NIH Public Access
Author Manuscript
Radiat Res. Author manuscript; available in PMC 2011 February 3.

Published in final edited form as:
Radiat Res. 2008 December ; 170(6): 698–710. doi:10.1667/RR1403.1.

The Ukrainian-American Study of Leukemia and Related Disorders among Chornobyl Cleanup Workers from Ukraine: II. Estimation of Bone Marrow Doses

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Abstract

After the accident that took place on 26 April 1986 at the Chornobyl nuclear power plant, hundreds of thousands of cleanup workers were involved in emergency measures and decontamination activities. In the framework of an epidemiological study of leukemia and other related blood diseases among Ukrainian cleanup workers, individual bone marrow doses have been estimated for 572 cases and controls. Because dose records were available for only about half of the study subjects, a time-and-motion method of dose reconstruction that would be applicable to all study subjects, whether dead or alive, was developed. The doses were calculated in a stochastic mode, thus providing estimates of uncertainties. The arithmetic mean individual bone marrow doses were found to range from 0.00004 to 3,300 mGy, with an average value of 87 mGy over the 572 study subjects. The uncertainties, characterized by the geometric standard deviation of the probability distribution of the individual dose, varied from subject to subject and had a median value of about 2. These results should be treated as preliminary; it is likely that the dose calculations and particularly the uncertainty estimates will be improved in the follow-up of this effort.

INTRODUCTION

The accident that took place on 26 April 1986 at the Chornobyl (Chernobyl)[2] nuclear power plant (ChNPP) located in Ukraine, about 12 km south of the border with Belarus, occurred during a low-power engineering test of the Unit 4 reactor (also called the 4th block of

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SUPPLEMENTARY INFORMATION

Study of the Health Status of Liquidators. Subject Questionnaire. Revised 08/2001. http://dx.doi.org/10.1667/RR1403.1.S1.

Study of the Health Status of Liquidators. Co-worker Questionnaire. Revised 08/2001. http://dx.doi.org/10.1667/RR1403.1.S2.

Study of the Health Status of Liquidators. Spouse (or Relative) Questionnaire. Revised 08/2001. http://dx.doi.org/10.1667/RR1403.1.S3.

[2]Standard Ukrainian spellings of place names are used in this paper. The most noticeable differences are for the site of the accident and the nation's capital, Kyiv, but the names of other locations also differ from those used in previously published papers.

ChNPP) and is the most severe that the nuclear power industry has ever known (1). The workers involved in various ways after the accident include (a) the approximately 600 emergency workers who participated in firefighting and other emergency measures during the first day of the accident and (b) the hundreds of thousands of cleanup workers, also called "liquidators" or "recovery operation workers", who were active in 1986–1990 at the power station or in the 30-km restriction zone surrounding it for decontamination work, sarcophagus construction, other cleanup activities, and the operation of other units of the nuclear power plant. All together, about 600,000 persons (civilian and military) have received special certificates identifying them as cleanup workers, according to laws promulgated in Belarus, the Russian Federation, and Ukraine (1). Although the principal tasks carried out by the cleanup workers involved decontamination or construction (2), a broad variety of other activities, such as administration and research, infrastructure support (housing, food, transportation), radiation monitoring, communication, security and transportation, were also included.

The most important pathway of exposure for the cleanup workers was external irradiation from the γ-ray emitters deposited on building surfaces (indoors or outdoors) or on the ground. This resulted in a relatively uniform irradiation of the whole body. The external γ-ray doses were measured or estimated, recorded and included in national registries for about half of the liquidators (3). However, the quality of these data was not uniform and was often rather low (4).

Studies of cleanup workers provide an opportunity to add to current knowledge about the possible health consequences of exposure to relatively low doses of ionizing radiation received gradually over a period of several months. The Research Center for Radiation Medicine (RCRM) of the Academy of Medical Sciences in cooperation with the Ministry of Health of Ukraine and the U.S. National Cancer Institute (NCI) have conducted a case-control study of leukemia and other related blood diseases involving 572 Ukrainian workers. General features of the method used to estimate the bone marrow doses for the study subjects and the dosimetric results that have been obtained are presented in this paper. Technical details of the method of dose estimation are given in a paper soon to be submitted for publication.[3] Two companion papers, one on the design of the epidemiological study (5) and the other on the results of the epidemiological analysis (6), are published in this issue.

MATERIALS AND METHODS

Characteristics of the Study Subjects—Dosimetric Perspective

The selection criteria for study subjects included (a) initial registration in the Chornobyl State Registry of Ukraine (SRU) as a cleanup worker residing in Kyiv City or in Cherkasy, Chernihiv, Dnipropetrovsk, Kharkiv or Kyiv oblasts (locations in which approximately 46% of Ukrainian liquidators resided); (b) first year of service from 1986 through 1990; (c) gender (male); (d) age (year of birth between 1926 and 1972); and (e) Chornobyl-related work within the 70-km zone around ChNPP.[4] Subjects were not required to be alive at the time of selection. Detailed information on the design of the study, creation of the cohort, case identification and validation, selection of controls, and tracing and recruitment is provided in ref. (5). The subjects who were diagnosed with hematological disease or who

[3]The working title of the paper to be submitted to Health Physics is "RADRUE method for reconstruction of external doses to Chernobyl liquidators in epidemiological studies." The authors are V. Kryuchkov, V. Chumak, E. Maceika, L.R. Anspaugh, E. Cardis, E. Bakhanove, I. Golovanov, V. Drozdovitch. N. Luckyanov, A. Kesminiene, P. Voilleque and A. Bouville.

[4]Technically, eligibility criteria for being certified as a liquidator include work within the 30-km restriction zone around the ChNPP site in the years 1986–1990. However, in the course of tracing and enlisting the subjects of the study, it turned out that not all officially certified liquidators actually worked within the 30-km zone. Therefore, for the purposes of this study, eligibility criteria were expanded to include work within the 70-km radius around the ChNPP.

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served as controls were not identified to the dosimetrists. The distribution of the 572 study subjects according to oblast or city of residence at the time of registration in the SRU is given in Fig. 1; about half of the study subjects originated from Kyiv City and Kyiv Oblast.

The study subjects have been classified into 11 categories according to (a) the period during which they were at the Chornobyl site or (b) their affiliation and thus the type of work performed at Chornobyl. These 11 categories fall into four broader groups reflecting particular characteristics of their involvement into Chornobyl cleanup.

Group 1, early respondents, includes three categories:

1. *Witnesses of the accident* were at the ChNPP site when the accident happened or came there before May 1, 1986, and who were not diagnosed later with acute radiation syndrome (ARS).
2. *Victims of the accident* are the witnesses of the accident who were later diagnosed with ARS.
3. *Early liquidators* are all civilian liquidators (except for ChNPP personnel) who worked within the 30-km zone, including the industrial area of the ChNPP, between April 27 and May 31, 1986.

