quality of tooth samples. It should be stressed that selection of subjects for the validation test is one of the most demanding and responsible elements of such application. In general, subjects of the validation test should meet the following criteria:

- A tooth must be good for EPR dosimetry, i.e. it should be molar or premolar, have sufficient amount of enamel.
- Enamel must be distributed among buccal and lingual parts of a tooth, allowing thus separate analysis of these parts and evaluation of x-ray exposure.
- Indication on absence of medical x-ray examinations (e.g. from the tooth ID form).
- Availability of auxiliary dosimetric information, e.g. official dose record.
- Affiliation of a subject to the studied group (category).
- Adherence of a subject to given dose interval.
- Residence of a subject in a respective territory (for instance, the area included into certain study).
- Availability of actual postal address.
- Availability of a telephone number.
- Agreement to participate in a study (test).
- Possibility to establish personal contact with the subject (home visit or invitation for examination).

One may see that some of the requirements are difficult to meet and, moreover, sometimes they are contradictory. Certainly, depending of particular plan of the validation test, the rigidity of the above-listed criteria may vary to some extent. In general, however, the enlistment of subjects into the study group is a difficult task. There is very limited flexibility at the level of EPR dosimetry. Effectively this means that application of all criteria leads to reduction of the number of appropriate subjects. The only way to deal with depletion of the original sample is to prepare an abundant number of candidates in order to keep a desired sample size even after washing out some subjects. Since collection of teeth is very slow and inertial process, the solution lays in collection of all available teeth, their storage and selection of subjects following the criteria set by a particular study. This approach (large-scale acquisition of teeth and their retrieval from the central bioprobe bank) was implemented in Ukraine. Success of several validation studies, which involved EPR dosimetry as a reference method, unequivocally proved adequacy of this approach.

As an example of this application of EPR dosimetry, we will take the testing of classical ADR (Analytical Dose Reconstruction). This method (ADR) makes use of the information about the motions and durations during the work of liquidators at Chernobyl NPP site as well as dose rate data for assessment of their radiation doses. . The plan of the test, which was performed in 1998 in the framework of the pilot phase of Ukraine-US leukemia study, included independent evaluation of doses to 20 liquidators by ADR [47] and EPR. The following selection criteria were applied:

1. Availability of a tooth good for EPR dosimetry (no requirement regarding separate analysis of buccal and lingual parts was set at that time).
2. No more than one dental x-ray examination according the tooth ID form data.
3. Affiliation of liquidators to one of the categories for which ADR was applicable (Chernobyl NPP staff).

Totally 30 candidates were selected for this study, 20 of them were interviewed according to ADR procedure and enlisted into the study. ADR was performed by the expert-dosimetrists which routinely perform this work. Comparison of two independent dose estimates revealed quite a significant discrepancy, ADR results had a tendency to overestimation of doses. In depth analysis of ADR analysis, in particular separate consideration of isolated components of dose (note that EPR is able to assess a total dose of lifetime occupational and accidental exposure) allowed to identify the source of discrepancy. Fig.13 presents the comparison of EPR dose and a total dose assessed using ADR. For the latter, breakdown to separate components is given. Finally, it was determined that inadequately high dose estimates were assigned to the episodes of transportation across heavily contaminated territories around the NPP site. In addition, contrary to the ADR protocol, practitioners did not apply respective correction factor to the final result, i.e. the products of wrongly applied ADR were almost two times higher than the results of a canonic ADR procedure. These observations allowed us to fix the weak points of ADR and resulted in development of a substantially revised version of this analytical technique (RADRUE). From the point of view of EPR application, abbreviated account of lifetime x-ray exposure was justified by high levels of exposure of this group of liquidators and, respectively, lower contribution of x-ray exposure to a total dose.

