Appendix I

DOSIMETRIC ANALYSIS

Post-accident dosimetry has two main objectives:

(1) to provide input to the clinical prognosis, especially in anticipating difficulties in medical management associated with bone marrow depression; and

(2) to provide data to help improve the understanding of the effects in man of acute exposure to high doses of radiation.

In this accident only crude physical dose estimates were available in the critical period for clinical decisions concerning bone marrow depression and the expression of localized injury to the skin and underlying tissues. Thus, most of the dosimetric analysis performed was directed towards the second objective. Under the IAEA's assistance programme, dosimetry was principally carried out by REAC/TS. A summary of the dosimetric procedures, based on the interviewing of patients, data relating to the source, and radiobiological and cytogenetic considerations, is presented here. The sequence of presentation reflects the refinement of the dose estimates over time.

AI.1. INITIAL ESTIMATES

When the accident in San Salvador was first reported to the IAEA and assistance was requested, the range of whole body doses sustained by the three irradiated workers was estimated in San Salvador to be from 4 to 6 Gy. The workers had not been wearing personnel dosimeters, and this crude estimate was based largely upon the signs and symptoms of acute radiation injury expressed by the patients. Attempts were made to estimate the doses received on the simplified basis of a point source and the exposure times and positions estimated by the workers. However, the whole body doses so estimated were so high (of the order of 40 Gy) as to be manifestly unrealistic.

In view of the deteriorating medical condition of the patients, it was decided in mid-February to transfer them to the Angeles del Pedregal Hospital in Mexico City. There was already a mutual assistance agreement between El Salvador and the Angeles del Pedregal Hospital. By Day 33 (Thursday 9 March), all three patients had been transferred to this hospital, where the medical team made preliminary dose estimates for each patient on the basis of haematological analysis and the extent and severity of local radiation injury. At this stage it was evident that the irradiation had been very non-uniform. The orders of magnitude of doses to the lower limbs and the equivalent whole body doses that were estimated on Day 32 (Wednesday 8 March) upon admission to the Angeles del Pedregal Hospital are presented in Table II.

TABLE II. ESTIMATES OF DOSES TO THE LOWER LIMBS AND EQUIVALENT WHOLE BODY DOSES MADE ON DAY 32 (WEDNESDAY 8 MARCH) BY REAC/TS, OAK RIDGE, USA, FOR PATIENTS A, B AND C

Patient	Dose to lower limbs (Gy)	Whole body dose (Gy)
Patient A	100	6–8
Patient B	100	6–8
Patient C	10	2–4

AI.2. DOSE PROFILES FROM BIOLOGICAL EFFECTS

From Day 32 to Day 36 (Wednesday 8 to Sunday 12 March), the medical team at the Angeles del Pedregal Hospital worked together with an IAEA expert group from REAC/TS which assisted in both medical and dosimetric aspects. Refined assessments of the dose distributions were made on the bases of the onset and extent of epilation and dry and wet desquamation and early signs of necrotic lesions. These assessments, which did not substantially change afterwards, are presented in Fig. 17.

AI.3. CYTOGENETIC ANALYSIS

Blood samples for cytogenetic analysis were collected from the patients upon their admission to the Angeles del Pedregal Hospital: from Patient A on Day 24 (Tuesday 28 February), from Patient B on Day 26 (Thursday 2 March) and from Patient C on Day 33 (Thursday 9 March). Further samples were collected on Day 32 (Wednesday 8 March) and were independently analysed by the specialist centres at REAC/TS in Oak Ridge and the Angeles del Pedregal Hospital. The results of the cytogenetic analyses at the two centres, summarized in Table III, were in very good agreement. Further information on cytogenetic analyses by REAC/TS is presented in Tables IV and V.

REAC/TS staff also estimated from the cytogenetic data what proportions of the patients' bodies received radiation doses (for a detailed description of the methods used, see IAEA Technical Reports Series No. 260[3]). In brief, homo-

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Biological Dosimetry: Chromosomal Aberration Analysis for Dose Assessment, IAEA Technical Reports Series No. 260, IAEA, Vienna (1986).