Group 2, professional nuclear workers, includes four categories:

1. *ChNPP personnel* are the plant staff members who worked between May 1986 and the end of 1990 to conserve and prepare other units of the ChNPP for regular operation.
2. *Sent to assist ChNNP* are employees of other nuclear power plants who were sent to assist and temporarily substitute for the regular ChNPP staff at time of recovery and preparation for restart of Units 1–3.
3. *Staff of AC-605* are persons from the organization, named Administration of Construction No. 605, involved in the construction of the shelter covering the damaged reactor.
4. *Staff of Kurchatov Institute* are scientists and engineers from the Kurchatov Institute of Atomic Energy who studied the condition and distribution of the fuel mass inside the Unit 4 reactor building.

Group 3, uniformed liquidators, also called *Military liquidators*, are either regular military or civilian reservists who performed decontamination (e.g., in Unit 4 and on the roofs) and other tasks not requiring skilled labor.

Group 4, other, includes three categories of subjects who do not fall into any of above three groups:

1. *Civilians Sent on Mission* (*CSOM*) are those persons who were sent to perform various tasks in the 30-km zone after June 1, 1986.
2. *Staff of Combinat* are individuals from that organization who performed a variety of tasks in the 30-km zone and coordinated the work of persons sent on mission to the 30-km zone.
3. *Mixed* refers to a set of liquidators who worked on the Chornobyl site several times as members of different categories.

The distribution of the study subjects according to category is presented in Table 1. About two-thirds of the study subjects were either military or CSOM. Most of the study subjects worked at Chornobyl in 1986, with decreasing numbers during the following years (Table

1). It should be noted that, based on our previous studies, we expected that about 50% of liquidators would be military. The lower percentage of military workers among the 572 study subjects (39%) can be explained by the large number of liquidators from the city of Kyiv and Kyiv oblast, who were mostly temporarily assigned specialists sent on mission. Separate consideration of the breakdown of liquidators from the city of Kyiv and Kyiv oblast by different categories compared with the other four oblasts supports this assumption (Table 2). Based on proper weighting, the structure of the whole Ukrainian liquidator population was estimated, yielding results consistent with our previous studies.

It should be noted that 65 study subjects (11%) spent more than 1 year at the site, either on a single mission or on separate missions. Some missions were separated in time, leading to long periods between the beginning and the end of work in the restriction zone (see Table 3). In fact, 133 subjects (23%) had more than one mission; the maximum number of missions was 11 and the average was about 1.4.

Normally only part of the time of a mission to Chornobyl was allocated to cleanup activities. Some time (e.g. while resting, training, waiting for assignment, etc.) was spent in areas with low contamination. Thus a distinction should be made between the total duration of a mission and the number of active days spent at work in relatively high radiation fields. The number of active days is smaller than the total number of days in mission for about 30% of the subjects, averaging 69% of total time. The average active duration was 92 days per mission and 124 days per person (all missions). In total, the 572 subjects spent 2369 man-months of active work in Chornobyl. The distribution of the duration of active work for the study subjects is presented in Fig. 2; Fig. 2a shows the distribution of the active duration of all individual missions, and Fig. 2b illustrates the distribution of the total time spent on active work by the study subjects. The distribution of durations of both missions and total times at Chornobyl is quite broad and, as can be seen from Table 2, varies significantly for different categories.

Status of Dosimetric Information Related to Study Subjects

For about one-quarter of the study subjects, Official Dose Records (ODR, also called “official doses”) are available in the SRU. The quality of ODR is variable (3,4). Official doses were generally obtained in one of four ways: (a) individual dosimetry measurements, (b) group dosimetry measurements, (c) group dose assessments, and (d) time-and-motion analysis soon after the accident. Civilian workers with individual dose measurements [method (a)] were the staff of AC-605, ChNPP personnel after June 1, 1986, and part of the staff of the organization Combinat. A few military personnel, who worked in locations where the exposure rate was greater than 1 mR h^{-1} were also supposed to have individual dosimeters. For group dose measurements [method (b)], an individual dosimeter was given to one member of a group of cleanup workers assigned to perform a particular task, and all members of the group were assumed to receive the same dose. In the group assessment [method (c)], the dose to the whole group of liquidators was assessed by a dosimetrist in advance by considering the exposure rate at the work location and the planned duration of work. Similarly, time-and-motion analyses [method (d)] for more complex tasks were based on measurements of γ-radiation levels at various locations and the individual's dose was estimated using knowledge of the places where he worked and the time spent in these places. Methods (b) and (d) were used for the civilian workers before June 1986, when the number of individual dosimeters was insufficient, and method (c) was used for the majority of the military personnel at all times.

Table 4 shows the fractions of each liquidator category for which ODR are available. Personal interviews revealed that many liquidators possess information on doses (like dose certificates or records in military ID book) that is not included in the SRU. This is not surprising because the ODR in the SRU were derived from documents provided personally by liquidators at the time of primary registration. Some liquidators did not have such dose documents at the time of primary registration and obtained them only after being registered in the SRU.

Victims and witnesses of the accident, early liquidators sent to the 30-km zone, and others did not have measured doses because the personal dosimetry system in use at the early time after the accident had failed (4). During the 1990s, doses from external irradiation were reconstructed using a time-and-motion method called Analytical Dose Reconstruction (ADR). This technique was used to estimate doses to the staff of ChNPP and workers who had been detailed to assist them for the period from 26 April to 5 May 1986 (2). Personnel location record cards (route lists) filled in by workers and confirmed by eyewitnesses were analyzed by experts who had reliable information on the radiation conditions and who had personally participated in ensuring the radiation safety of all operations after the accident. Using this method, two doses were estimated: an upper bound dose and an expected dose. The upper bound doses ranged from less than 100 mGy to a few thousand mGy and were estimated to be about twice the expected doses (2).

Other available sources of dosimetric information, such as the archives of the Ministry of Defense or the dosimetry databases that were acquired during the course of the study, provided information for only a limited number of subjects. It was found that dosimetric information (total individual doses and, in some cases, daily or monthly doses) in the archives of the Ukrainian Ministry of Defense had been stored in paper form and was not linked with the SRU, while individual dose values were recorded in the personal military certificates possessed by all military liquidators and had already been entered into the SRU at time of registration. Information from the military archive was entered into a computer database. This facilitated a comparison of these data with ODRs in the SRU, which revealed large overlap of information and good coincidence of individual dose records from these two files. Therefore, inventory and data entry of the military archives added little to the already existing information on individual dose records of military liquidators. The individual dosimetric monitoring (IDM) databases were also of little use because only a small fraction (17,754 out of about 168,000) of dose records in the IDM databases had sufficient identifiers (full names, year of birth) and the liquidators to whom these records were related were identified only as residing in Ukraine. Moreover, only 1,893 records (out of 17,754 possessing necessary keys) were linked with certainty with the SRU, adding 1,613 new dosimetric data entries previously missing in the Registry (7).

Development of the Routine Dose Reconstruction Method; Its Principles and Application

The methods of dose estimation discussed above are very different in nature and are applicable to differing fractions of the study subjects. In addition, some of the methods lead to results that cannot be easily verified. Therefore, it was necessary to develop a universal method of dose estimation that would be (a) applicable to all subjects, whether deceased or alive, and (b) based on information that would be relatively easy to process and to check.

