Dosimetry system of the Ukrainian-American Chernobyl Ocular Study

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Abstract. The goal of the effort was to estimate total (beta+gamma) dose to the lenses of the liquidators - subjects of the Ukrainian-American Chernobyl Ocular Study (UACOS) study. This problem was approached in several steps constituting the UACOS dosimetry system. Assessment of gamma doses was based on maximum use of existing dosimetric information (historical dose records) after their inventory, validation and adjustment. Traceability of gamma doses was established to EPR retrospective dose reconstruction, used in this study as 'gold standard'. The problem of beta dose assessment was solved through establishing relation between beta and gamma doses for particular time and conditions of exposure. Partial beta to gamma ratios for various geometries and electron energies were calculated by Monte Carlo; overall beta/gamma ratios were assessed individually for each subject by convolution of the partial ratios with the parameters of radiation environment for every subject of the study. The total doses along with their uncertainties were estimated by stochastic modelling of both beta and gamma components of the eye dose and production of the file with 500 random realizations of the total dose, as well as separate beta and gamma components for each of 8,607 subjects of the study. The presented dosimetry system is essentially a first approximation of eye lens dosimetry for liquidators and has great potential for improvement.

1. Introduction

Cohort study of the eyes of radiation-exposed Chernobyl Liquidators - a joint effort by scientists of Ukraine and the United States known as the Ukrainian/American Chernobyl Ocular Study (UACOS) which was initiated in 1996, ten years after the Chernobyl accident. Two major objectives of this study are to: 1) address whether radiation cataract is a stochastic or a deterministic process, 2) define the risk of radiation-induced cataracts among Liquidators on a per unit dose basis. As any other radiation effects epidemiological study, UACOS critically depends on the assessment of individual doses of the study subjects (Chernobyl clean-up workers).

In general, dose assessment for Chernobyl clean-up workers is a challenging task. The problem is that during the clean-up activities dosimetric monitoring (and not least important – dose management) was performed by a number of facilities affiliated to various ministries of the Soviet Union. Unfortunately, neither methodological unity nor coordination were achieved before the end of active phase of the clean-up (1986-1987). This situation resulted in existence of dispersed and unmatched data arrays (mostly in paper form) of very variable quality. The situation was complicated by the known fact that in some cases dosimetric information was intentionally distorted (falsified) in order to achieve compliance with existing dose limits or obtain certain social benefits. Moreover, sometimes available dosimetric information was incomplete, i.e. dose records were covering not all period of individual clean-up activity or do not reflect all episodes of the personal clean-up history. It was also known that some techniques used for dosimetric monitoring were not adequate for individual dose assessment (one example is so called ‘group’ method, when only one person in a whole group wore personal dosimeter and the reading of this dosimeter was assigned to all co-workers and recorded in a logbook).

This was the status of the existing dose records as at the time of beginning of the UACOS; such situation made direct application of existing dose records of the liquidators for the epidemiological analysis impossible. Accordingly, a substantial sub-study was needed for investigation of existing dosimetric data arrays, rejection of non-reliable data and improvement of the quality of the reliable data subsets.
In addition, individual beta doses to a lens were never monitored in Chernobyl. For UACOS this meant that for all study subjects beta doses needed to be evaluated retrospectively.

Another challenge was set by the scale of the study. Original UACOS plan envisaged enlistment and examination of 12,000 subjects – Ukrainian liquidators of 1986-1987, who presumably received the highest exposures. The size of the cohort was preventive for application of retrospective dose assessment alone and called for maximum use of available dosimetric data.

Obviously, each of the aspects of dosimetric support of UACOS is worth separate consideration in other more technical papers. Here we will provide the outline of the undertaken effort and present main results of this dose reconstruction. The structure of the following sections will comply with the main stages of dosimetric work and, eventually, individual dose assessment.

2. General approach to UACOS dosimetric support

The UACOS dosimetry system was based on several assumptions:

- The general design of the study allows to start from dosimetry, e.g. assemble the study cohort based on the dosimetric considerations, in particular – on availability (or potential availability) of adequate dose records and possibility to assess individual exposures along with their uncertainties.

- The officially registered doses are of mixed quality, e.g. along with falsified and incomplete records contain the data, which is complete and non-falsified. It is possible to identify the groups (categories) of liquidators for whom the last statement is true and enlist study subjects from these data arrays.