TABLE III. RESULTS OF CYTOGENETIC ANALYSES MADE BY THE ANGELES DEL PEDREGAL HOSPITAL, MEXICO CITY, AND REAC/TS FOR PATIENTS A, B AND C

	Angeles del Pedregal Hospital		REAC/TS	
Patient	Dose estimate (Gy)	95% confidence interval Gy)	Dose estimate (Gy)	95% confidence interval (Gy)
Patient A	8.19	7.62–8.59	7.97	7.29–8.65
Patient B	3.58	3.40–3.72	3.77	3.52–3.96
Patient C	2.96	2.73–3.17	2.92	2.74–3.10

TABLE IV. CYTOGENETIC DOSE ESTIMATES MADE BY REAC/TS FOR PATIENTS A, B AND C

	Patient A	Patient B	Patient C
Number of metaphases scored	35	350	500
Number of dicentrics observed	131	306	266
Dicentrics·cell^{-1}	3.74	0.87	0.53
Equivalent whole body dose estimate (Gy)	7.97	3.77	2.92
95% confidence interval (Gy)	7.29–8.65	3.52–3.96	2.74–3.10
Dose to exposed fraction (Gy)	8.27	4.41	3.24
95% confidence interval (Gy)	7.56–8.99	4.15–4.67	3.04–3.45
Percentage of lymphocytes exposed	99%	91%	92%

Source: Cytogenetic Dosimetry Laboratory, Oak Ridge Associated Universities, Radiation Emergency Assistance Center/Training Site (REAC/TS).

TABLE V. DISTRIBUTION OF DICENTRICS IN FIRST DIVISION METAPHASES OF LYMPHOCYTE CULTURES INITIATED ON DAY 35 (SATURDAY 11 MARCH) FOR PATIENTS A, B AND C

		Patient A	Patient B	Patient C
Number of metaphases scored		35	350	500
Number of dicentrics observed		131	306	266
Number of cells with n dicentrics				
n = 0	Observed	3	170	304
	Expected	0.8	147	294
n = 1	Observed	4	104	143
	Expected	3	128	156
n = 2	Observed	2	44	39
	Expected	6	55	41
n = 3	Observed	6	19	11
	Expected	7	16	7
n = 4	Observed	7	10	3
	Expected	7	3.5	1
n = 5	Observed	4	2	—
	Expected	5	< 1	—
n = 6	Observed	7	—	—
	Expected	3	—	—
n = 7	Observed	1	1	—
	Expected	1 6	< 1	—
n = 8	Observed	< 1	—	—
	Expected	< 1	—	—
Index of dispersion		1.18	1 44	1 14
Unit normal deviation		0.74	5.90	2.28

Source: Cytogenetic Dosimetry Laboratory, Oak Ridge Associated Universities, Radiation Emergency Assistance Center/Training Site (REAC/TS).

geneous whole body irradiation results in a Poisson distribution of dicentric aberrations among the blood cells. Non-uniform exposure produces an overdispersed distribution, which may be approximated by a Poisson distribution of aberrations distorted by a fraction of undamaged cells. By this analysis, the fractions of cells scored that had been damaged by irradiation and the doses to these fractions were estimated.

Additional calculations were made to correct for the effects of interphase death and mitotic delay, both of which reduce the number of irradiated cells observed. It was estimated (see Table IV) that the proportion of the body irradiated exceeded 90% for each patient. In each case the estimated dose to the exposed fraction of the body was only a few per cent higher than the 'estimated equivalent whole body dose'.

AI.4. RECONSTRUCTION OF THE ACCIDENT

Attempts were made to reconstruct the accident on the basis of interviews with the patients and others in order to estimate the doses received. The main factors of which knowledge is required in order to make such estimates are:

(a) the distribution of radioactivity in the source module;
(b) the position of the source module at the time of the accident;
(c) the positions of the exposed persons relative to the source and to any shielding;
(d) the durations of exposure for each configuration.