The task of selection or development of the universal dose assessment method, applicable to all subjects of the study, was addressed during the pilot phase of the project (1996–2000). Readily available techniques like ADR, EPR (electron paramagnetic resonance) dosimetry with teeth, and FISH (fluorescence *in situ* hybridization) using chromosomes in human lymphocytes were considered from the point of view of the above criteria and were found to be inadequate for the purposes of the study. An overview of the methods of dose reconstruction evaluated during the feasibility study is given in Table 5. It can be seen that biodosimetry and instrumental methods depend on the availability of specimens (blood or teeth) and have sensitivity thresholds that are not always compatible with anticipated doses to liquidators. Both these methods have the disadvantage of measuring total dose, including components due to medical exposures or to occupational exposures other than those received during Chornobyl cleanup work.

Analytical techniques, which rely on the results of interviews with liquidators, do not have a dose threshold and can be applied to virtually all subjects, both alive and deceased. In the latter case, a proxy for the subject can be interviewed to collect the necessary information regarding the activities of the subject in the radiation zone. However, the readily available ADR technique had several shortcomings that prevented it from being applied routinely to the subjects of this study. First, the ADR route lists required a high degree of precision and specificity (supported by witness reports), so only a few highly skilled and motivated liquidators were capable of providing the necessary information. The general liquidator population, many of whom performed unskilled work without personal initiative, could not describe their activities sufficiently. The second limitation of ADR was that the dose calculations were designed to overestimate the received doses. This was due to a “radiation protection approach” in which longer exposure times and higher dose rates were normally selected to avoid underestimating the dose received. This qualitative effect was confirmed in comparisons with individual dose estimates obtained using EPR analysis of tooth enamel (8). Given the shortcomings of the ADR method, a new method called SEAD (Soft Expert Assessment Dosimetry) was designed (9). The procedure used interview data and dose distributions for each liquidator category to assess the individual dose received by the liquidator according to a set of objective and subjective parameters. This conceptually non-trivial methodology uses fuzzy-set algebra for uncertainty propagation. In addition, reliable dose distributions needed to implement the method for each worker category were not available. In view of these limitations, the SEAD method was not considered to be applicable to all study subjects.

In view of the limitations of the approaches discussed above, a new time-and-motion method, known as Realistic Analytical Dose Reconstruction with Uncertainty Estimation (RADRUE), was developed by an international group of scientists including experts from Belarus, France, Russia, the U.S. and Ukraine.[5] The RADRUE method was conceived for this study as well as for International Agency for Research on Cancer (IARC) studies of Baltic, Belarusian and Russian cleanup workers. It is based on a detailed analysis of the liquidator's activities during cleanup, including all places of work and residence, types of work, transportation, etc. This information is combined with data on the radiation fields at the locations and dates where the liquidator spent any time to reconstruct a history of the radiation exposures received during the period when the liquidator was involved in cleanup activities. Although RADRUE can be considered to be a further development of ADR, there are fundamental differences between the methods. First, universal application of RADRUE to all study subjects was achieved by simplification of the questionnaire. In the RADRUE method, activities and movements of liquidators are described in more general terms with fewer details. Because the information requested is less specific, the questionnaire can be administered both to living subjects and to proxies (coworkers and next of kin) for subjects who are deceased. Most importantly, estimates of residence times and exposure rates are intended to be realistic and to provide central, rather than conservative, estimates of doses received by Chornobyl liquidators.

[5]The International Dosimetry Group included at different times the following persons: Dr. Andre Bouville (NCI, USA), Dr. Lynn Anspaugh (University of Utah, USA), Dr. Geoff Howe (Columbia University, USA), Dr. Elisabeth Cardis, Dr. Ausra Kesminiene and Dr. Evaldas Maceika (IARC, France), Dr. Philippe Hubert and Dr. Margot Tirmarche (Institute of Radioprotection and Nuclear Safety, France), Dr. Viktor Kryuchkov and Mr. Ivan Golovanov (Institute of Biophysics, Russia), Prof. Viktor Ivanov, Dr. Valery Pitkevich (Medical Radiological Research Center, Russia), Dr. Anatoly Mirkhaidarov (Institute of Radiation Medicine, Belarus), Mr. Sergey Illychev, Mr. Alexander Tsykalo, Mr. Viktor Andreev, Mr. Viktor Glebov (ChNPP, Ukraine), Dr. Vadim Chumak, Dr. Natalia Gudzenko and Dr. Elena Bakhanova (RCRM, Ukraine).

Within the Ukraine-U.S. study, special sub-studies were designed and performed for different liquidator categories (e.g. military and CSOM) and helped to refine the RADRUE methodology (8). The high-precision EPR dosimetry technique with teeth developed in the RCRM (10) was used as the main reference method for checking doses estimated using the RADRUE technique. All comparisons of RADRUE dose estimates with the reference dose values were analyzed rigorously and used for refinement of the technique.

Some dose estimates obtained using the unrefined RADRUE method were found to overestimate doses actually received by groups of cleanup workers whose exposures were controlled by the radiation protection staff of the group. The exposures of these workers were routinely monitored and limited according to applicable guides, such as daily dose limits, established for the organization. Three worker groups operated under some version of dose control: military liquidators who worked in an organized team, the staff of the ChNPP, and the staff of the AC-605 construction organization. The RADRUE method was modified to include an evaluation of whether such dose limitation should be reflected in the estimate for a particular subject. The key components of the evaluation were (a) whether the individual was in one of the three groups of workers and (b) whether the same daily activity was repeated three or more times.

A second important refinement of the method was implementation of new techniques of handling uncertain itinerary data. In the revised approach, three options are provided to reflect the differing levels of detail provided by subjects. If the subject provides a specific sequence of movements to specific locations, the path defined by the subject is used for dose estimation. If the locations, but not the sequence, are given, then the average dose rate for the activity is more uncertain. The least definite description is when only the work area is recalled, which leads to the greatest uncertainty in dose estimation.

The latest version of RADRUE incorporates these improvements and is the one used to make the dose calculations for the study subjects. Prior to implementation for the study, the RADRUE calculations were compared with other reliable dose estimation techniques that were applied to workers who received a wide range of doses. Victims and witnesses of the accident received the highest doses; estimates based on dicentric chromosome aberration frequencies in 20 persons covered a dose range of 200–14,000 mGy, with most doses above 1,000 mGy. Comparisons showed that RADRUE estimates were comparable but somewhat (~20%) lower than those based on unstable aberrations. For a group of workers carefully monitored using TLDs, the dose range was 1–190 mGy and ratios of RADRUE to TLD doses ranged from 0.5 to 3.6, with a median value of ~1.4. A third set of RADRUE estimates was compared with dose estimates based on EPR in the dose range 50–200 mGy; the median dose ratio was close to unity, with values lying within a range of 0.26–3.9. These comparisons showed that the RADRUE estimates were not highly biased in either direction.