- The above does not mean that ‘complete and non-falsified’ dose records are precise, e.g. are not endowed with bias and uncertainty. The precision of historical dose records should be evaluated retrospectively and necessary adjustment could be introduces.

- Beta exposure of the lens made significant contribution into the total dose and need to be quantified.

- All dose values obtained by different methods are calibrated against EPR (Electron Paramagnetic Resonance) dosimetry with teeth, which was used as a ‘gold standard’ in this study.

Accordingly, the plan of UACOS dosimetric support included several stages:

1. Categorization of the whole liquidator population according to their affiliation at the time of clean-up (and, accordingly, their dose management and dosimetric monitoring practice) and the period (time) of their stay in the 30-km restricted zone.

2. Search for auxiliary data (in particular, individual dose databases).

3. Reconstruction of doses for both ‘routine’ and ‘calibration’ subjects of the study (here term ‘calibration subjects’ means the subjects which were used in the calibration of other dose values by the ‘gold standard’).

4. Retrospective evaluation of bias and uncertainty of Official Dose Records (ODR) – essentially re-calibration of existing dose records, which were known to be imprecise.
5. Separate analysis of various categories of liquidators (see item 1 above) and study of the degree of falsification of the official dosimetric information. Identification of the categories with adequate quality of dose records.

6. Screening of the candidates for inclusion to the study cohort and identification the individuals which fall into one of the appropriate categories. Forwarding the lists of the ‘dosimetrically approved’ subjects along with their actual home addresses to the epidemiological branch of the project for tracing and recruitment.

7. Consideration of beta component of the lens dose as a function of time after the release (reflecting the evolution of nuclide composition), conditions (geometry) of exposure and use of protective eyewear. Elaboration of gamma-to-beta conversion factors for use in assessment of individual beta exposure.

8. Survey of the enlisted subjects in order to identify the conditions of beta exposure.

9. Elaboration of the dose calculation software which through stochastic modeling allowed to evaluate uncertainties of dose estimates and come up with individual dose distributions.

As the result of this activity, each study subject obtained individual uncertainty distribution (500 trials) from which the statistical moments (like median, geometric standard deviation) can be assessed and used in risk analysis. All dosimetric estimates were performed in completely blind manner, e.g. neither health status, nor the stage of ophthalmologic and epidemiologic follow-up were known to the dosimetrists. The final linkage of dose values and clinical findings was conducted at the very late stage of the project, right prior to the epidemiological analysis.

3. Search for dosimetric data

In Chernobyl both dosimetric monitoring and dose management were performed by individual facilities, unfortunately operating according to their own regulations and techniques. In the years of clean-up, basically four major distinct services were responsible for radiation protection of liquidators. The direct consequence of this situation is that information on individual doses, if preserved at all, became dispersed among several bodies belonging to various ministries of the former Soviet Union. As a result, the archives happened to stay in Russia after the decay of the USSR. This fact complicated by all means uneasy task of collecting all available information on individual doses.

The only readily available database was the State Registry of Ukraine (SRU) for individuals affected by the Chernobyl accident, operated by the Ministry of Health of Ukraine. However, only about 50% of liquidators in the registry have official dose record (ODR). Another extremely serious drawback of the SRU data was an absence of the information on affiliation of a subject, though affiliation at the time of clean-up had determined the quality of available dose records as well as dose management practice. The strong side of SRU is that it contains data on home address of the registered subjects, though in many cases outdated. This information was extremely important for tracing the subjects and enlisting them into the cohort.

Data from all other possible sources was not readily available at the time of beginning of the study. Therefore, special efforts were allocated for acquiring of the electronically available dosimetric databases and filling the gaps in the SRU data. This work was accomplished with the help of colleagues from the Institute of Biophysics (Moscow) and with financial provisions from the Columbia University and National Cancer Institute (USA). As a result of this effort, all together six various databases were collected, representing the contingents belonging to the USSR Ministry of Atomic Energy and Ministry of Medium Machinery. These databases, containing in total 170,708 records were linked with the SRU in order to assign dose values to the individuals registered in SRU.
Results of the linkage turned to be frustrating – due to lack of reliable identifiers (like full name and passport number), only 1,893 records were linked certainly, at the end, only 410 individuals belong to the study cohort and have dose data covering the whole period of work in Chernobyl; respectively, only those 410 subjects were assigned dose estimates from this source.

