Electron Spin Resonance Analysis of Tooth Enamel Does not Indicate Exposures to Large Radiation Doses in a Large Proportion of Distally-exposed A-bomb Survivors

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ESR-estimated dose/Tooth enamel/Distally-exposed A-bomb survivors.

The atomic bombs in Hiroshima and Nagasaki led to two different types of radiation exposure; one was direct and brief and the other was indirect and persistent. The latter (so-called exposure to residual radiation) resulted from the presence of neutron activation products in the soil, or from fission products present in the fallout. Compared with the doses from direct exposures, estimations of individual doses from residual radiation have been much more complicated, and estimates vary widely among researchers. The present report bases its conclusions on radiation doses recorded in tooth enamel from survivors in Hiroshima. Those survivors were present at distances of about 3 km or greater from the hypocenter at the time of the explosion, and have DS02 estimated doses (direct exposure doses) of less than 5 mGy (and are regarded as control subjects). Individual doses were estimated by measuring CO2- radicals in tooth enamel with the electron spin resonance (ESR; or electron paramagnetic resonance, EPR) method. The results from 56 molars donated by 49 survivors provided estimated doses which vary from –200 mGy to 500 mGy, and the median dose was 17 mGy (25% and 75% quartiles are –54 mGy and 137 mGy, respectively) for the buccal parts and 13 mGy (25% and 75% quartiles: –49 mGy and 87 mGy, respectively) for the lingual parts of the molars. Three molars had ESR-estimated doses of 300 to 400 mGy for both the buccal and lingual parts, which indicates possible exposures to excess doses of penetrating radiation, although the origin of such radiation remains to be determined. The results did not support claims that a large fraction of distally-exposed survivors received large doses (e.g. 1 Gy) of external penetrating radiation resulting from residual radiation.

INTRODUCTION

Making continual improvements in the estimates of the individual doses of radiation received by atomic-bomb (A-bomb) survivors has been an important effort which should lead to a better understanding of the health effects of radiation exposure to humans. Since the 1980s, the yields of gamma rays and neutrons released from the bombs at detonation have been extensively discussed and re-calculated, and have been measured in exposed materials by physicists. Those efforts led to the creation of the Dosimetry System 1986 (DS86),1) and later to an improved Dosimetry System 2002 (DS02).2) Radiation doses from residual radiations, which emanated from neutron activated products in the soil and from fission products contained in the fallout in downwind areas or in the “black rain”, were estimated in DS86.3,4) However, an estimate of possible radiation doses acquired from inhaled radionuclides has not been made because no pertinent data are available for this purpose.

Currently, individual doses received from the residual radiation are not taken into account in the evaluation of cancer risk for several reasons. Those reasons include difficulties in assessing individual doses without detailed behavior records (location and time after the bomb), and the belief that the total estimated dose from residual radiation was relatively small compared with the dose derived directly from the bomb.3,4) However, some authors have suggested that the dose from residual radiation could be so large as to invalidate current estimates of cancer risk and dose
response, but attempts to physically validate such estimates have not been challenged. For example, Watanabe et al. used mortality data from Hiroshima and Okayama prefectures (Okayama is Hiroshima’s eastern neighboring prefecture) and estimated the standardized mortality ratios (SMRs) for all deaths, all cancers, solid cancers etc. and compared them with data from the control group in the Life Span Study cohort at the Radiation Effects Research Foundation (RERF) (i.e., those survivors with DS02 free-in-air [FIA] kerma doses below 5 mGy). The results indicated that, for example, the SMR from the control group was 18% higher in terms of solid cancer risks than the SMR from Hiroshima prefecture. This was used as an argument that a contribution from a residual radiation exposure could be quite significant. If one assumes that the difference is attributable entirely to an exposure from residual radiation, the 18% increase can be interpreted as the equivalent of having the entire control group exposed to 0.5 Gy (or it could be even larger if the chronic nature of the exposure is considered), since the mean excess relative risk (ERR) of the specific age group investigated here is estimated as 0.38 per Gy of immediate radiation from the bomb. Furthermore, if only one half or one third of the control subjects were exposed to the residual radiation (for example, through downwind exposures) while the others were not, the estimated dose would double or triple and would reach nearly 1 Gy in the affected individuals. The present report describes an attempt to measure CO2 radicals contained in the enamel component of teeth with the ESR method to determine if a large proportion of distally-exposed survivors (who were about 3 km or further away from the hypocenter) received large radiation doses.

