EVALUATION AND DOSIMETRY OF ACCIDENTAL EXPOSURES TO AN X-RAY ANALYSIS BEAM.

I.S. Leith and W.A. Cornelius

Australian Radiation Laboratory
Melbourne, Australia.

(Accidental exposure of two research workers to an X-ray analysis beam during two days resulted in large area burns to the arms and chest. The dosimetry performed was later corroborated by the clinical findings.)

Introduction

During the period 23rd to 25th June 1970, three persons were inadvertantly exposed to low-energy radiation in a direct X-ray beam from a mis-assembled X-ray analysis unit at an established research institution. Late on 25th June 1970, the assistance of the Australian Radiation Laboratory was sought following report of an erythema by one of the exposed persons and discovery of the X-ray beam by another. Measurements made by the authors on the following day indicated that three persons may have received radiation doses sufficient to lead to injury. The Director of the Australian Radiation Laboratory arranged for examination of the three persons by a medical specialist in therapeutic radiology. Two of the exposed persons exhibited extensive erythema over a period of several weeks which was consistent with the doses estimated by the authors. The third exposed person showed no erythema and this also was consistent with the estimated doses.

Conditions of the Accident

The accidental exposures occurred over a period of almost three days. The exposure conditions varied during this period, which complicated the dose estimates. Investigation disclosed that three persons only could have been exposed to the X-ray beam. These persons were an experienced post-doctoral research worker, an instrument maker and a technician. Some eighteen months prior to the accident the X-ray analysis unit had been modified but subsequently had been operated on one occasion only until the days of the accident. On this single other occasion the unit was operated for 12 to 20 hours, but was largely unattended. The modification had been made to the tube housing of the X-ray unit (Philips Model PW1016 with copper target) to permit use with diffraction cameras previously used with an older X-ray unit. The X-ray tube housing had been dis-assembled and two opposite shutter mechanisms had been modified by removal of the solenoid-operated shutter opening devices and conversion of the shutters to manual operation. The remaining two opposite shutters were not modified and the standard shutter-closing mechanism was allowed to operate. This mechanism operates by means of closing springs which act on a lever which engages the shutter by means of a metal pin (see Fig. 1). However, one of these shutter mechanisms had been dis-assembled and re-assembled incorrectly so that the lever no longer engaged the shutter. The shutter then remained permanently open under the force of gravity as illustrated in Figure 1.