Another effort was focused on recovery of the missing in the SRU information regarding the affiliation of the subjects at the time of clean-up. For this purpose the mini-questionnaire was designed and sent by mail to the liquidators who have dose records in SRU and are residing in the oblasts covered by the UACOS. The simple questionnaire contained five questions related to affiliation, type of work, methods of dosimetry and places of work. It was printed on a prepaid postcard, a liquidator was asked to fill out the questionnaire and put it to a mailbox. Totally 13,820 questionnaires were sent out to the liquidators for whom dose records were available in SRU, response was obtained from 4,681 individuals (response rate - 34%). Results of this survey turned to be quite educative: 89% of liquidators with registered doses were the military reservists, another 5% are cadre military. Another important piece of the data obtained in course of this survey was the information regarding the methods used for assessment of doses. In summary, ‘group method’ was used in 33% of cases, ‘group assessment method’ – in 45% of cases, only 16% of doses registered in the SRU were measured by individual dosimeters. This survey provided important characteristics of the potential UACOS subjects.

All collected information - both individual dosimetric monitoring results and the data on affiliation and tasks as acquired by the dosimetric survey were rigorously inventoried and organized in the respective databases.

4. Application of retrospective dosimetry techniques

In addition to the use of the collected and inventoried historical data, the UACOS dosimetry system did include a good deal of dose reconstruction. Retrospective dosimetry was applied for quite different purposes: (a) for routine dose reconstruction for early liquidators, who presumably received the highest doses, and (b) for calibration of the dose estimates used in this study.

In this section we will focus on the first application area of the dose reconstruction, leaving application of retrospective dosimetry for calibration of dose estimates for a separate section.

The need for reconstruction of doses to the early liquidators was caused by the fact that the most exposed individuals (high dose group) were working at the ChNPP site during the first days and weeks after the accident when dosimetric monitoring was absent. Dose reconstruction for this contingent was provided both via EPR dosimetry with teeth and by the Analytical Dose Reconstruction (ADR), a technique based on ‘time-and-motion’ principle, which uses the information about the tasks and movements of early liquidators acquired through an interview and supported by the witnesses. By the time of UACOS initiation, the ADR was already in place [1] being applied to about 1,600 NPP workers, who were exposed during the first several weeks after the accident.

Our task was to evaluate the ability of this technique to provide unbiased and accurate dose estimates. This task was achieved via target investigation when EPR dosimetry with teeth was used as a ‘gold standard’ for calibration of ADR. In course of this test it was found that ADR tends to overestimate doses, sometimes up to two-fold. Closer consideration of the ADR operation manuals and interviews with ADR practitioners revealed the following fact: the main concept of ADR application was based on the traditional in the field of radiation protection conservatism, e.g. the dose estimates could only overestimate the dose received by a subject (conservative approach). Therefore, prior to use of the ADR within the UACOS, ‘realistic’ not ‘radiation protection’ doses needed to be estimated. This task
was achieved by the ADR reevaluation of about 100 representative questionnaires with special emphasis on avoiding unjustified conservatism in dose estimates. The results of ‘conservative’ and ‘realistic’ ADR dose estimated were compared providing the information concerning the overestimation of dose by the first approach. Based on the results of this exercise, all other ADR dose estimates were adjusted with respect to the observed bias and random uncertainty within the studied sample.

5. Validation and adjustment of existing dose records

5.1. Study of reliability of official dose records

One of the greatest concerns preventing immediate application of ODR was related to the possibility of falsification of dosimetric data at time of Chernobyl clean-up. In order to evaluate the degree of falsification of ODR and its impact on the reliability of existing dosimetric data arrays, a special sub-study was undertaken. This sub-study was based on the observation of statistical regularities of the dosimetric data arrays as related to different groups of liquidators. The results of this sub-study are in details described elsewhere [2, 3].

The findings of this investigation are the following. It was demonstrated that for the military liquidators distributions of daily doses (total dose divided by a number of days spent in Chernobyl) can be adequately described by hybrid-lognormal law [4] with the parameters complying well with the existing dosimetric monitoring practices. Time evolution of the parameters of the distributions (µ and ρ) is in a good qualitative agreement with the change of conditions of exposure and dose management practice. Investigation of the possible contribution of extraneous admixtures (falsified values) into the dosimetric array was based on analysis of behavior of the entropy coefficient (fractal dimension) of the experimental distribution [5], in our case – distribution of daily doses. It was demonstrated that possible percentage of abnormal admixtures in case of military liquidators does not exceed 10% of total dose records. This conclusion supports the use of official dose records of military reservists as a source of non-falsified dosimetric information. However, conclusion regarding the lack of falsification of military dosimetric records, of course, does not mean high precision of this data. The next section is devoted to the evaluation of the degree of precision of official dose record of the military liquidators, in particular, assessment of their possible bias and uncertainty.