Besides to the discussed test, this approach had been successfully implemented for testing various methods of retrospective dosimetry. Among the tested methods were FISH, SEAD (Soft Expert Assessment Dosimetry - a novel method, which makes use of typical dose distributions of particular groups of liquidators) [48] and, finally RADRUE (ADR derivative, aimed to provide most universal dose estimates to the subjects of the post-Chernobyl epidemiological study).

In general, results of such application of EPR proved to be very informative. For example, based on these validation exercises, SEAD was rejected, classical ADR revealed its weak points and suggested ways of its revision and improvement. Finally, the mentioned above RADRUE method was approved for

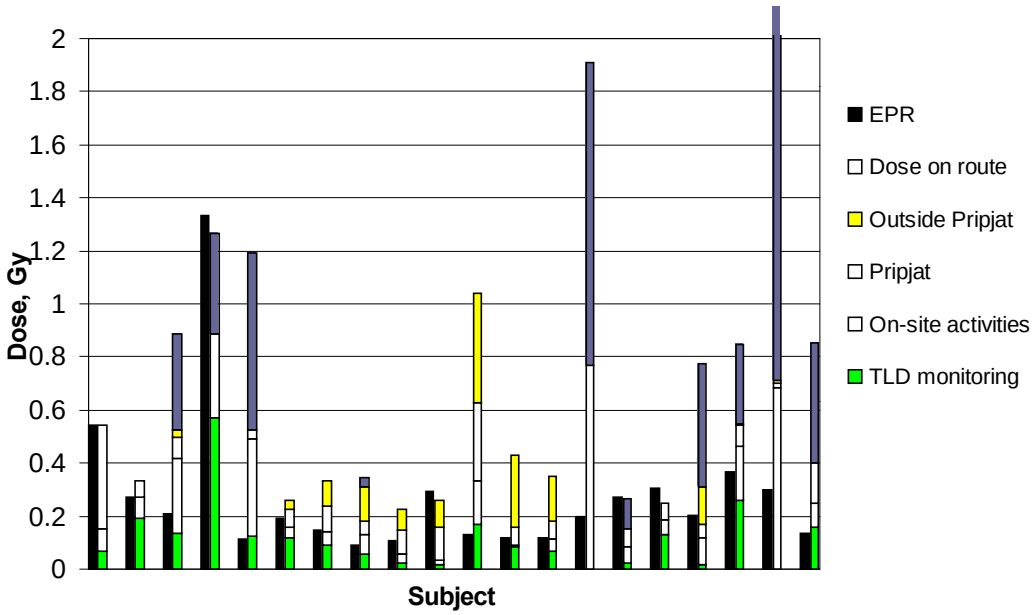



**Fig.13. Results of ADR test. EPR doses vs. cumulative dose assessments with breakdown to components.**

use in the framework of Ukraine-USA case-control leukemia study on the basis of the results of verification by EPR.

**Conclusions**

EPR dosimetry with teeth in Ukraine over the last decade went all way from first laboratory tests to a large scale routine application. A large cycle of methodological research was conducted in order to develop an original version of the EPR dosimetric protocol as well as investigate the effects caused by confounding factors and develop approaches to their account and mitigation. In the development of the EPR dosimetric protocol, the main attention was concentrated on achievement of high accuracy and reproducibility, low sensitivity threshold as well as high throughput. Elaborate quality assurance program, including a series of international intercomparisons had demonstrated high precision and sensitivity of the SCRM version of the EPR protocol. Creation and continuous operation of the nationwide tooth acquisition network is another key to the success of EPR dosimetry in Ukraine.

The main applications of EPR dosimetry in Ukraine are both routine high precision reconstruction of doses to Chernobyl clean-up workers and the use of EPR dose estimates as a reference dose for validation of other retrospective dosimetry techniques. The latter proved to be the most efficient application of EPR dosimetry in the post-Chernobyl situation. EPR dosimetry was used for testing such methods of retrospective dosimetry as FISH, ARD, SEAD and RADRUE. In general, EPR dosimetry plays inevitable role in dosimetric support of post-Chernobyl medical follow-up studies.

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