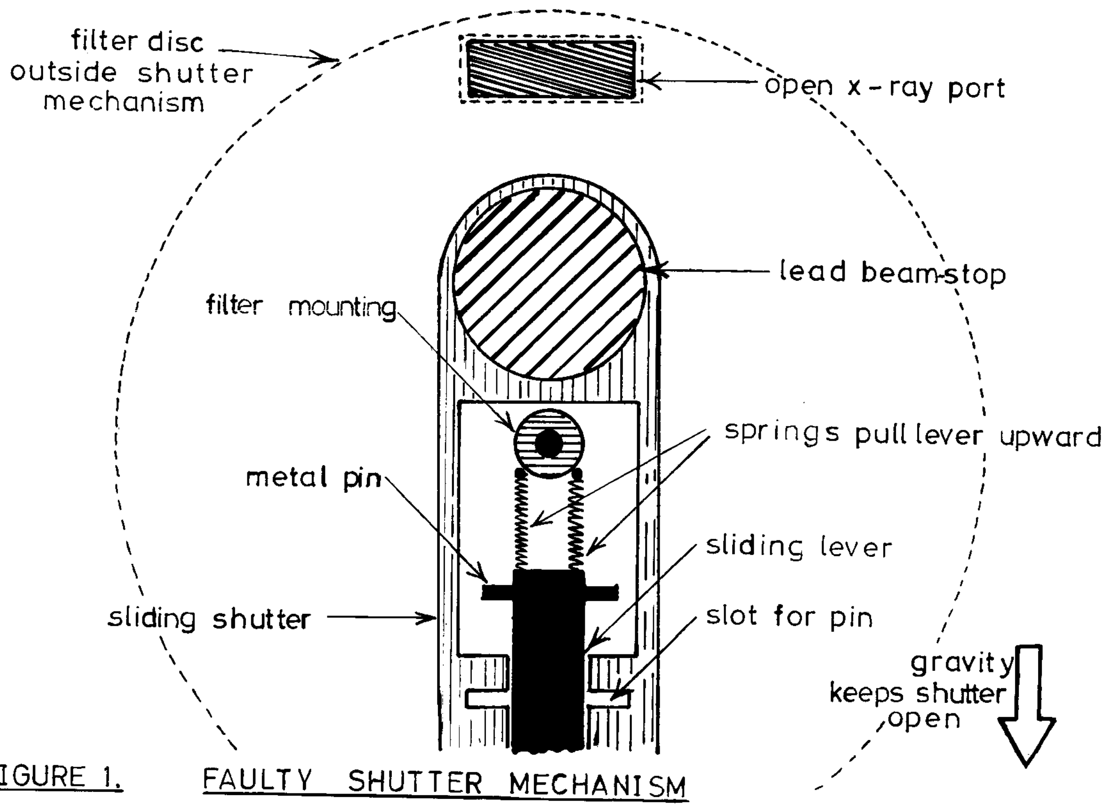

FIGURE 1. FAULTY SHUTTER MECHANISM

The microswitches operated by each solenoid were disconnected and a warning light was connected to switches operated by the two modified shutter mechanisms only. It was possible to see that the shutter which remained open due to mis-assembly was in the open position, as the filter disc was in a no-filter position, but this was not observed.

During the accidental exposures the X-ray unit was operated with a diffraction camera at the modified port immediately to the right of the open shutter. The camera was undergoing alignment and adjustment by the research worker during the days of the accidental exposures. It proved a difficult operation for him, and he enlisted the assistance of the instrument maker who was working on modification of the same camera. The difficulty encountered by the research worker may have been due to poor eyesight. The X-ray beam was viewed by means of a hand-held fluorescent screen mounted on a stick approximately 20 centimetres long. The camera was open, allowing access to the beam path inside it.

The X-ray analysis unit incorporated a camera table below the level of the X-ray ports which were at waist level. The X-ray beams from the open shutters are emitted almost horizontally.

During the afternoon of Tuesday 23rd June, 1970, the research worker attempted to align the camera from 2 p.m. till 4 p.m. then left the room after requesting the instrument maker to continue the attempt. This the instrument maker did from 4 p.m. till 4.30 p.m., when he switched the unit off. During these (unsuccessful) attempts to align the camera, the X-ray tube was operated at 35 kilovolts with a tube current of 10 milliamperes. In Figure 2, a diagram of the room and equipment is given, indicating the positions occupied by the persons involved in the accidental exposure.

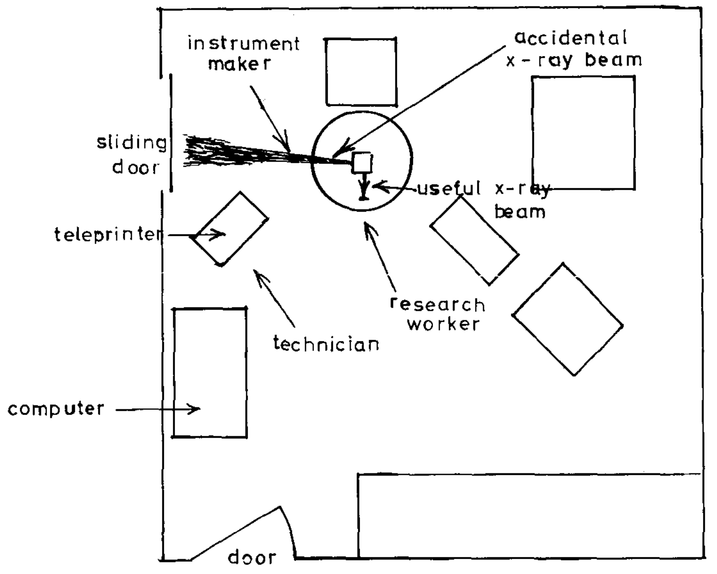

FIGURE 2. DIAGRAM OF X-RAY ROOM

The research worker took up a position in the line of the X-ray beam with which he was working during alignment, being protected from that beam by a beam stop in the camera. In this position he was not exposed to the X-ray beam from the mis-assembled shutter to his left except on repeated brief occasions when his left arm was in that vicinity. However, when his arm was exposed, it may have been fairly close to the open shutter, inside the perimeter of the camera table. During this time, he observed a faint fluorescence on the screen not caused by the beam which he was aligning but did not investigate its source.

The instrument maker, however, took up a position to the left of the camera he worked with and in this position was directly in line with the beam from the unintentionally open shutter. The beam irradiated his abdomen outside the line of the camera table at a distance of 40 centimetres or more from the open shutter throughout the period in which he worked on the camera. During the following morning, the X-ray unit was energised, using the same operating factors as before, and the instrument maker again attempted to align the camera, from 9 a.m. till 10 a.m. Due to a change of position, he was in the accidental beam for approximately half this period. The X-ray unit was then switched off.