5.2. Calibration of ODR: retrospective evaluation of the bias and uncertainty

Once the absence of falsification of individual doses of the military liquidators was demonstrated, the question regarding the accuracy of ODR came to agenda. It was known that methods of dose assessment for this cohort were rough and, most likely, quite conservative. Therefore, the special sub-study was undertaken in order to estimate uncertainty and possible bias of ODR for military liquidators. This was achieved by comparison of ODR with the high precision EPR dose estimates.

In order to perform this retrospective calibration, the test group was formed of the individuals whose teeth had been collected and were stored in the central bioprobe bank [6] and who belong to the category of military liquidators. The latter was achieved in two ways. First, the database of the responses to dosimetric mini-questionnaire was linked with bioprobe database. Second, the tooth donors with teeth good for high precision EPR dosimetry (tooth big enough for cutting into two parts
and analysis for absence of medical x-ray irradiation) were checked for membership in SRU (linkage with SRU file) and then the target interviewing by telephone or by post was undertaken. Only EPR doses free of the contribution of medical x-ray irradiation were used in this analysis. In total the test group consisted of 106 subjects possessing ODR and the high precision EPR doses in excess of 50 mGy to be used as reference values.

High precision EPR dosimetry protocol is described in [7, 8] and may be characterized by the following metrological parameters: sensitivity threshold (minimum detectable dose) – 25 mGy, absolute term of uncertainty in low dose range (below 300 mGy) – 25 mGy (1σ), relative error in high dose range – not worse than 10%; these parameters were confirmed in a number of multi- and bilateral intercomparisons, in particular in the latest 3rd International Intercomparison of EPR dosimetry with teeth [9].

Since accuracy of EPR dose estimates (about 10%) was superior to anticipated uncertainty of ODR evaluated by group assessment method (expected GSD 2.0+), the EPR doses were used as point values and the EPR/ODR ratio was applied as experimental distribution of actual doses in the study group and thus the model distribution for adjustment of original ODR data. This distribution is lognormal in shape and reflects the bias and random uncertainty of ODR for military liquidators obtained by group assessment method. The parameters of this distribution are the following: geometric mean (GM), which characterizes the bias was 0.39 and geometric standard deviation (GSD) – 2.14. This means that official doses of military liquidators on average overestimate actual exposure by a factor of ca. 2.5 (1/0.39). This finding is in a good agreement with qualitative considerations regarding the nature of group assessment of doses in Chernobyl.

The described above model distribution was used as modifier for adjustment of available ODRs for their bias and assignment of uncertainty to these dose estimates. This was achieved by stochastic modeling expressed in multiplying the ODR (point estimate) for each particular liquidator with the random realizations sampled from the model modifying distribution.

6. Screening of the candidates for inclusion to the study cohort

With the regard of the above discussion, two categories of liquidators, who possess official dose records, were considered as reasonably adequate for the purposes of UACOS. These categories, namely, are:

- workers of AC-605 (Unit 4 Shelter construction) because of high quality of their dosimetric monitoring (IDM) at time of the clean-up, and;
- military liquidators because the low percentage of falsification of their dosimetric information was demonstrated.

Respectively, the study cohort was to be based on the two above categories of the liquidators. All other categories of liquidators were left out the scope of the study because their dose records (if exist al all) are considered as incomplete and/or unreliable.

Once this decision was made, the task arose to identify the subjects belonging to one of these categories (as was mentioned above, information on affiliation of liquidators was missing in SRU). This was partially achieved in course of the postal survey with dosimetric mini-questionnaire (see section 3 for details). Since the percentage of military liquidators among the candidates with ODR proved to be very high (about 95%), decision was made to enlist into the study cohort all the liquidators possessing ODR, perform dosimetric questioning at the time of ophthalmic examination.
and discriminate the ill-affiliated subjects at the later stage of the study. This approach deliberately lead to 5 to 10% abundance of ophthalmic examinations, but helped to save time and effort otherwise directed on tracing and interviewing of excessive number of candidates for inclusion into the cohort.