Spatial and Temporal Variations of Exposure Rates[6]

A key element of the time-and-motion approach employed by RADRUE is knowledge of the radiation exposure rates at the locations where the liquidators lived and worked during their stays in the vicinity of the Chornobyl facility. The radiation exposure rates in the 30-km zone around Unit 4 of the ChNPP varied substantially in space and time after the accident. Spatial variations were due to (a) complex deposition patterns that reflected conditions during the period when most releases occurred, (b) localized hot spots where reactor core debris and/or pieces of highly radioactive equipment landed, and (c) local exposure-rate

[6]At the time of the Chornobyl cleanup work in 1986–1990, all the radiation measurement devices used for monitoring were calibrated in terms of exposure rate (mR h^{-1}), and it is therefore convenient to use exposure rates (in those units) in the retrospective dose calculations.

extrema produced by unshielded beams of radiation passing through fractures in reactor shielding. The temporal variations of exposure rates were caused by (a) the continuing radioactivity release (especially for the first 10 days to 1 month after the accident), (b) radioactive decay of deposited materials, and, later, (c) the effects of massive decontamination activities conducted within the 30-km zone. For the purposes of dose estimation using the RADRUE method, all available exposure-rate measurement data were inventoried, checked for consistency, and compiled according to location and time of measurement. These measurements were supplemented by measurements of deposition densities of specific radionuclides that could be used to estimate exposure rates. The available information was interpolated in space and time to generate standardized data sets for areas of interest during the 4.7-year period when subjects were exposed.

Figure 3 gives a snapshot of the exposure-rate pattern over the ChNPP industrial site 30 days after the accident and illustrates the wide range of values encountered. (One should note that the RADRUE exposure-rate database operates with the maps of different scales that are related to particular "geographical" areas. In Fig. 3, the exposure rate isolines are only given for the "Industrial site of the ChNPP" map. Although this area also includes "Roofs of ChNPP" and "The main building of ChNPP", the map scales differ and isolines of those exposure-rate maps are not shown.) Figure 4 shows the time dependence of measured and estimated exposure rates for a location close to the ChNPP Units 3 and 4. The estimated minimum, mean and maximum values used in dose calculations by RADRUE are shown in the figure. Effective γ-ray energies for the radiation fields encountered were in the range 100–500 keV and depended on the contamination level (in general) and any peculiar features affecting the exposure location.

Practical Considerations of RADRUE Application

RADRUE is a complex technique containing many specific aspects and features. In this paper, only the features of RADRUE that are specific to the Ukrainian-American case-control study of leukemia and other related blood diseases are presented and discussed. A separate paper (see footnote [3]) is devoted to a more detailed description of the technical aspects of RADRUE as used in both the Ukrainian-American and the Belarus/Baltic/Russia/IARC studies.

The implementation of RADRUE is a multi-stage process; the main steps are presented schematically in Fig. 5. This process engages various specialists, including interviewers, data registration operators and coders, expert dosimetrists, and developers of the RADRUE technique and dose calculation code. Some significant features of this process are discussed below.

1. Interviews—Persons who conducted interviews within the Ukrainian-American study were carefully selected and trained. They were themselves liquidators who had a detailed knowledge of the 30-km zone and of the cleanup work that was conducted after the accident. They conducted personal interviews with the liquidator himself, if he was alive and not incapacitated, to obtain descriptions of his Chornobyl work and other activities. Approximately 15% of the study subjects were deceased (5). For the 76 deceased and two incapacitated study subjects, interviews were carried out with proxy respondents. Two types of proxies were selected for each deceased subject: a spouse or next-of-kin proxy to provide data on demographic factors and medical history and one or several coworker proxies (usually nominated by the spouse) to provide information on the deceased liquidator's experience at Chornobyl. This would include military unit (if applicable), temporary residence location, type of activities, and duration of work as a liquidator.

2. Registration and scanning of questionnaires. Role of the Data Coordination Center—All processes of document turnover are conducted under supervision of the Data Coordination Center (DCC). Completed questionnaires were registered in DCC and then dispatched for scanning into computer graphical files, coding of the responses, and entry into the computer database. Information essential for classification of liquidators, was extracted into a special form called the dosimetric synopsis. This form was also used for recording the expert's evaluation of completeness and trustworthiness of the interview data. Data from the dosimetric synopsis were used for classification and categorization of the study subjects. The DCC coordinated all stages of the questionnaires processing and provided participants with the auxiliary information (e.g., affiliation, non-Chornobyl occupational history, health records, etc.). Results of simulation (arithmetic and geometric means, standard and geometric standard deviations as well as 10,000 random realizations of dose; see below) are also stored at the DCC to be used in further epidemiological analysis.

3. Roles of the experts—Relatively general questionnaires (see Supplementary Information) completed during the personal interview were processed by the expert dosimetrists. Their task was to reconstruct the itinerary followed by the liquidator and to provide information on the uncertainties associated with the itinerary, including alternative options, when applicable. An expert must have unique skills. He must be extremely familiar with the history of Chornobyl cleanup activities, including the sequence and duration of the main activities in the 30-km zone, and with the geography of the area. He must be aware of radiation protection issues and, for example, know the routes of movement and transportation usually chosen to minimize doses. Within this study, two experts were qualified and trained for this role. Both were long-time employees of the radiation safety department at the Chornobyl NPP and were actively involved in the Chornobyl cleanup over several years after the accident. In the course of their work, they used archives related to Chornobyl chronicles and consulted with persons in charge of cleanup activities. This auxiliary information was used for verification of the questionnaire data and reconstruction of a liquidator's itinerary based on information available from the questionnaire. Summarized information about the work history is entered into the dosimetric synopsis.

The work of the experts was reviewed independently. The reviewer examined the expert's interpretation of the questionnaire responses for each subject. Additionally, the reviewer made independent dose estimates for about 5% of the subjects, and his results were compared with those of the expert. For about 5% of the subjects, the two experts analyzed the same questionnaire independently and estimated the doses received. The independent dose calculations were compared (reviewer and expert, expert 1 and expert 2) and were found to be in good agreement.

The experts were also asked to evaluate the completeness (quality) and trustworthiness of the questionnaires according to five- and four-grade scales, respectively. The first attribute refers to the success of the interviewer in obtaining the desired information, and it naturally reflects the recall of the liquidator (or proxy) as well. The assessment of trustworthiness relates to the plausibility of the reported activities and whether the report is credible or embellished. These grades were entered by experts into the dosimetric synopsis and were recorded in the DCC in a separate database for possible consideration in the evaluation of uncertainties.