**MATERIALS AND METHODS**

A total of 56 molars were examined. They were extracted for medical reasons and donated by 49 Adult Health Study (AHS) participants in the RERF program. Since the mean age of the donors at the time of radiation exposure was 18.9 years and the ESR measurements were mostly conducted in around 2005 (60 years after the exposure), the mean age of the enamel at the time of ESR measurements was about 70 years assuming that the molars were established when the donors were about 10 years old. Among the 56 teeth, seven were seriously decayed and contained a sufficient amount of enamel for measurement from only the buccal or lingual parts, which gave rise to 55 buccal and 50 lingual samples in total (49 paired samples from 42 individuals). While most of the survivors donated single molars, four survivors donated two and one survivor donated four molars. In the case of the multiple-tooth donations, means were calculated separately for buccal and lingual parts, and were used as representative values of each survivor (total 48 persons for buccal parts and 43 persons for lingual parts). Only molars were used because past studies indicated that other teeth, especially front teeth, often contain ESR signals which are unlikely to be related to radiation exposure while the signals look indistinguishable from radiation-related ones. Wisdom teeth were also excluded from this study because of the large variation in the age at which they erupt. The tooth samples used in this report were donated from A-bomb survivors who were ≥ 10 years old at the time of the bomb’s detonation. That criterion was used partly to maximize the number of samples which would be available for the study, and also to minimize the number of cases which could lead to a false negative. Specifically, testing molars from younger survivors who were less than 10 years of age at the time of the exposure increases the probability of sampling teeth which had not yet finished forming their enamel when they were exposed to A-bomb radiation. This is because the mean age of eruption is 11 to 12 years old for the second molars (however, it is about 6 years old for first molars). The breakdown of the donor ages is as follows: there was one survivor at the age 10, one at age 11, 4 at age 12, 8 at ages 13–15, and 32 ≥ 16 years old. The tooth donors had a DS02 FIA kerma dose below 5 mGy; specifically, 22 had an estimated dose of 0 mGy, 23 had a dose of 1 mGy, 2 had a dose of 3–4 mGy. Those subjects who had a record of radiotherapy were excluded from this study. The study plan was approved by the institutional review boards (IRBs) at RERF.

To identify possible cases of excess exposures originating from low energy dental X rays, each tooth was cut into two parts (the buccal and lingual parts) for subsequent enamel isolation by either mechanical or chemical techniques as has been done in our previous studies. To identify radiation-related signals, the selective saturation method was used. In order to estimate radiation doses from the ESR signal intensity which was thus obtained, a calibration curve was used, which consisted of pooled enamel from 20 wisdom teeth donated by young residents (i.e., 17 to 23 years old) of Fukushima prefecture (located in northern Japan) in the mid 1980s. The young age of the donor was intended to minimize exposures of the samples to dental X rays or any other medical radiation. This pooled sample was then divided into 20 aliquots, and each aliquot was irradiated with a different dose of 60Co gamma radiation (i.e., duplicate samples for doses of 0, 0.1, 0.2, 0.3, 0.4, 0.5, 1.0, 2.0, 3.0, and 4.0 Gy) under standard exposure conditions at a facility in the Chiyoda Technology Laboratory (Ibaraki, Japan). The calibration curve was expressed as

\[ y = a + bx \]

where \( y \) is the ESR signal intensity, \( a \) and \( b \) are coefficients, and \( x \) is the known radiation dose. The ESR signal intensity in a survivor’s enamel (\( y_i \)) was then substituted to solve for the radiation dose (\( x \)).