This approach proved to be efficient. Though no delay in the study was caused by lengthy process of pre-examination acquiring information on affiliation, and only 621 examined subjects (5.3% of the original cohort) were rejected because their affiliation did not fall to the two listed above categories.

7. Assessment of the beta dose to a lens

During the initial period following the accident (for at least two years) a beta hazard was present in Chernobyl and therefore the beta component of the lens dose cannot be neglected. According to Osanov and co-authors [10] under the most unfavorable conditions the beta dose to the lens might actually exceed the respective gamma dose by a factor of 20. In addition, beta exposure depends, in a very complex way, on a number of factors, in particular – geometry of exposure, nuclide composition (as a function of time) and use of protective eye-wear in addition to the anatomical peculiarities of a given person [11]. From the dosimetric point of view, estimation of beta doses (both instrumental and analytical) is also very complicated – beta rays are strongly attenuated by soil, air and biological tissues, so an analytical representation of an absorption function is possible to a very limited extent. In fact, methodological difficulties associated with determining beta doses prevented the determination of individual beta exposures at the time of clean-up [1].

Due to the noted above reasons, the estimation of beta doses to lenses required very rigorous consideration of all the factors affecting beta exposure and the elaboration of original approaches to retrospective assessment of this component of a dose. The proposed approach is based on two assumptions. First, beta doses could be estimated based on the gamma dose values by applying certain conversion coefficients. Second, specific gamma to beta conversion coefficients should depend on the particular conditions of exposure of any cohort member (i.e. beta dose assessment must be individualized).

The first step in assessment of beta exposures was expressed in calculation of partial per unit source beta doses estimated for various elementary sources (elements of horizontal and vertical surfaces of different roughness and with different energies of emitted electrons). Based on these partial results, the modeling of gamma-to-beta conversion coefficient was possible for any configuration and energy spectrum of both gamma and beta emitters. In order to implement this approach, calculations involved the Monte Carlo method using the MCNP-4B code [12] for a number of mono-energies (in order to model doses caused by the sources of any energy spectrum), partial sources and a variety of surface textures (variable roughness). Although these calculations were extremely time consuming, they provided the data necessary to assess beta-to-gamma conversion coefficients for any specific scenario of beta exposure.

Individualization of beta dose assessments was achieved through composing individual beta exposure profiles for the subjects of the study. In order to acquire the necessary information regarding the conditions of the beta exposure, a special questionnaire had been developed and administered to the subjects by mail or at the time of their ophthalmic examinations. Since a liquidator could work in Chernobyl under a wide variety of conditions, a respondent was asked to describe his/her activity using one or more of the six possible categories of work locations, e.g. roof of the NPP, industrial site, indoor locations etc. Each section of the questionnaire contains a set of more specific questions designed to characterize the circumstances of beta exposure. Upon completion of the questionnaire, its analysis includes assessment of conversion factors for each category (work location) as a function of time and specific circumstances of beta exposure (geometry). The total beta dose then is calculated as
a sum of gamma doses received at each work location multiplied by the respective conversion coefficients. This assessment of individual beta doses was performed by the means of stochastic modeling, when all parameters of the model were treated as random values and 500 trials were used in order to assess individual uncertainty distribution.

8. Stochastic modeling of individual doses

The procedure to calculate a total (beta + gamma) dose is conditioned by the need to provide uncertainty assessment along with the point dose estimate. This was achieved by the means of stochastic modeling in the following manner (see flow-chart, Fig. 1). Each of the original dose estimates was converted to a random value by multiplying by a random number sampled from the lognormal distribution of respective Geometric Mean (GM) and Geometric Standard Deviation (GSD) values. So in those cases, when the original dose records are believed to be unbiased (see Table 1), GM is equal to 1.0. For biased ODR dose values, an empirically determined GM was used in order to adjust for the bias. For each of the stochastic realizations, the beta calculation algorithm (see section 7) was applied in order to assess the respective total dose realization. As a result, stochastic realizations of total (beta + gamma) doses are scored generating an individual uncertainty distribution. An example of these distributions is given in Fig. 2. For each person 500 random realizations are scored, these arrays along with results of their statistical analysis are forwarded to epidemiological branch of the project for analysis.