Good data were available for (a), but the other details, particularly those for (c) and (d), were not precise enough to permit reliable estimation of doses from the reconstruction alone. However, as described in the following, consideration of these details in conjunction with the biological effects of the doses helped in forming and validating an understanding of what happened in the accident. (See Figs 2–6.)

The physical size of the source module and the distribution of radioactivity within it were well known for the undamaged source module. For the normal operating position of the source rack, the dose rates at various points in the radiation room could be calculated and corrections could be made for gamma attenuation by the product boxes and for room scatter.

However, it soon became known that the source had not been in the normal operating position at the time of the accident. The irradiator operator, Worker A, said that the source module had been intact but had become stuck while being lowered from the operating to the storage position. The exact position of the source rack during the accident could not be determined since it was freed by the workers and lowered into the pool.

Since the dose rate decreases rapidly with distance from the source, knowledge of the relative positions of the source and of the workers is especially important if the workers were close to the source, which they were. The calculation of the radiation doses received also requires knowledge of the length of time for which each person was exposed in each different position relative to the source. Further information would help to refine the calculations; however, such refinements are only useful if the basic details are accurately known. In the present case, the exposure times and the configurations of the source and of the three workers could not be exactly determined.

Each of the three men was interviewed on several occasions in an attempt to determine his probable positions and that of the source. As might be expected, their recollections differed and varied somewhat with each telling. On the basis of these statements, adjudged in conjunction with the resultant biological injury and the physical dimensions of the facility, it seems that the source became stuck with the top of the upper source module about 10 cm above the upper platform. The normal operating position of the source rack is with its top about 30 cm above the upper platform. In the accident, the source was raised briefly by 10 cm before being lowered into the pool.

Dose rates in the radiation room were calculated for a 10 cm x 10 cm x 10 cm matrix, on the assumption that the source was in the position just described. Figure 13 shows resulting horizontal isodose lines at one metre above the upper platform and Figs 14 and 15 show vertical isodose lines half-way along the length of the source rack. The actual isodose lines would have been asymmetrical owing to the uneven loading of the source module.

The next requirement was to determine the positions of the individuals during their exposure. Worker A reported that he initially entered the radiation room to examine the pistons. He estimated that he was in the room for five minutes. The dose he received in this period was enough to induce nausea but was probably only a fraction of the dose he later sustained when he was working close to the source, and has therefore not been considered in detail. He then left the room to seek help and returned later with Workers B and C.

All three men then entered the radiation room. They removed some of the product boxes and freed the source rack, lowering it to the storage position in the pool. From the interviews with the three men it seems that while so doing their positions on the upper level were as shown in Figs 13 and 16 for most of the period of exposure. They did not remain in fixed positions, of course, but such an approximation serves as a reasonably good model. Worker C may also have been on the lower level for some time; however, the present dose estimates are based on all three workers having received the principal share of their doses while on the upper level.

The greatest uncertainties in the dose calculations were in the lengths of time for which each man was exposed. Each mentioned different time intervals, ranging from a few minutes to ten minutes. The exposure intervals were also estimated on the bases of the probable dose rates for the positions in which the exposures occurred and the specific biological effects of exposure on the men (see Figs 18–20), which indicated the doses received. By this iterative process, the best estimate of their exposure time was about three minutes. Knowledge of the distribution of biological injury also helped in determining the positions in which the men were exposed.

Patient A described his position as shown in Figs 13, 15 and 16. His pattern of desquamation (see Fig. 18) was assessed on the basis that a dose of at least 15 Gy is necessary to cause dry desquamation and a dose of 30 Gy or more for wet desquamation. The results suggest an exposure period of about three minutes. Patient A's