For screening purposes, tooth samples were measured...
only once, while for some specific samples, ESR measurements were repeated several times. The results of the repeated measurements indicate that the standard deviation of dose estimates for replicate measurements on identical samples is about 25 to 50 mGy (see Table 1).

A subset of the survivors previously had cytogenetic data collected prior to the present study. That data was acquired with either conventional Giemsa staining or with the more recent fluorescence in situ hybridization (FISH) method, and the results were compared with the ESR-estimated doses.

**Statistical method**
The two-sample Wilcoxon rank-sum (Mann-Whitney) test was used for comparison of the mean estimates between the two age groups (≤15 years old vs. ≥16 years old at the time of exposure).

**RESULTS**

**Distribution of ESR dose estimates**
Distributions of the ESR dose estimates are shown in Fig. 1. The buccal parts gave rise to dose estimates which varied from −100 mGy to over 500 mGy, and the median estimate was 17 mGy (25% and 75% quartiles are −54 mGy and 137 mGy, respectively) (Fig. 1A). Similarly, the lingual parts produced ESR estimates which varied from about −200 mGy to 400 mGy, and the median was 13 mGy (25% and 75% quartiles are −49 mGy and 87 mGy, respectively) (Fig. 1B), which was not very much different from that for the buccal parts. In order to test for a possibility that some of the molars donated by young survivors were not fully developed at the time of radiation exposure, the donors were grouped according to their age in 1945 (e.g., 17 survivors were ≤15 years old vs. 32 survivors who were ≥16 years old). The median doses were 7 mGy vs. 24 mGy for the buccal parts, and −31 mGy vs. 39 mGy for the lingual parts, but the differences were not statistically significant for either the lingual or buccal parts (Mann-Whitney test, \(p = 0.21\) and 0.09 for the buccal and lingual parts, respectively). Thus, it appears that our restriction to use molars whose donors were ≥10 years old at the time of exposure did not include many teeth that were immature at the time of exposure. As seen from the histograms in Fig. 1, the dose distribution is skewed toward higher doses. For example, four lingual samples showed distinctly higher estimates of over 300 mGy while none gave rise to an estimate between 200 and 300 mGy. Thus, if samples over 300 mGy were considered to be unusual and were excluded, the dose distribution of the remaining samples would move closer to normal, while the medians became only slightly smaller to 13 mGy for the buccal portions and −20 mGy for the lingual portions.

**ESR-estimated dose vs. distance from hypocenter**
Figure 1 also shows the ESR dose estimates in relation to the survivor’s distance from the hypocenter of the bomb. It is clear that the apparent higher-dose cases are clustered at distances around 3,000 m where the majority of the cases were located. Hence, no particular relationship is observed between the estimated dose and the distance from the hypocenter.

![Fig. 1. ESR estimates of tooth dose in relation to distance from the hypocenter. Panels A and B show results from the buccal and lingual parts, respectively. Also shown on the right are histograms of estimated doses to the respective parts. The horizontal dotted line in each panel indicate median dose of all the estimates.](image-url)
**Relationship between the buccal and lingual doses for each tooth**

In order to determine if the individual variations seen in Fig. 1 are due to random measurement errors or to intrinsic characteristics of the samples, ESR dose estimates for the buccal parts were compared with those for the lingual parts (Fig. 2). It was found that the two estimates correlate reasonably well ($r^2 = 0.668$), which indicates that the apparent wide variation seen in Fig. 1 is primarily due to intrinsic characteristics of each tooth and not to measurement errors. It is also clear that the slightly larger mean estimate for the buccal portions compared to that for the lingual portions does not seem to be due to a small number of specific samples, but rather to a general trend seen over many samples.

Figure 2 also indicates that there are 3 samples whose buccal and lingual dose estimates are consistently larger than 300 mGy, and three additional samples gave the estimates of $> 300$ mGy for only the buccal (two cases) or lingual (one case) part. Unfortunately, none of the six donors had records of their personal behavior after the bomb. Not all the points shown in Fig. 1 are shown in Fig. 2 because 7 teeth had an insufficient amount of enamel and measurements were made from only the buccal or lingual parts.