In order to implement this approach, a special software code was developed de novo using MathLab. This procedure takes the original dose record, type of dosimetry, period after the accident and the results of the beta dosimetry interview as input parameters for calculation. Therefore, both the point dose assessment and its uncertainty are individual for each subject and depend on specific circumstances of his/her exposure in Chernobyl.

The practical implementation of gamma dose calculation protocol was following. To begin with, the original deterministic value of a dose estimate (raw record) was converted into a stochastic value. As a rule (see Table 1) this was achieved by multiplication of the original deterministic value with the random realization sampled from the distribution of modifying factors $f$ according to the following expression:

$$d = D_{raw} f,$$

where $D_{raw}$ is original individual dose value (i.e. ODR, ADR or IDM), $f$ – dimensionless modifying distribution (stochastic variable); $d$ – resulting distribution of individual dose (also stochastic variable). Parameters of the distribution $f$ depend on the model of uncertainty used and are attributed to the given category of raw data. We used different uncertainty models for simulation of $f$ for various categories of data – the summary of these models is presented in Table 1.

The resulting individual uncertainty distributions are illustrated by the Fig. 2, where one such distribution for one study subject is presented. As an output of dose assessment effort, individual uncertainty distributions of this kind (500 realizations each) were forwarded to epidemiologists for use in the risk analysis. The parameters of the doses within the cohort may be illustrated by Fig. 3 where distribution of geometrical means (GMs) of individual uncertainty distributions is presented.

At this point it should be stressed, that some of the dose assessment methods/raw dose sources (ODR, ADR) were calibrated by EPR dosimetry, while compatibility of EPR itself and IDM data was

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1 In this section stochastic variables are presented by italic letters, whereas deterministic values are given in normal font.
achieved by calibration in the same terms. In this way unity and metrological traceability of all dose estimates was achieved. Concerning error models, used for simulation of individual uncertainty distributions, empirical parameters were used for the methods calibrated by EPR, while the results of type testing were applied by directly calibrated techniques (EPR and IDM). In this sense EPR performed as secondary standard for calibration of ODR and ADR.

10. Exclusion of the subjects from dose assessment

It should me mentioned that despite all efforts to assure a high success rate for dosimetry at the time the cohort was assembled, some subjects had to be excluded from the analysis due ultimately to a failure to assess individual doses and uncertainties. This occurred for several reasons.

1. Incorrect affiliation of the person in the ODR (i.e. not military or AC-605 staff). This condition is discussed in the report and is caused by the inability to judge or correct the ODR for the categories other than the two methods mentioned above. Of the examined subjects, 621 proved to belong to the ‘wrong’ category and therefore were removed from the study cohort.

2. Lack of data regarding the period of work. This parameter is absolutely critical to assess beta dose because the beta/gamma ratio has a strong time dependence. Totally (for all categories of data) 1,049 examined individuals were excluded for this reason. It should be stressed, however, that this information can be recovered relatively easily, e.g. in course of the routine examination.

3. Period of work for subjects with IDM doses begins before 1 July 1986. It is known that before this time dosimetric monitoring in the 30-km zone was not well established, so it is likely that for the individuals from the IDM file who started their service in Chernobyl before 1 July the dose records are incomplete and do not cover the entire period of work. All told, 406 examined individuals were excluded from the consideration due to doubts in completeness and adequacy of their IDM records. In fact, another 111 subjects had suspect IDM but they overlapped with the ADR file which means that the gaps in dosimetric monitoring had been already filled by application of ADR and, therefore, the problem of incomplete coverage with dosimetry had been addressed.

4. Failure of some tooth samples to meet the stringent modern requirements regarding quality of a sample. At the stage of cohort selection, more relaxed criteria were used for evaluation of the possibility to do EPR dosimetry. Since that time, requirements had tightened (i.e. only big teeth which are good for separate determinations of the buccal and lingual portions are considered to be appropriate for EPR dosimetry). This resulted in the exclusion of some of 51 of the original candidates from the “EPR” category.

5. And finally, some examined subjects were withdrawn from the study due to other, non-dosimetric considerations. Doses to such subjects were not calculated as well. It should be noted that liquidators excluded by criteria 1-4 significantly overlap those excluded by criterion 5.

In summary, 2,127 individuals were excluded from the consideration due to failure to meet stringent requirement of the high quality dosimetry (criteria 1-4 solely). In fact, almost half of this number (1,049 records) may be recovered and returned to useful application by interviewing the liquidators in the future. This means that loss for analysis solely by dosimetric criteria is about 18% of the original study cohort. Recovery of the periods of work may reduce this fraction to less than 9%. Fortunately, 781 subjects for whom dosimetry failed, had been already excluded by other, non-dosimetric considerations, reducing the effective failure rate of dose reconstruction.