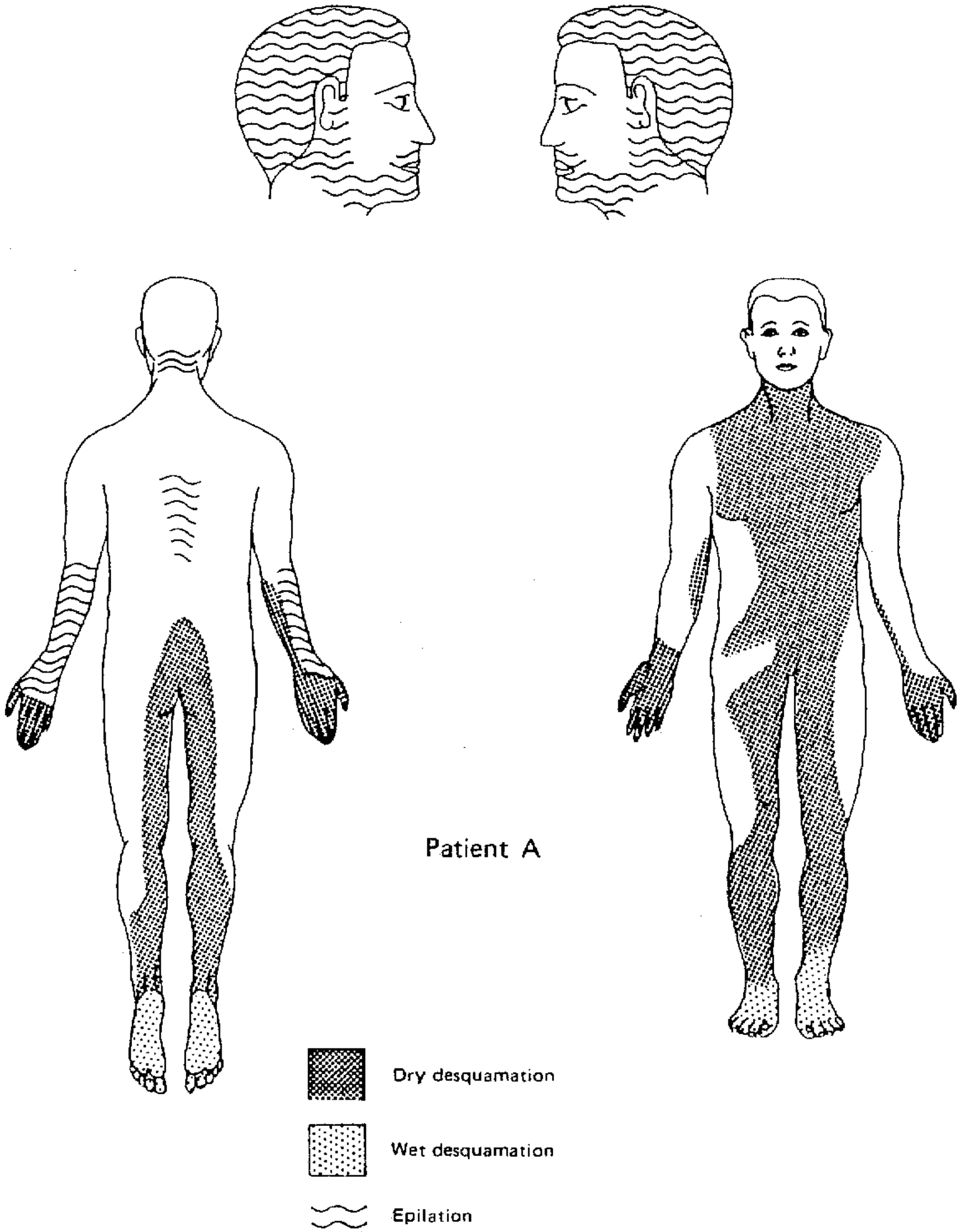

FIG. 18. Patient A: corporal distribution of effects of exposure. (Source: REAC/TS.)