**Survivor’s direction from the hypocenter at the time of the bomb**

After the explosion of the bomb, a fraction of both uranium (which did not undergo a nuclear chain reaction) and fission products descended to the ground (and a part of them were contained in the “black rain”), and the location of their deposition would have been dependent on the weather. The direction of the rain was mainly north to northwest from the hypocenter (but the contour of the rain area includes the hypocenter),$^{15}$ thus, it is important to know not only the survivor’s distance from the hypocenter, but also their direction from the hypocenter. The results shown in Fig. 3 indicate that there were four survivors who were within the estimated area of black rain and the individual estimated doses are shown in Table 1. Survivors 1 and 4 in Fig. 3 reported they were exposed to the rain (they became wet), and their ESR dose estimates appear to be slightly larger than that of survivor 2 (who reported no exposure to the rain) or survivor 3 (no information available). But exposures are not outstandingly high when compared with the estimated doses from

![Fig. 2. Relationship between buccal and lingual doses of each tooth for 42 survivors ($r^2 = 0.668$). The solid line indicates results of a linear regression and the dotted line indicates $y = x$.](image)

![Fig. 3. Location of 49 survivors at the time of the bomb. “+” indicates the hypocenter; open circles “○” indicate the location of each survivor; contour with a solid line indicates the heavy rain area; and contour with a broken line indicates the light rain area. The numbers 1 to 4 indicate the locations of four survivors who were in the area of the black rain (see Table 1).](image)

<table>
<thead>
<tr>
<th>Survivor number in Fig. 3 (tooth ID, position*)</th>
<th>ESR-estimated dose (mGy)**</th>
<th>Distance from hypocenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (R1276, R7U)</td>
<td>Buccal dose 295 ± 53 (228)</td>
<td>3346 m</td>
</tr>
<tr>
<td></td>
<td>Lingual dose 210 ± 60 (157)</td>
<td>3491 m</td>
</tr>
<tr>
<td>2 (R556-4, R7L)</td>
<td>51 ± 56 (119)</td>
<td>3491 m</td>
</tr>
<tr>
<td></td>
<td>55 ± 24 (77)</td>
<td></td>
</tr>
<tr>
<td>2 (R556-1, L6L)</td>
<td>153 ± 25 (155)</td>
<td>2924 m</td>
</tr>
<tr>
<td></td>
<td>43 ± 28 (49)</td>
<td></td>
</tr>
<tr>
<td>3 (R413-1, R6U)</td>
<td>−19 ± 53 (2)</td>
<td>2924 m</td>
</tr>
<tr>
<td></td>
<td>212 ± 64 (163)</td>
<td></td>
</tr>
<tr>
<td>3 (R413-2, R7U)</td>
<td>30 ± 57 (−40)</td>
<td>2826 m</td>
</tr>
<tr>
<td></td>
<td>−56 ± 25 (−76)</td>
<td></td>
</tr>
<tr>
<td>4 (R552, 76/7L)</td>
<td>93 ± 42 (162)</td>
<td>2826 m</td>
</tr>
</tbody>
</table>

*First digit, R = right, L = left in the mouth, ? = unknown; second digit, 6 = first molar, 7 = second molar; third digit, U = upper jaw, L = lower jaw.

**Results are shown as the mean ± SD of four independent measurements. The numbers in the parentheses indicate the estimates obtained in the first screening and are shown in Figs. 1, 2 and 4.
other samples examined in this report (Fig. 1). In other words, at least for the two survivors examined here who reported that they were exposed to the rain, the radiation doses possibly received from the rain are not large enough to be easily recognized over the observed variation among the distally-exposed individuals.