Conclusions
As a result of UACOS dose assessment activity, a consistent dosimetry system was elaborated. This dosimetry system, based on combination of the utility of historical dose records and state-of-the-art retrospective dosimetry techniques allowed to assess individual lens doses from both gamma and beta radiation to 8,607 subjects of the ocular study.

However, this dose assessment should be treated as a tentative, first approximation, because there is still a great potential to improve the precision of the dose estimates.

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REFERENCES


Table 1. Summary of uncertainty models used for simulation of a gamma dose realizations

<table>
<thead>
<tr>
<th>Bias of</th>
<th>Model of uncertainty</th>
</tr>
</thead>
</table>

10
<table>
<thead>
<tr>
<th>Category of data</th>
<th>source data (need for correction)</th>
<th>Analytical expression (equation)</th>
<th>Type of distribution</th>
<th>Parameters of distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>ODR</td>
<td>yes</td>
<td>( d = D_{\text{raw}} f ) (1)</td>
<td>lognormal</td>
<td>GM=0.5, GSD=2.2</td>
</tr>
<tr>
<td>ADR</td>
<td>yes</td>
<td>( d = D_{\text{raw}} f_{\text{ADR}} f_{\text{adjust}}(D_{\text{raw}}) ) (4)</td>
<td>combination of two lognormal distributions</td>
<td>see expressions (5) – (6)</td>
</tr>
<tr>
<td>IDM*</td>
<td>no</td>
<td>( d = D_{\text{raw}} f ) (1)</td>
<td>lognormal</td>
<td>GM=1.0; GSD=1.4</td>
</tr>
<tr>
<td>EPR (two halves of tooth – no x-ray dose)</td>
<td>no</td>
<td>( d = D_{\text{raw}} + d_{\text{EPR}} ) (2)</td>
<td>normal</td>
<td>M=0; SD=25 mGy</td>
</tr>
<tr>
<td>EPR (whole tooth – unknown x-ray dose)</td>
<td>possible</td>
<td>( d = D_{\text{raw}} + d_{\text{EPR}} - d_{x\text{-ray}} ) (3)</td>
<td>combination of normal and lognormal - non-negative realizations from the distribution (3)</td>
<td>M=0; SD=25 mGy; GM=34 mGy; GSD=3.2</td>
</tr>
</tbody>
</table>

* calculations are valid for subjects who started their service after 1 July 1986

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**Input**

- Questionnaire data: - section flags \( F_i \) - dates of mission - work conditions
- Category of the subject (ODR, IDM, ADR, EPR)
- \( \beta/\gamma \) time dependence \( B(t) \)
- original \( \gamma \)-dose \( D \)
- parameters of dose distribution \( \mu, \sigma \)
- weights for sections of dosimetry questionnaire \( w_1, w_2, w_3, w_4, w_5, w_6 \)

**Processing**

500 realization

- \( \beta/\gamma \) ratio \( b = S \) (questionnaire data) 500 values
- Realization of \( b \)
- Accounting time dependence \( b_i B(t) \)
- Generate realization of \( \beta \)-dose \( D_{\beta} = \Sigma b_i d_i \)
- Generate realization of \( \gamma \)-dose \( D_{\gamma} = \Sigma d_i \)
- Total dose \( D = \Sigma d(1+b) \)

**Output**

- results of simulation 500 realizations;
- dose distribution parameters:
  - mean;
  - standard deviation;
  - geometric mean;
  - geometric standard deviation;
  - median;
  - 2.5% tile
  - 97.5% tile
FIG. 1. Flow-chart of stochastic model for individual dose assessment.

FIG. 2. Individual uncertainty distribution.
Subject P01279. Male, 1955 year of birth, worked in Chernobyl from 1 June to 3 September 1986. Locations of work – variable but not including roof decontamination.
Distribution Parameters: mean – 128 mSv, SD – 96 mSv, GM – 101 mSv, GSD – 2.01, Median – 103 mSv, 2.5% percentile – 25 mSv, 97.5% percentile – 370 mSv.

FIG. 3. Distribution of individual doses (GMs of individual uncertainty distributions) for 8,607 study subjects