Consideration of Uncertainties

Uncertainties of doses estimated by RADRUE technique can be divided into two categories referred to as intrinsic uncertainties and human factor uncertainties. In the first category are uncertainties in exposure-rate data and soil contamination measurements, uncertainties in the interpolation of these data in time and space, uncertainties in location factors used to characterize the effectiveness of shielding, and imprecision of data from the questionnaire (e.g., failure to recall the specific time of a particular mission expressed in indication of some broad time interval instead of specific dates), even though the latter could have been included in the human factor uncertainties. Some of these can be categorized as errors that are shared by subgroups in the cohort or by the entire group. Although there is little overlap in dose for multiple workers experiencing the same exposure rate at the same time, the process of development of the exposure-rate grids is a common element of the dose calculations.

In the second category are blunders in responses to questions, particularly by worker proxies, the recording of those responses by the interviewers, and the interpretation of the information by the expert. Variations in analysis between the two experts are included in the "human factors" category as well. Initial investigations of human factor uncertainties were performed as special studies. These included evaluation of proxy-interview variability, repeated interviews of individual liquidators, and repeated analysis by the second expert. On the basis of these studies, the human factor component of uncertainty was only qualitatively characterized as "large", especially when proxy responses are used in the dose calculations.

A detailed analysis of shared and unshared errors has not yet been performed. The geometric standard deviations reported in the next section reflect an elementary Monte Carlo approach for the intrinsic uncertainties. Repeated calculations in which parameter values are selected randomly from distributions of individual parameters (e.g. dose rates, times, location factors) produce a distribution of doses for each subject. The results from 10,000 trials are summarized in terms of arithmetic mean, geometric means and geometric standard deviations (GSDs) of the output dose distributions.

RESULTS AND DISCUSSION

The results of the dose evaluations for liquidators in the Ukrainian-American study are presented in the following subsections. The first deals with the dosimetry interview process. Then the dose estimates for subjects are summarized and the checks on those estimates are described. Finally, plans for improvement of the method are indicated.

Experts' Evaluation of Questionnaires

The experts judged 91% of the liquidators' questionnaires as "reliable" (highest grade of trustworthiness), while only 3% were considered "unlikely." As for the quality of questionnaires, grades of "excellent", "good" and "fair" were given to ~31%, ~39% and ~29%, respectively. The lowest grade was assigned to fewer than 2% of the questionnaires. Quality of interviews measured by average grades did not depend on year of cleanup activity by a subject and was comparable for different interviewers and dates of interview. Ratings of data quality were in general higher for subjects than for proxies. These results indicate that, with few exceptions, subjects provided valid information. They also indicate that training of the interviewers was uniformly effective and that, in general, they all performed well.

Bone Marrow Dose Estimates for Subjects

The RADRUE methodology was applied to estimate bone marrow doses for the 572 subjects of the study, including 71 cases and 501 controls. Both annual and cumulative doses over the entire period of work were calculated. For 76 deceased and two incapacitated subjects, interviews were performed with proxies. Results of dose estimation were delivered to the Data Coordination Center of the project and were used in the epidemiological analysis (6).

The ranges of estimated doses and uncertainties for each liquidator category are presented in Table 6. For each category the average, minimum and maximum values of the mean doses to individuals are presented for each group. The uncertainty in the dose estimate for each subject is expressed individually as the GSD of the stochastic dose distribution obtained. The last column of the table gives the average value of the GSDs of the dose estimates for members of each category of study subjects. As noted above, the uncertainties of intrinsic type in the dose estimates reflect the uncertainties in the routes and in parameters used in the dose calculations. The distribution of the GSDs for all study subjects is shown in Fig. 6. Information about the collective and annual doses for each liquidator category and first year of work is presented in Tables 7 and 8, respectively, while average dose estimates for all study subjects according to time of work are presented in Table 9. As shown in Fig. 7, the cumulative dose estimates for these individuals cover a broad range, which is not surprising considering the wide variety of mission durations and types of tasks performed by the liquidators. The range of values seen is illustrated in the following discussion.

Consistency Checks and Validation of the Data

The critical analysis of the dose estimates included various kinds of consistency checks and, in particular, an independent consideration of the highest and lowest doses in each category of workers. The lowest and highest doses estimated for individuals in any category are considered below:

1. The lowest dose to a person sent on a mission to the 30-km zone was 0.00004 mGy. This individual flew in an airplane over the 30-km zone at an elevation of 600 m. The exposure rate calculation for this person required a special calculation that considered both the distance and the shielding provided by the plane.

2. The highest dose calculated for any study subject was 3300 mGy for one of the individuals in the “mixed” category of liquidators. About 95% of his estimated dose was received as an early liquidator, when he reported multiple visits to the industrial site to perform work. At that time, the exposure rates at industrial site locations were high, and the total dose estimated for this individual reflects that fact. Experts reviewing the reported information suspect that the individual overstated the number of visits to the industrial site. Nonetheless, the dose was calculated using the information provided by the subject and is thus likely to be an overestimate. The dubious nature of the information in answers found in this particular questionnaire was indicated in the expert dosimetrist's report and was reflected in a low grade of trustworthiness (grade 2 of 4).

An indirect check on the validity of a high individual dose estimate can be the review of the medical information to see whether the person was diagnosed as having ARS. Symptoms of ARS are expected to occur for absorbed doses in excess of 1.5–2.0 Gy. All together, RADRUE dose estimates for three subjects in the study exceeded this threshold. One person (dose 2600 mGy) was known to have second-degree ARS and was initially classified as a victim of the accident. Closer consideration of the case with a dose estimate of 3200 mGy revealed that the subject was a ChNPP employee who worked there the night of the accident. He was evacuated to Moscow Hospital no. 6 on April 27 and was diagnosed with the second-degree ARS. The person died in 1998; according to his widow, his estimated “dose” was about 3000 mGy. Therefore, the observed clinical effects support the high dose estimates for these two victims of the accident. The medical record of the subject with the highest, but dubious dose estimate of 3300 mGy (case 2 above) did not include an established ARS diagnosis. This observation supports doubts concerning the trustworthiness of the interview data in this particular case.

Planned Improvements

Data obtained not from liquidators but from proxies can be a major source of uncertainty. Although the central estimate for the whole group of proxies seems to be unbiased, individual deviations from the "true dose" can be extremely large. The arithmetic mean dose estimates for subjects whose doses are based on proxy responses could therefore be increased by a substantial factor because of uncertainties in those responses.

Plans are being made to assess the full extent of the uncertainties (shared and unshared components of intrinsic uncertainties and the human factor uncertainties) related to the current dose estimates and to look for ways to reduce the overall uncertainties as much as possible for future calculations.

SUMMARY AND CONCLUSIONS

The reconstruction of bone marrow doses for the subjects of a case-control study of leukemia in Chornobyl cleanup workers from Ukraine illustrates a systematic approach to dosimetric support of an epidemiological study. This effort included the investigation of the available information on individual doses and the study of the feasibility of finding an existing technique or inventing a new method of dose reconstruction that could be applied to all study subjects. As a result of this pilot phase, a new method called RADRUE was developed. The developmental stage of RADRUE included testing against reference dose estimates (results of dosimetric monitoring for professional atomic workers and EPR dosimetry with teeth for other categories of liquidators), which provided feedback to guide modification and refinement of the RADRUE technique.