At 5.15 p.m. on the same day, Wednesday 24th June, the research worker switched the unit on again and worked until 6.00 p.m. He took up positions mainly out of the accidental beam and was probably exposed for a maximum time of 5 minutes, again to the left arm.

On the evening of Wednesday 24th, the instrument maker observed an erythema on the skin of his abdomen in the region of the diaphragm but did not associate this with an X-ray burn.

On Thursday 25th June, the X-ray unit was operated at increased tube factors of 45 kilovolts and 15 milliamperes, to provide higher X-ray intensities to assist in viewing the beam. The same camera as before was again worked on by the instrument maker from 9 a.m. to 10.30 a.m. but he was aligning an eyepiece and stood in line with the beam with which he was working. In this position he received little or no exposure to the accidental beam. The research worker was in the vicinity of the unit for approximately 15 minutes during this period and may have been exposed to the accidental beam for a maximum of 5 minutes. At 11.15 a.m. the instrument maker returned to the unit and worked until 12.30 p.m. on the camera mechanism. During approximately 30 minutes of this period he took up a position in the accidental X-ray beam. At 12.30 p.m. it was noticed that the phosphor screen continued to glow brightly when removed to the left from the useful X-ray beam in the camera. The accidental X-ray beam and faulty shutter mechanism were then discovered. The technician, who had occupied a position in the room, but away from the X-ray unit and not in line with the accidental beam until this time, then exposed his fingers to the accidental beam for approximately 15 seconds while holding the phosphor screen. At approximately 1.00 p.m. the X-ray unit was switched off. During this period of discovery the instrument maker recalled the erythema he had observed and associated it with the accidental beam.

Investigational Dosimetry

Late on the afternoon of Thursday 25th June, the Australian Radiation Laboratory was notified of the accident and its advice sought. Early on the following morning, the authors assembled radiation monitors and travelled to the scene of the accident to investigate and perform dosimetry. Our object was to assess the likelihood of injury to the exposed persons and provide dose estimates to assist the medical specialist who would examine the exposed persons. The research worker reported a slight erythema on his left forearm and upper arm at this time.

Measurements of the direct beam were made with a Victoreen Model 555 Radocon II Integrating Ratemeter with Timer-Trip Module. A Victoreen Model 555-100 LA low energy probe was used for the measurements. This probe is calibrated by the manufacturer for the energy range of 6 keV to 30 keV. The energy correction factors provided by the manufacturer for this probe vary from 1.02 at 8 keV to 1.05 at 20 keV. This monitoring equipment had been earlier purchased for the specific role of dosimetry of X-ray analysis beams because of the very high intensity limit (100,000 R/min) and flat low-energy response of the 555-100 LA probe and the accuracy of the meter. The intensity limit is not sufficiently high to permit accurate measurement close to shutters under all circumstances but due to the estimated distances to the heavily exposed persons in this accident, accurate dosimetry was possible.

Measurements of scattered radiation around the room and direct radiation at large distances from the open shutter were made using a Berthold TOL/D-HF radio-frequency shielded X-ray monitor. This monitor uses probes employing gas amplification, permitting calibration over a very wide range of exposure-rate by adjustment of the high tension voltage applied to the probe. The radio-frequency shielded probe (purchased for other monitoring situations) has a more energy-dependent response at very low energies than the unshielded probes by this manufacturer, requiring a correction factor of 1.7 to be applied to readings at 8 keV.

The mis-assembled X-ray shutter produced a rectangular beam 18 centimetres wide by 5 centimetres high at a distance of 40 centimetres from the shutter. While working with the X-ray unit, the instrument maker was wearing a cotton laboratory coat, a woollen sweater, a woollen shirt and a cotton vest. Measurements were made of the exposure-rate in the middle of the accidental beam at 40 centimetres from the tube shutter with and without attenuation by material used to closely simulate the instrument maker's clothing. These measurements are given in Table 1.

TABLE 1

Exposure-Rates Measured at 40 cm. from X-ray Tube Shutter

X-ray Tube Factors	Exposure Rate in Air R/min	Exposure Rate Under Clothing R/min
35 kilovolts, 10 mA	420	178
45 kilovolts, 15 mA	785	336

In Figure 3, the scattered radiation exposure-rates measured around the X-ray room are shown.