The relative paucity of tooth donors located at either the northwest or northeast quadrants (who have DS02 doses of less than 5 mGy) as seen in Fig. 3 is due to the rugged terrain of Mt. Mitaki and Mt. Futaba, respectively. Compared with the numbers of AHS subjects in each quadrant (who were requested for donation of extracted teeth) with estimated dose of < 5 mGy, the actual numbers of donors may look underrepresented in the northwest and southwest quadrants; namely, 2 donors out of 308 members (0.6%) and 7 out of 834 (0.8%), respectively, as compared with 9 out of 556 (1.6%) and 31 out of 1370 (2.2%) in the northeast and southeast quadrants, respectively. However, the difference in the ratio (the number of donors to the number of members) among the four quadrants was not statistically significant (Fisher’s exact test, p = 0.056).

Figure 4 shows plots of ESR dose estimates in relation to survivor’s direction relative to the hypocenter. Here the x-axis indicates degrees counter-clockwise from the east and the y-axis indicates the ESR estimates. It is clear that few cases exist between the northeast and west (45 to 180 degrees) as seen in Fig. 3, and that the highest dose points are located in the direction between the south (270 degrees) and the east (360 degrees) where the majority of the samples were located. Thus, there appears to be no specific direction which is related to high ESR-estimated doses.

Comparisons between ESR dose estimates and chromosome aberration frequencies

Some of the survivors were previously examined to determine the frequency of chromosome aberrations (specifically translocation frequencies) in their blood lymphocytes. That frequency is known to be a good quantitative indicator of radiation exposure. While our previous study clearly showed a good correlation between the ESR-estimated dose and the translocation frequency, the same comparisons here at low doses did not indicate an increasing trend for translocation frequencies with increases of the ESR estimates (Fig. 5). The dotted line indicates the expected net increase of translocation frequency with dose, which was derived from the dose response curve for the induction of dicentrics (the...
unstable counterpart of translocations) following irradiation of blood lymphocytes in vitro. The results indicate that occasional small increases in the translocation frequency (e.g., over 4%) are not correlated with radiation dose estimates based on the ESR measurements, which indicates that they are not necessarily caused by systemic exposure to high energy photons.

**DISCUSSION**

No evidence that a large proportion of distally-exposed survivors received large doses

There is a long history of arguments about the magnitude of the dose received from residual radiation. It is certain that exposures from both neutron activation and fallout depended largely on individual behavior after the bomb, and radiation doses from the fallout depended not only on the distance from the hypocenter but also on the direction from the hypocenter. Further, soil samples were not systematically collected and hence measurements of soil radioactivity to clarify the fallout distribution are very limited. Those conditions have made estimating radiation doses from the fallout (including black rain) an extremely difficult task. In the present study, 56 molars were examined from 49 survivors who are considered to be the control group (i.e., DS02 FIA kerma doses of below 5 mGy), but the results did not suggest an exposure to a large dose such as 1 Gy from any source. Thus, it can be concluded that either the mean dose from residual radiation was small and/or the fraction of survivors affected by a large (but hypothetical) amount of residual radiation from external sources is small (i.e., internal exposures may not be detected by the ESR).

Possible pitfalls in underestimating the dose

In the present study, we used the calibration curve method to estimate individual doses, which consisted of pooled enamel from wisdom teeth. The teeth were selectively obtained from young patients of about 20 years old so that exposures from dental or medical X rays would be relatively small. The curve is expressed as $y = a + bx$ where the value $a$ represents the mean background signal intensity of a pair of aliquots (duplicate samples) derived from pooled enamel of wisdom teeth from 20 different individuals. Therefore, if the tested samples had not been exposed to radiation, it is expected that nearly one half of the samples would give rise to ESR signal intensities ($y_i$) smaller than $a$, and hence negative estimates in the $x_i$ (Fig. 1) because individual $y_i$ should vary to some extent for each test sample. (It is noted that negative values would not be produced if the “additive dose method” were used to estimate the dose.) Given the older average age in the survivor group (i.e., the mean donor age of the test sample was 18.9 years old in 1945) vs. the Fukushima group (the mean donor age of wisdom teeth used to establish a calibration curve was about 20 years old in the mid 1980s), the difference in the mean estimates is in the right direction, and although the sample size is small, the results are still consistent with the age difference between the two groups (i.e., 45 years), within the uncertainty involved.