The dose reconstruction process includes several stages, namely, questioning of a liquidator or a proxy by a trained interviewer, analysis of the questionnaire by an expert and conversion to RADRUE program input, deterministic and stochastic calculations, and a post-calculation phase, which included comparison with other available data on personal exposure. To obtain necessary information regarding movements and behavior of the subjects, a group of interviewers was hand picked and trained to administer a special questionnaire developed for studies of liquidators.

Doses to 572 subjects of the study were reconstructed, including 494 subjects who were alive and 78 deceased or incapacitated for whom proxies were interviewed. The subjects of the study represent all categories of liquidators, with dominance of military (39%) and CSOM (32%). It should be noted that both locations of work and durations of activity in Chornobyl vary significantly. As a result, doses to study subjects vary over seven orders of magnitude from virtually natural background level to life threatening. The pool of study subjects is a good representative sample of the whole liquidator population.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Practical implementation of leukemia dosimetry relied greatly on the dedicated work of expert dosimetrists—Mr. Alexander Tsykalo, Mr. Viktor Glebov and Mr. Petro Bondarenko—as well as the team of interview-ers—Mrs. Nadezgda Gurova, Mr. Yuri Spichak and Mr. Vassily Kudreiko. The concept of RADRUE was founded by Dr. Lynn Anspaugh, while the IARC team led by Dr. Elisabeth Cardis contributed as motivated (and motivating!) consumers of dosimetric data and co-developers of interviewing and quality control approaches. The success of this study is due to a large extent to the efforts and inspiration of the researchers of the Ukrainian-American team, including but not limited to Academician Volodymir Bebeshko (director of the Research Center for Radiation Medicine AMS Ukraine), Prof. Dimitry Bazyka, Prof. Maria Pilinskaya, Dr. Irina Dyagil, Mrs. Natalia Babkina, Mr. Yuri Belyaev, the late Dr. Geoff Howe, Dr. Stuart Finch and Dr. Robert Reiss. This research was supported by the Intramural Research Program of the U.S. National Cancer Institute, NIH, DHHS, and the Department of Energy. The U.S. Nuclear Regulatory Commission and the French Institute of Protection and Nuclear Safety provided the initial funds for purchase of equipment.

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FIG. 1.

Geographic regions of Ukraine where the 572 subjects resided. The numbers of subjects in each oblast are shown, except for Kyiv, where the number from the city (indicated as “in Kyiv”) is separated from the total for the remainder of the oblast.

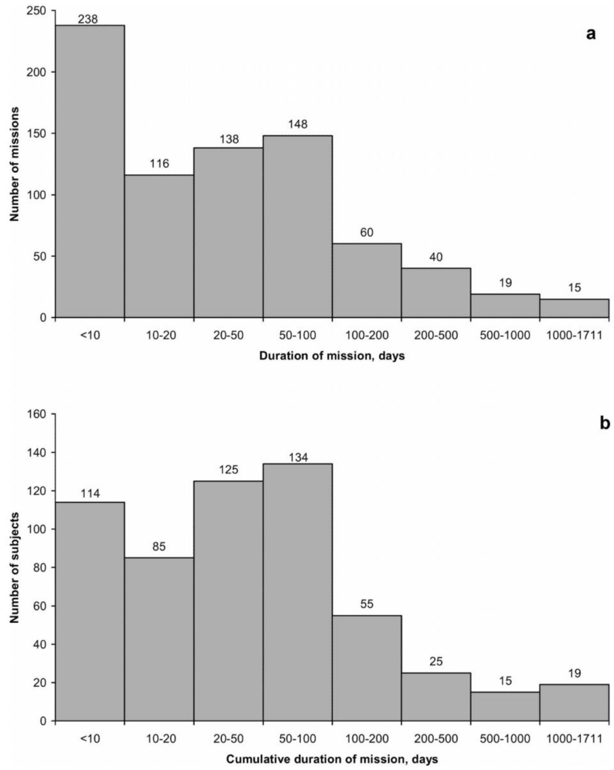

FIG. 2.

Distribution of times (active days) spent in Chornobyl: (panel a) individual missions and (panel b) cumulative periods of work. The maximum possible duration of work in Chornobyl was 1711 days, corresponding to the number of days within the period from April 26, 1986 to December 31, 1990.

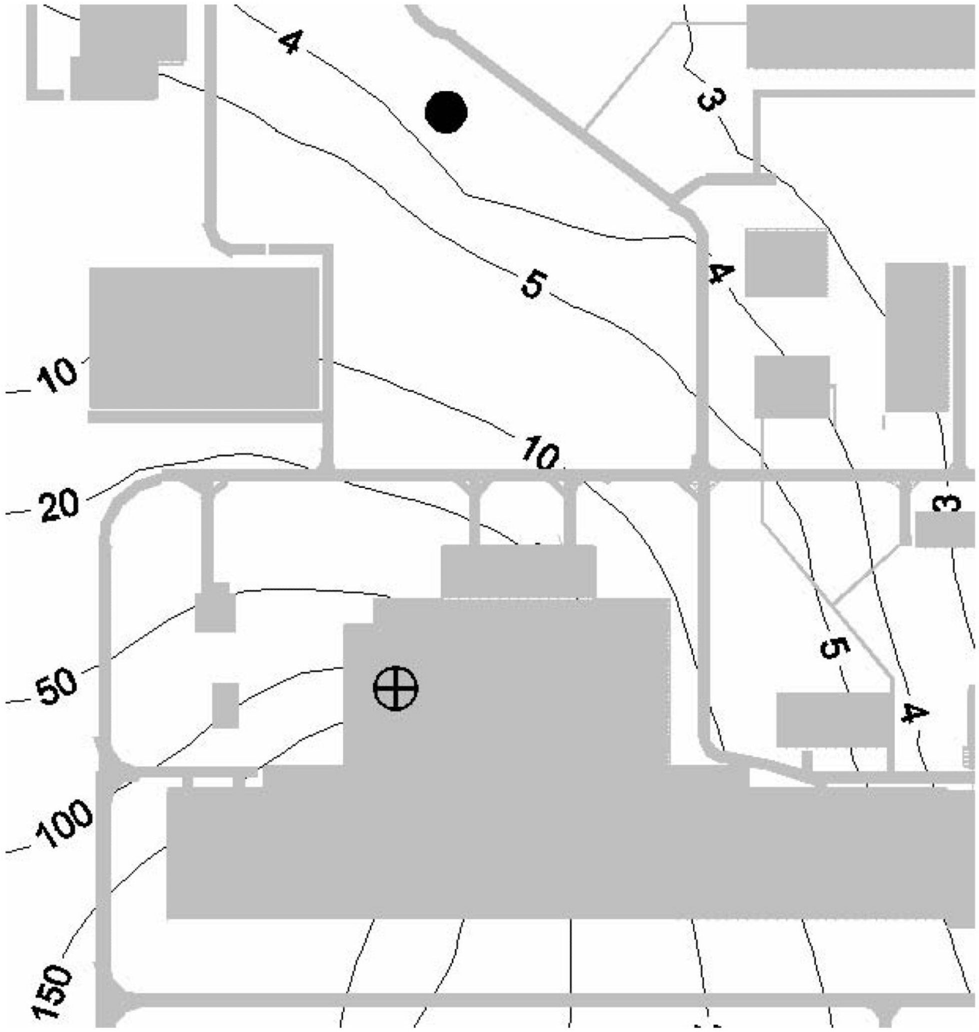

FIG. 3.