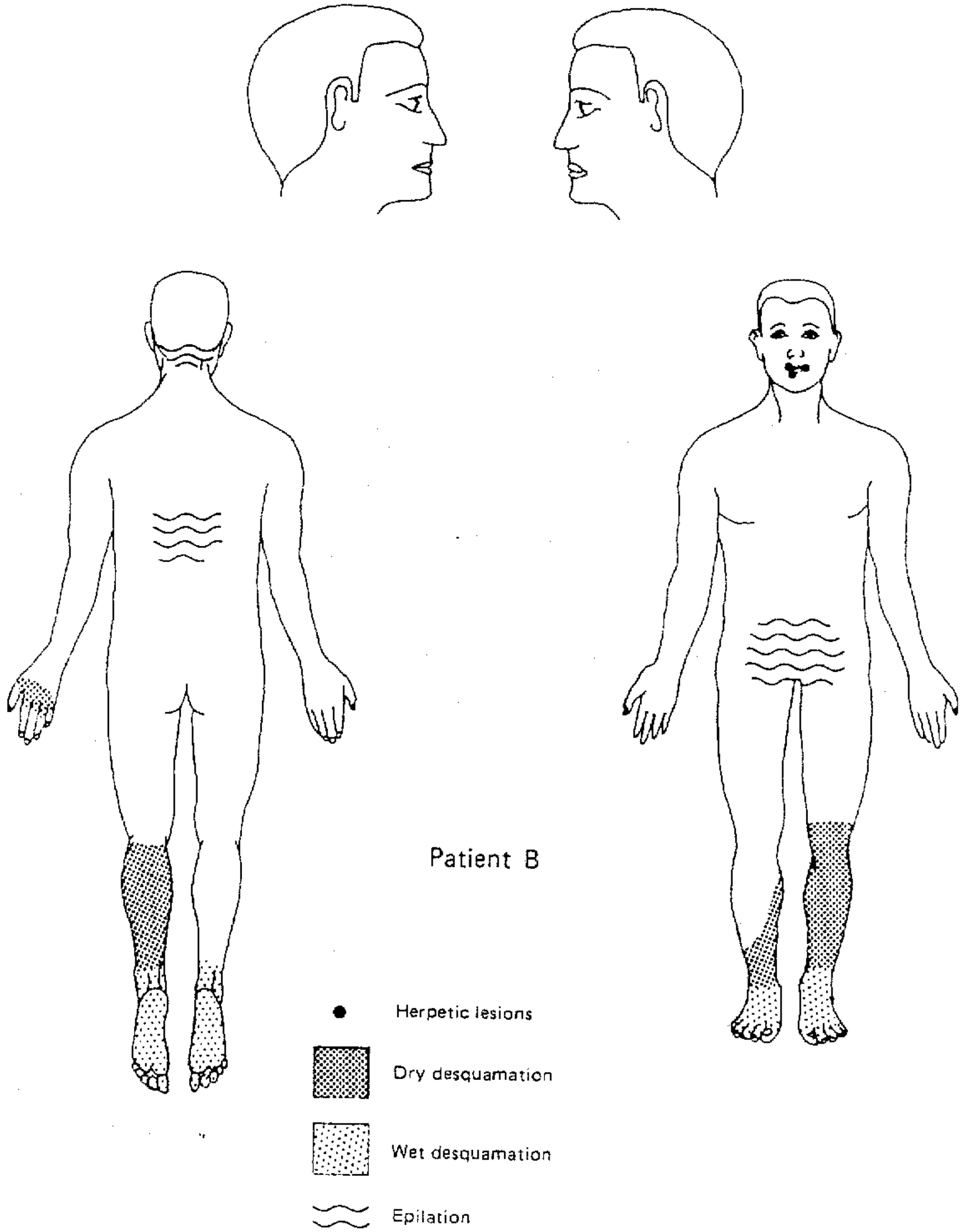

FIG. 19. Patient B: corporal distribution of effects of exposure. (Source: REAC/TS.)