Another possibility is that the negative estimates could have been caused by an artifact; for example, although it is very unlikely, one of the 20 wisdom teeth used to establish the calibration curve had been exposed to medical radiation. Since the enamel from 20 teeth was first pooled and then divided into 20 aliquots, such a condition would have given rise to a uniform increase of the signal intensity of all samples used for establishing the calibration curve, and in turn this could have led to a consistent underestimate of the dose in all of the test samples. However, this possibility is not supported by our past experience; namely, shared measurements of the same enamel samples from the Mayak nuclear workers at both RERF and GSF in Germany showed that the paired sets of the estimated doses were in close agreement.17)

Finally, while measurement errors of the same samples are 25 to 50 mGy, inter-sample variation is much larger (Table 1), even between buccal and lingual parts of the same teeth (Fig. 2). At least three possibilities can be raised to explain the observations; namely, different levels of exposure to radiation (A-bomb and/or medical radiation), different levels of contamination of dentin (this affects the total weight), and different radiosensitivity of the teeth—although the last possibility is probably low as the inter-tooth variability is reported to be less than 10%.18).

Possible sources of the radiation dose estimate measured by ESR

The slightly higher median estimates of buccal parts as compared with that of lingual parts (17 mGy vs. 13 mGy for all the samples, or 13 mGy vs. –20 mGy for those below 300 mGy) may be attributed to several sources. One possibility is exposures from dental X rays (low energy photons), which in most cases come from outside of the mouth, and one exposure may give rise to an ESR signal equivalent to a $^{60}$Co gamma-ray exposure of about 2 mGy to the whole molar (or about 4 mGy for buccal and 0.5 mGy for lingual parts).19,20) Another possibility is related to the observation that the outer part of a tooth tends to give rise to a larger ESR signal than the inner part. The trend is most pronounced in the front teeth; for example, the maximum difference in the ESR-estimated doses between the two parts varied from > 1 Gy equivalents for incisors to 0.3 Gy equivalents for second bicuspid teeth, whereas molars usually show much smaller differences which are often difficult to distinguish from random measurement errors.21) This may not necessarily mean, however, that molars are totally free from this buccal versus lingual problem, but that they may be only minimally affected. If this were the case, the assumption that the ESR estimates from the two parts of a tooth should be equal for molars
might be naïve, and buccal parts of molars may actually have slightly larger signals than the lingual parts. It has been suggested that the observed difference between the two halves is due to exposure from ultraviolet light (UVL) contained in solar light, but this theory does not seem to be applied to molars as the buccal parts face so close to inner cheek and are hence difficult to be exposed to UVL. It is still not practical to distinguish ESR signals caused by UVL from those caused by ionizing radiation.

In contrast, estimates of > 300 mGy (Fig. 1) seem to require additional sources of exposures; e.g., exposures from direct radiation from the bomb (i.e., the survivor’s exposure might have been more proximal than reported),\textsuperscript{22} from medical radiation including radiotherapy for cancer (but the information was not collected), or from residual radiation. With regard to radiotherapy, one case was encountered (not included in the present report) in which the buccal and lingual dose estimates were 300 mGy and 600 mGy, respectively (Hirai, unpublished observation). The donor was found to have undergone radiotherapy for cervical cancer (2 Gy of gamma rays × 33 exposures) prior to the extraction of the molar. Although a careful study is necessary to estimate the tooth dose from scattered radiation in order to determine contributions from radiotherapy, this case could have been misinterpreted (as a result of possible exposure to residual radiation, for example) if the medical history had failed to provide the radiotherapy information. Another potential source of medical exposures is CT scans, but this does not seem to affect the ESR results. Specifically, eight molars (included in the present report) were examined from eight donors who had histories of CT scans of the head, but multiple examinations did not indicate any larger ESR estimates for these subjects compared with the estimates from cases subjected to single CT examination. The results are consistent with the estimated doses on the order of a few tens of mGy following head CT scans.\textsuperscript{23}