Spatial pattern of exposure rates (R h^{-1}) at the ChNPP industrial site on May 26, 1986. Position of reactor No. 4 is marked with crossed circle; the location of the point considered in Fig. 4 is marked with shaded circle. Gray objects represent NPP buildings and roads.

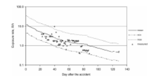

FIG. 4.
Time course of exposure rate (R h^{-1}) at the ChNPP industrial site. Triangles mark measurement data, the solid curve the estimated mean dose rate in this area, and the dashed lines the estimated maximum and minimum exposure rates for this area. See Fig. 3 for the location of the measurement point.

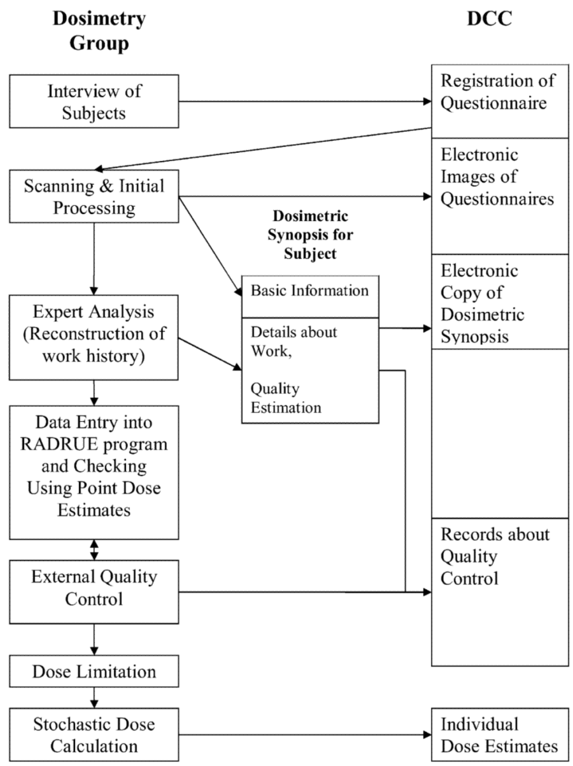

FIG. 5.

Flow chart of dose reconstruction using RADRUE. DCC is the acronym for the Data Coordination Center. The dose limitation procedure applies only to liquidators in certain groups who performed tasks repetitively (see the text).

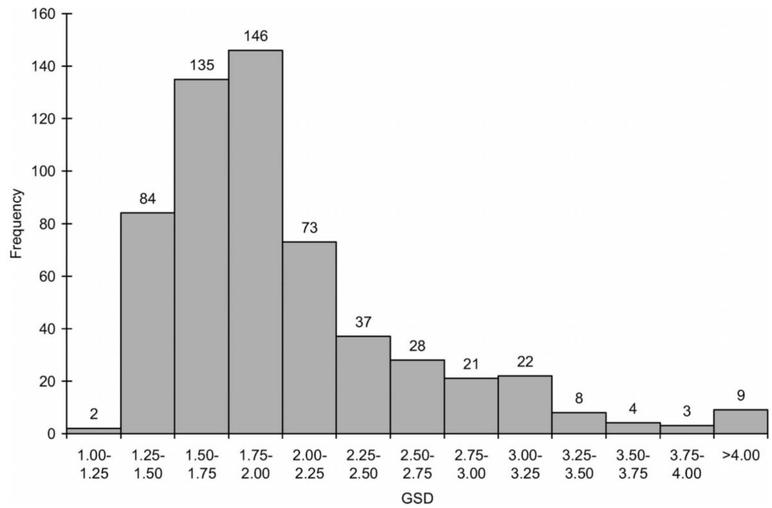

FIG. 6.
Distribution of the geometric standard deviations (GSDs) of the bone marrow doses of the subjects.

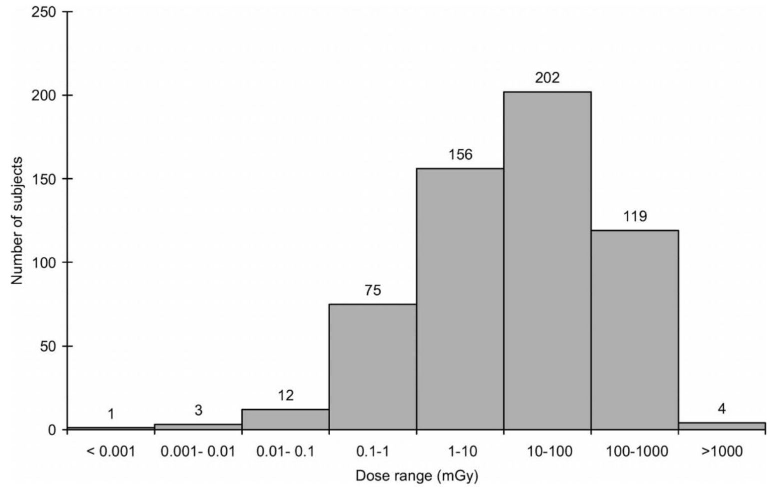

FIG. 7.
Distribution of the bone marrow doses for all subjects.

TABLE 1

Distribution of the Subjects According to Category and First Year of Work

Category	Total number	Year of beginning of work				
		1986	1987	1988	1989	1990
Group 1: Early respondents						
Witnesses of the accident	3	3				
Victims of the accident	2	2				
Early liquidators	66	66				
Subtotal early respondents	71	71				
Group 2: Professional atomic workers						
ChNPP personnel	9	6	3			
Sent to assist the ChNPP staff	1	1				
Staff of AC-605	5	5				
Staff of Kurchatov Institute	2			1	1	
Subtotal atomic workers	17	12	3	1	1	
Group 3: Uniformed liquidators						
Military liquidators	220	109	49	42	17	3
Subtotal uniformed	220	109	49	42	17	3
Group 4: Other						
Civilians Sent on Mission (CSOM) to the 30-km zone	181	138	32	6	3	2
Staff of Combinat	4		4			
Mixed	79	78		1		
Subtotal other	264	216	36	7	3	2
All	572	408	88	50	21	5

TABLE 2

Structure of the Liquidator Population in the Study and Reconstruction of the Structure of Whole Liquidator Population in Ukraine