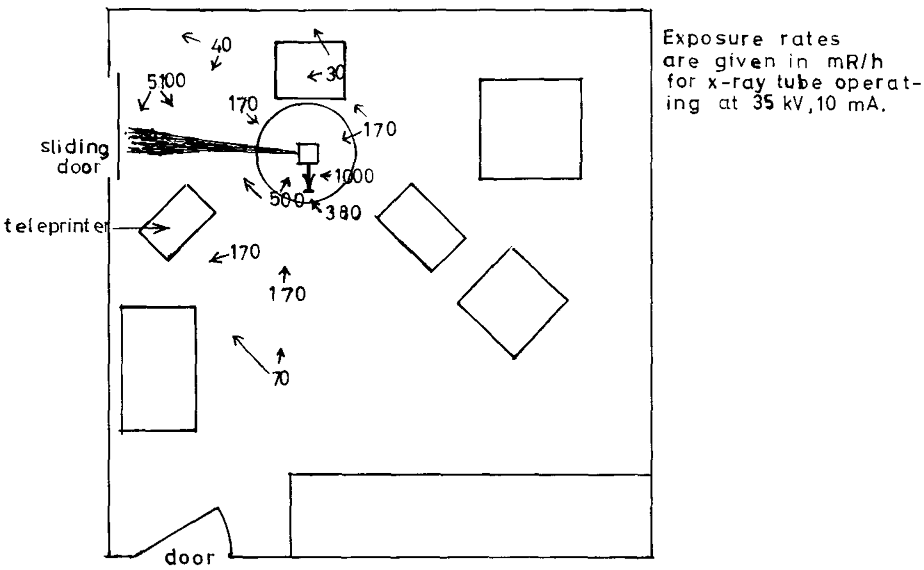

FIGURE 3. EXPOSURE RATES FROM SCATTERED RADIATION

From the measurements of attenuation in clothing and in air, an approximate calculation of the energy of the radiation in the accidental beam was made. The estimate of half-value thickness was 0.055 millimetres of aluminium, corresponding to approximately 8 keV effective. It was expected that the effective energy of the X-ray beam would not be significantly different from that of the characteristic radiation from the copper target (i.e. approximately 8 keV) because of the thin window of the X-ray tube.

Dose Estimates

The accuracy of estimates of dose in this accident is largely dependent on estimates of exposure time and distance. Distances to exposed persons were fairly constant and mostly relatively large. Persons were exposed mainly in regions where exposure-rate is not a strong function of distance. Errors due to distance uncertainty are thus not of major importance. However, errors due to exposure time uncertainty are potentially very large. In this case, significant reduction of this uncertainty was shown to be possible and the value of patient and tactful enquiry, retracing the accident history several times to improve recall, was proven. As a result, initial estimates of duration of exposure made by the exposed persons were very much reduced. For example, initially periods of exposure were estimated as starting or stopping at the official hours of duty. These estimates were reduced firstly by time and motion study to determine the probable proportion of working time during which persons were exposed to the accidental beam. In the next stage, patient questioning and better recall by the exposed persons indicated longer than usual tea-breaks and early departures from duty, leading to the final estimates of exposure time given in this paper.

Estimates of doses at the skin surface were made based on exposure-rates measured using the Victoreen Model 555. Account was taken of the attenuation of clothing. However, the critical tissue lies at a depth of approximately 1 to 2 millimetres below the skin surface in the stratum germinativum or replicating layer. Estimates of dose at this depth were derived using a tenth-value thickness in skin of 1.80 millimetres. This value was derived for monochromatic radiation at 8 keV using the data for muscle given in I.C.R.U. Report No. 17.[1] This coincides closely with a value of 1.85 derived by extrapolation of the data of Lubenau et al[2]. Thus the dose at the critical tissue is estimated to be in the range 0.28 to 0.077 of the dose at the surface. In table 2, the estimates of total exposure time and doses at the surface and at the critical tissue are given. The dose estimates are based on maximum estimated exposure times at a distance of 40 centimetres. It was believed that the estimates of doses to the research worker may have been only a small fraction of the true doses as exposure to his arm may have occurred much closer to the X-ray shutter than 40 centimetres. The dose estimates for the research worker and instrument maker were derived from exposure-rates measured after attenuation by clothing and would need to be increased by a factor greater than 2 if bare skin was exposed. The dose estimates for the technician were derived from exposure-rates measured without attenuation by clothing. The vertical width of the erythema visible on the abdomen of the instrument maker was approximately 5 centimetres, which suggested that he received most of his dose at a distance of 40 centimetres.

TABLE 2

Estimated Exposure Times and Doses

Person	Total Exposure Time (min.)	Dose at Surface (rem)	Dose at Critical Tissue (rem)
Instrument Maker	90	19,200	1500 - 5400
Research Worker	30	5,500	400 - 1500
Technician	0.25	180	14 - 50

Clinical Findings

The clinical examinations confirmed that the erythema which appeared on the abdomen of the instrument maker was consistent with a dose of 1500 to 2000 rem to the replicating layer of the skin. Dry desquamation appeared at 3 to 4 weeks after exposure on the abdomen and on the backs of the hands. These clinical findings indicated a dose to the hands of approximately 2000 rem.