**ESR vs. cytogenetic dose estimates**

When the chronic nature of exposures from the residual radiation is considered, the ESR method is superior to the cytogenetic method for retrospective dose estimation because radical production in tooth enamel is independent of the dose rate (e.g., the ESR method can be used even for archeological dating of calcified samples).\textsuperscript{24} In contrast, induction of chromosome aberrations is well known to depend on the dose rate (there is a decreased radiation effect for protracted exposures). This was the situation in the study of the Mayak nuclear workers; the ESR tooth dose estimates and the film-badge doses were in close agreement\textsuperscript{15} while a dose response of translocations by the FISH method showed an estimated slope of only about 1% (genome-equivalent frequency) per Gy, which is much smaller than the slope under acute exposure conditions. Since control subjects aged over 60 years old often show a 1 to 2% rate of translocations,\textsuperscript{20} any attempt to estimate chronic doses below 2 Gy by using cytogenetic tests does not seem useful. In this context, although one may raise the possibility that the survivors who showed elevated translocation frequencies, e.g., ≥ 4% (Fig. 5) could have been exposed to residual radiation, it does not seem likely because an acute gamma-ray dose of about 540 mGy is required to increase the translocation frequency by 3%\textsuperscript{16} above the possible spontaneous level of 1%, and such doses as high as 540 mGy should be readily measurable by ESR if the dose is derived from external highly penetrating radiation.

**Compatibility with physical estimates from neutron activation**

The estimated dose from neutron activation of the soil can be summarized briefly as follows.\textsuperscript{26} At the hypocenter in Hiroshima, the total cumulative dose of residual radiation from time zero to infinity was estimated to be 800 mGy, of which 600 mGy was released within the first 24 h after the explosion. In those calculations, radiation doses from the decay of \(^{26}\text{Al}\) were not taken into account since the radioactivity should have become essentially zero at 30 min after the explosion (the half life is 2.2 min).\textsuperscript{31} These assumptions appear to be reasonable for survivors who were distally exposed but entered the city shortly after the explosion. Furthermore, the degree of neutron activation fell off rapidly with increasing distances from the hypocenter, and at a ground distance of 500 m from the hypocenter, the total dose was estimated as 91 mGy, of which 68 mGy was released within the first 24 h in Hiroshima. Since the central part of the city was difficult to reach on the day of detonation due to extensive fire, it seems that most people entered the city (and stayed) starting from the next day. In this case, the estimated cumulative dose is, at most, approximately 200 mGy (at the hypocenter) to 23 mGy (at 500 m from the hypocenter). Thus, some survivors could have received radiation doses of, say, 50 to 100 mGy, which is not measurable with high precision with the present ESR method. Use of an improved technique, the deconvolution method of the ESR signal processing,\textsuperscript{27} would improve the current method to permit the detection of lower doses. Even so, however, it would still be a difficult task to attribute the measured dose to a specific source of radiation such as residual radiation or medical exposures.

**Possibility of an alternative approach**

To better understand the levels of doses received from residual radiation, it is important to reduce the variation in the personal behavior after the bomb. This may be achieved by examining molars from a group of people who were not in the city at the time of the bomb detonation, but who entered the city shortly afterwards and spent several days there as a group. One example consists of groups of men who were ordered to come to Hiroshima on the day of det-
onation and who stayed in the city for about a week together to rescue survivors and help with cremations. Among such groups, the Kahoku troop is well recognized because their activities were broadcast in 1987 in a TV program. In that program, a cytogenetic study was conducted for ten members of the troop, and the largest dose estimate was 130 mGy (one person) followed by 100 mGy (three persons), 60 mGy (one person), and less than 10 mGy (five persons). We thought it would be valuable if the cytogenetic results could be confirmed by examining tooth samples anew from the members of the troop. Unfortunately, however, a preliminary survey indicated that quite a large fraction of the troop members were already deceased (Mr. H. Herai and Mr. T. Okada, personal communications to N.N.). Therefore, when we think of the current age of the troop members (mid 80s or older), the number of molars that are remaining, and which might be extracted for medical reasons and donated for the ESR measurements, it seems that the opportunity has been lost to examine tooth samples from such troop members.

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