Category	Study population (whole cohort)		City of Kyiv and Kyiv oblast		Other four oblasts		Estimated percentages for the liquidator population from Ukraine
	Number (%)	Median duration of work, days (min, max)	Number (%)	Median duration of work, days (min, max)	Number (%)	Median duration of work, days (min, max)	
Witnesses of the accident	3 (0.5)	7 (1, 11)	2 (0.7)	6 (1, 11)	1 (0.4)	7 (7, 7)	<1
Victims of the accident	2 (0.3)	2 (1, 2)	2 (0.7)	2 (1, 2)	0 (0.0)	— (–, –)	<1
Early liquidators	66 (11.5)	7 (1, 185)	50 (17.1)	7 (1, 185)	16 (5.7)	7 (3, 16)	~10
ChNPP personnel	9 (1.6)	317 (36, 1420)	8 (2.7)	379 (36, 1420)	1 (0.4)	225 (225, 225)	~1
Sent to assist the ChNPP staff	1 (0.2)	31 (31, 31)	1 (0.3)	31 (31, 31)	0 (0.0)	— (–, –)	<1
Staff of AC-605	5 (0.9)	31 (19, 63)	1 (0.3)	24 (24, 24)	4 (1.4)	46 (19, 63)	~1
Staff of Kurchatov Institute	2 (0.3)	157 (138, 175)	0 (0.0)	— (–, –)	2 (0.7)	157 (138, 175)	<1
Military liquidators	220 (38.6)	67 (6, 833)	33 (11.3)	65 (7, 366)	187 (66.7)	69 (6, 833)	48
Civilians Sent on Mission (CSOM) to the 30-km zone	181 (31.6)	19 (1, 1710)	121 (41.5)	18 (1, 1710)	60 (21.5)	21 (2, 103)	28
Staff of Combinat	4 (0.7)	458 (164, 1450)	4 (1.4)	458 (164, 1450)	0 (0.0)	— (–, –)	<1
Mixed	79 (13.8)	250 (4, 1710)	70 (24.0)	258 (4, 1710)	9 (3.2)	111 (9, 1710)	10
All	572		292		280		

TABLE 3

Distribution of Subjects According to Time of Work

First year of work	Number of subjects: Year of completion of work 1986	1987	1988	1989	1990	All
1986	291	50	20	11	36	408
1987		63	16	4	5	88
1988			46	4		50
1989				18	3	21
1990					5	5
1986–1990	291	113	82	37	49	572

TABLE 4

Number of Study Subjects with Official Doses Records (ODR) in the Registry and with ODR in their Possession

Category	Number of subjects	Number of ODR	Percentage in registry	Number of doses in personal records[a]	Percentage in personal records
Witnesses of the accident	3	0	0%	1	33%
Victims of the accident	2	0	0%	1	50%
Early liquidators	66	4	6%	7	11%
ChNPP personnel	9	0	0%	3	33%
Sent to assist the ChNPP staff	1	0	0%	0	0%
Staff of AC-605	5	1	20%	3	60%
Staff of Kurchatov Institute	2	2	100%	1	50%
Military liquidators	220	106	48%	174	79%
CSOM to the 30-km zone	181	11	6%	14	8%
Staff of Combinat	4	0	0%	2	50%
Mixed	79	1	1%	13	16%
Total	572	125	22%	219	38%

[a] Data acquired in course of interview include dose certificates possessed by subjects.

TABLE 5

Methods of Dose Assessment that were Considered in the Feasibility Study but Not Approved for Routine Dose Reconstruction

Method	Source of information/ type of sample	Sensitivity threshold	Applicability	Reason for rejection
Analytical Dose Reconstruction (ADR)	Interrogation after exposure, witness confirmation	No threshold	Not universal	Applicable only for highly skilled ChNPP employees, tends to overestimate actual dose
Electron paramagnetic resonance (EPR) dosimetry with teeth	Teeth extracted for medical reasons	50 mGy	Not universal	Applicable only for tooth donors; useful dose range only partially matches liquidators' dose range
Fluorescence *in situ* hybridization (FISH)	Blood samples	250–300 mGy	Universal for living subjects	Useful dose range does not match the dose range for most liquidators
Soft Expert Assessment Dosimetry (SEAD)	Interview	No threshold	Universal	Conceptually non-trivial, bad results of testing for some categories of liquidators

TABLE 6

Ranges of Estimated Bone Marrow Doses and Uncertainties for each Liquidator Category

		Arithmetic mean bone marrow dose (mGy)			
Category	Number of subjects	Average	Minimum	Maximum	Average GSD[a]
Witnesses of the accident	3	160	38	377	2.3
Victims of the accident	2	2880	2580	3170	3.4
Early liquidators	66	97	0.48	1010	2.0
ChNPP personnel	9	234	23	966	1.7
Sent to assist the ChNPP staff	1	44	44	44	1.9
Staff of AC-605	5	110	1	295	2.0
Staff of Kurchatov Institute	2	129	15	242	2.7
Military liquidators	220	71	0.01	554	2.1
CSOM to the 30-km zone	181	30	0.000037	694	2.0
Staff of Combinat	4	16	3	45	1.7
Mixed	79	164	0.40	3260	1.7
All	572	87	0.000037	3260	2.0

[a]Only the intrinsic uncertainty is considered. The average GSD shown for each category is the arithmetic mean of the GSDs of doses for subjects in that category.

TABLE 7

Collective Annual Bone Marrow Doses (person-Gy) According to Liquidator Category[a]

	Collective bone marrow dose (person-Gy)				
	First year of work				
Category	1986	1987	1988	1989	1990
Witnesses of the accident	0.48				
Victims of the accident	5.76				
Early liquidators	6.42				
ChNPP personnel	1.90	0.20			
Sent to assist the ChNPP staff	0.04				
Staff of AC-605	0.55				
Staff of Kurchatov Institute			0.01	0.24	
Military liquidators	9.92	3.70	1.28	0.61	0.17
CSOM to the 30-km zone	4.43	0.90	0.02	0.03	
Staff of Combinat		0.06			
Mixed	12.96		0.02		
All	42.46	4.87	1.33	0.88	0.17

[a]See Table 1 for the numbers of subjects in each category.

TABLE 8

Mean Annual Bone Marrow Doses (mGy) According to Liquidator Category[a]

	Mean bone marrow dose (mGy)				
	First year of work				
Category	1986	1987	1988	1989	1990
Witnesses of the accident	160				
Victims of the accident	2880				
Early liquidators	97				
ChNPP personnel	317	67			
Sent to assist the ChNPP staff	44				
Staff of AC-605	110				
Staff of Kurchatov Institute			15	242	
Military liquidators	91	76	30	36	57
CSOM to the 30-km zone	32	28	4	9	0.05
Staff of Combinat		16			
Mixed	166		17		
All	104	55	27	42	34

[a]See Table 1 for the numbers of subjects in each category.

TABLE 9

Averages of Arithmetic Mean Bone Marrow Doses (mGy) According to Time of Work[a]

	Average arithmetic mean bone marrow doses (mGy)				
	Year of completion of work				
First year of work	1986	1987	1988	1989	1990
1986	95	41	128	215	221
1987		49	62	155	35
1988			28	12	
1989				48	7
1990					34
All	95	46	59	105	169

[a] See Table 3 for the numbers of subjects in each category.