The examination of the research worker revealed no later sequelae to the arm (which is consistent with the estimated dose) but at 3-4 weeks dry desquamation appeared on the hands and this was estimated to be equivalent to a dose of approximately 1500 rem. The specialist also noted some evidence of earlier facial injury, which he attributed to exposure to soft x radiation.

The technician showed no clinical signs of exposure, as expected.

The exposure to the hands of the instrument maker and research worker was not anticipated by their memory of their actions during the exposures. It probably occurred as a result of several brief exposures in close proximity to the open shutter but may have been due to exposure to the useful beam with which they were working. Dose estimates would be meaningless due to uncertainty of distance and exposure time and were not attempted.

Conclusions

The conditions of the accidental exposure described in this paper lead to a number of useful conclusions. Firstly, the conditions were such that much higher doses and severe injury may well have resulted and the workers concerned were fortunate to escape severe effects. Secondly, the need for many of the principles of good practice in the use of X-ray analysis units is clearly illustrated in this accident.

The adoption of one such principle, that of adequate radiation monitoring of facilities whenever modified, would have led to early discovery of the mis-assembled shutter. The safe principles and practices had been formalised and published in Australia in the previous year, 1969 as a code of practice. This Code, entitled "Code of Practice for the Safe Use of X-ray Analysis Equipment"[3] was published by the National Health and Medical Research Council of Australia in its series of publications and codes of practice on radiation health. One of the authors (I.S.L.) worked on the drafting of this Code of practice. The code details general working practices and equipment features essential to ensure radiation safety with all X-ray analysis units. However, the code recognises the great variety of X-ray analysis equipment in use and in particular, the improvement in design for safety which has proceeded for many years. While proceeding from the premise that in-built safety should be relied on in preference to relying on workers to maintain good practice, the code recognises that it is unpractical to modify many older X-ray analysis units and some units used in particular configurations to the extent that working rules are not required. Hence, the code categorises X-ray analysis units according to their degree of in-built protection and grades working rules accordingly. Nevertheless, it was recognised that some units in use do not meet the minimum requirements of any of the categories of unit specified. A separate set of very thorough and restrictive working rules is laid down for such units, in an attempt to ensure safety in their use and to act as a strong incentive to improve the built-in safety of these units. The X-ray analysis unit described in this paper was a unit of this type and several of the special working rules provided would have served to prevent the accidental exposures. These include not operating the unit if a person not essential to its operation occupies the room (this would apply to the instrument maker and technician) and not making alterations to the unit while it is operating (this would apply to the work on the camera performed by the instrument maker). Other rules include monthly radiation surveys, weekly examination of the unit for hazards and the requirement for an experienced observer to be present at all times when persons work with the unit to warn of hazards. Another rule requires that the operations of alignment or adjustment shall not be carried out by inexperienced persons unless under the direct supervision of an experienced worker. This rule would apply to the periods of exposure of the instrument maker, who had no appreciation of the radiation hazards involved. Each of these rules would have reduced or prevented the accidental exposures in this case.

There were many other elements of good practice and in-built safety not applied during this radiation incident, but certain examples of bad practice are more notable. The absence of any form of radiation survey monitoring or close examination of the unit after modification, the modification of the warning light system, the secondment of an instrument maker to work of a hazardous nature with which he was unfamiliar and in which he was not supervised and the siting of a small computer and console in the X-ray room are all good examples. We hesitate to asign such simple labels as "carelessness" to the cause of accident but a change of attitude of the research worker would appear to be essential in this case. This worker had been in the field for many years and was accustomed to working with open cameras and unshielded beams particularly when equipment design was in an early phase. However a change of attitude appears to be necessary, especially if this worker had been overexposed on one or more earlier occasions.

Another matter is illustrated in this incident. The initial dismantling of the unit was done to remove automatic shutter-opening mechanisms not provided by the manufacturer on earlier units, as these interfered with the use of cameras previously used with the older units. The same situation arises frequently when cameras from one manufacturer are used with X-ray units of another. Frequently, the built-in safety features are removed rather than construct a satisfactory part for inter-connection of the camera and X-ray unit while preserving the safety features. This illustrates an inadequate approach by many workers with these units but also points to a serious lack of planning and standardisation by manufacturers. Another question of design in this case is the particular shutter configuration used in the X-ray unit. The shutter was designed in such a way that mis-assembly was easily possible and represents a fundamental cause of the accident.

References

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