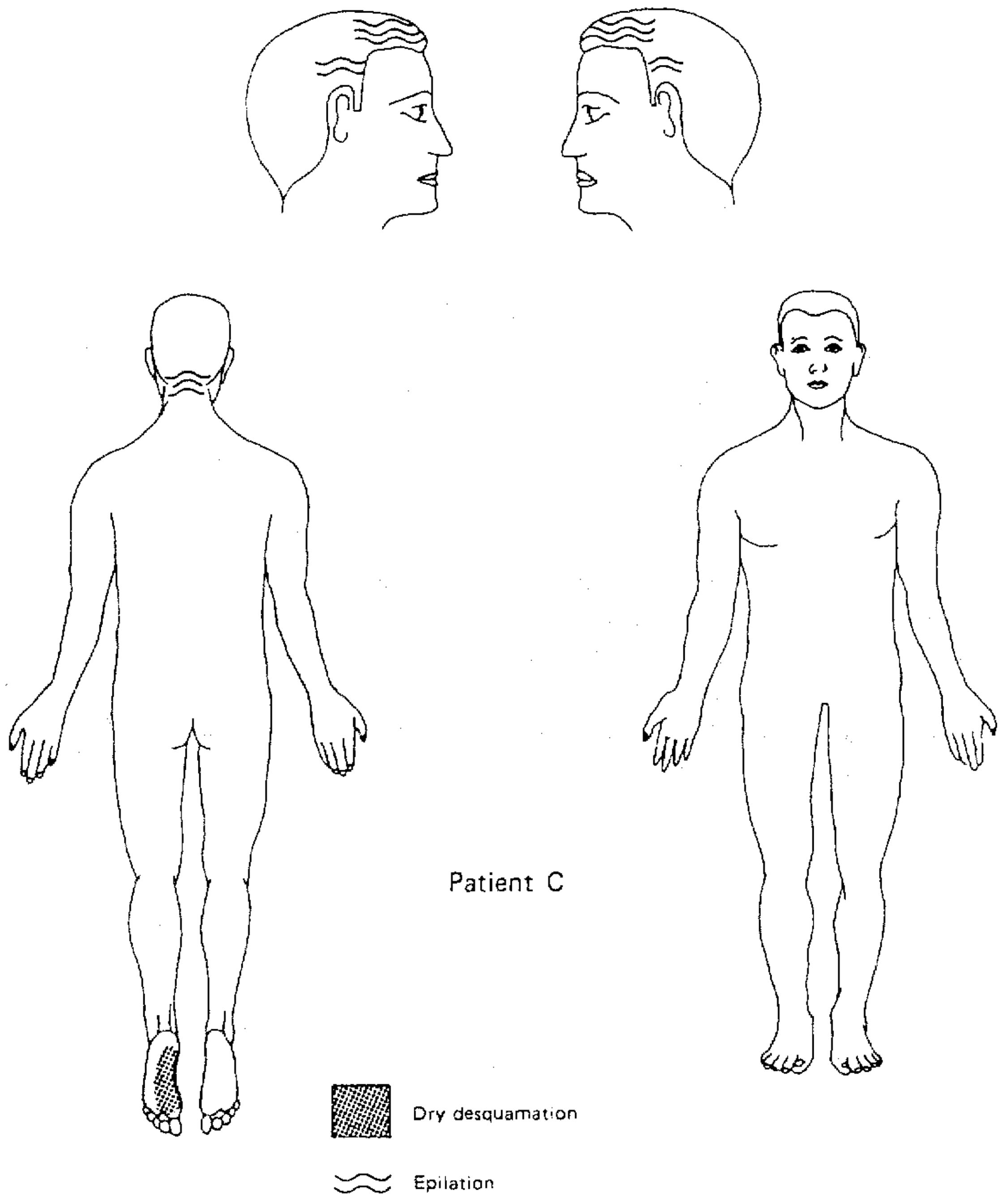

FIG. 20. Patient C: corporal distribution of effects of exposure. (Source: REAC/TS.)

exposure pattern differed from that of Patient B in that the medial surfaces of his legs were more seriously exposed. This suggests that he squatted with his legs apart while freeing the source rack. Adopting such a position rather than standing would have increased the dose to his upper body. His pattern of epilation and skin bronzing bears out such an exposure position. The pattern of wet and dry desquamation also suggests that the source was below the level of his knees. The difference in biological response between the medial and lateral surfaces of his legs also corresponds quite well with the expected results of attenuation by tissue. Worker A probably not only squatted but also bent over the source module.

Analysis of the information on Worker A's position and other factors yields the following dose estimates. The dose to his feet probably exceeded 200 Gy. His average mid-line air dose was about 10 Gy during his second period in the radiation room. The total mid-line air dose due to this period and to his earlier presence there could have been as high as 15 Gy. The average whole body dose, which depends upon the orientation of the individual and the quality and attenuation of the radiation, was determined to be about 80% of the average mid-line air dose. For Worker A, the average whole body dose would therefore have been up to about 12 Gy, rather uniformly distributed.

In view of the limited space in the radiation room, Worker B's position was probably as shown in Figs 13 and 16. In his case, epilation was from approximately the umbilicus down (see Fig. 19). Wet desquamation of the feet extended above the ankles to midway between the ankle and the knee of the right leg and somewhat higher on the left leg, above which dry desquamation occurred. On the basis that a dose of at least 15 Gy is necessary to cause dry desquamation and a dose of 30 Gy or more for wet desquamation, the dose rate must have been higher by a factor of about two at the ankle than at the knee. This factor of two for the decrease in the dose rate corresponds quite well to the position of the source as previously described. The biological response observed in Patient B also suggested an exposure time of about three minutes.

Given that the isodose lines and the biological effects correspond to a three minute exposure, the dose to the feet can be estimated to have been about 200 Gy. Owing to the rapid decrease in the dose rate with distance from the source, this can only be considered an order of magnitude estimate; however, it does seem to correspond to the biological response. The dose to the upper part of the body for Worker B would not have exceeded about 3 Gy. The uneven dose to the body corresponds to an estimated average mid-line air dose of between 4 and 5 Gy. This dose would also need to be multiplied by about 0.8 to yield an average whole body dose.

Patient C exhibited minor epilation and had a small area of dry desquamation on the big toe of the left foot (see Fig. 20). A reasonable estimate of the period of his exposure while on the upper platform is also about three minutes. His position was as shown in Figs 13 and 16. The exposure would thus have been more or less uniform to the whole body, primarily to the anterior surface. This exposure would have resulted in an estimated average mid-line air dose of between 2 and 4 Gy, and the average whole body dose would have been about 80% of this. This assessment is consistent with the cytogenetic dose estimates. However, it is difficult to conceive of a way consistent with Patient C's recollection of events in which he could have received a dose to the toe sufficient to cause dry desquamation. It would seem that at some stage he must have stepped close to the source rack for a short time.

All three men were required to bend while they were on the upper platform since the clearance to the ceiling is only 1.5 m. Workers B and C presumably lowered their heads.

None of the three received high enough doses to the hands to cause wet desquamation.

Further calculations have since been made but they do not significantly increase the accuracy of the dose estimates. The doses were probably incurred mainly during the few minutes for which the three workers were close to the source. In view of the biological damage the three men suffered, medical staff asked whether secondary electrons liberated in the interaction of gamma radiation with the stainless steel platform and surrounding materials may have contributed to the surface doses received. Irradiation by secondary electrons would cause greater surface biological damage in a shorter time than gamma irradiation alone, which would mean that the figures for the deep doses estimated on the basis of the surface damage were too high. However, a calculation of the possible electron dose and its distribution does not seem to support such a hypothesis.

In this case, cytogenetic dosimetry currently provides the best estimate of the doses received by the three men since it integrates exposure rates and exposure intervals. However, as discussed in Section AI.5, other techniques may provide further input to the dose estimates.

AI.5. OTHER DOSE ESTIMATION TECHNIQUES

After the irradiator accident in Norway in 1982, the main inputs to the dose estimation came from:

(1) thermoluminescence analysis of jewels in a wristwatch worn by the victim; and
(2) analysis by electron spin resonance of tablets that were in the victim's pocket.

In the accident in San Salvador, none of the three workers had items on their person that would readily have permitted the use of these techniques. However, the amputation of legs of Patients A and B permitted histopathological examination and analysis of sections of bone by electron spin resonance to derive further dose estimates for the lower limbs. The clothes that Patient A was wearing at the time of the accident were analysed by electron spin resonance dosimetry and lyoluminescence dosimetry to gain additional information on the dose sustained. The results of these investigations, performed in the USA and at the Institute of Biophysics of the Ministry of Health in the USSR, were not available when this report went to press.