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# RADIATION MEASUREMENTS AROUND X-RAY CABINET SYSTEMS

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**Security personnel who operate X-ray units for the control of hand luggage and personal items at airports are generally not under dosimetric surveillance. A significant increase in the number of inspected items per passenger, due to rigorous air traffic security measures, raises a question of extended exposure of these workers to scattered X-ray radiation. A new approach to investigating directions of breaches of scattered X-ray radiation in the area near to an X-ray cabinet system, which is based on using active electronic dosemeters is presented. Influence of the increase in the number of inspected items in time on the dose rate is described. Time-dependent dose rates have showed a very good correlation with passengers undergoing security control prior to boarding an airplane. Measurements confirmed that an increase in the dose rate, coinciding with rush hours, was caused by scattered radiation passing through incompletely closed lead curtains. It is found that the doses at the entrance to the inspection tunnel are 50 % higher than those at the exit, which is a consequence of inherent operational characteristics of X-ray cabinet systems.**

## INTRODUCTION

During the survey of exposure of security personnel who operate X-ray units, for the control of luggage and personal items, to ionising radiation[1, 2], the use of personal dosemeters such as TLDs was found not to be an adequate and reliable solution. In order to insure controlled measurement results which would provide reliable data for estimating the exposure, a need for mapping the spatial distribution of scattered X-radiation around such units has emerged.

Reliable real-time *in situ* measurements would enable better radiation protection planning and give a new insight into the exposure of security workers in response to their workload. Since dose rates of scattered radiation are moderately higher than the natural background (BG), the measurement equipment has to be sensitive enough and has to enable simultaneous measurements at as many points as possible around an X-ray unit. Using a number of regular survey meters connected to PCs was not possible, since such a measurement set is bulky, disturbs normal working process, and is financially demanding. Instead, cheaper and smaller active electronic dosemeters (AED) which were put on selected positions around X-ray units were employed, thus eliminating the incompatibilities mentioned above.

The larger number of inspected luggage and other items per passenger, due to strict security measures in air traffic, has increased the workload of the X-ray tube, i.e. the total radiation time. Measurements performed during regular quality control assessment of cabinet X-ray systems showed that the X-ray beam was activated while the lead curtains were still opened on the entrance side.

If the lead curtains at the entrance to the inspection tunnel were properly closed during the irradiation of an inspected item, the ambient dose equivalent rate near the X-ray unit was within the range of BG radiation variations while in the case of the curtains being partially opened the ambient dose equivalent dose rate was enhanced. In real working conditions, often there are many occasions when larger or/and longer pieces of personal luggage enter the inspection tunnel, leaving the curtains partially opened while the X-ray beam is on. Also, during rush hours, when a large number of passengers undergo security screening, a pile up of items entering into the inspection tunnel occurs in a way that a new object enters through the lead curtains while the previous one is still being irradiated. A similar situation happens at the exit from the inspection tunnel. Due to frequent opening of the lead curtains, there must be an increase in the ambient dose equivalent rate in the area around the X-ray unit as a result of radiation scattered on luggage.

If this is so, there must be a time correlation between the number of passengers and corresponding time-dependent dose rate around the cabinet X-ray system. Measurement of time-dependent ambient dose equivalent rate was feasible using the AED-type ALARA OD[3] which has a time-resolution capability.

Since X-ray cabinet systems with a plexiglass tunnel in front of the entrance/exit to the inspection tunnel are a novelty in Croatian airports, the authors evaluated its influence in radiation protection of security workers. The highest benefit from a plexiglass tunnel is not radiation shielding in the usual sense but detachment of the security officer's standing position away from the entrance/exit to the inspection tunnel. In particular, the plexiglass tunnel prevents operators putting hands beyond the lead curtains, which often happens when, in order to speed up the flow of passengers during rush hours, a security officer pushes in or pulls out items from the inspection tunnel. Increases in the detachment distance also reduces doses and therefore increases radiation protection.

## MATERIALS AND METHODS

In this investigation, a number of AEDs by which, besides a spatial resolution, for the first time introduce resolution in time (discrete time record of ionisation events) have been employed. A set of AEDs, which enabled time-dependent dose/dose rate measurement, were put on selected positions in the area around an X-ray cabinet system, thus enabling spatial resolution. AED ALARA OD is based on Geiger–Müller (GM) tube[4] and has a built-in software which records the total number of counts over a predefined integration time. This enables calculation of time-dependent dose/dose rate[3]. Its small size[5] permits to perform measurements without disturbing the security-workers routine. The choice of such measuring equipment and a number of AEDs set at various measuring points provides *in situ* dose/dose rate simultaneous measurements.

It was very important to tune different AEDs responses, which could vary due to the GM tube geometry and energy sensitivity[4]. Therefore, nine AEDs ALARA OD were put to stay for 5 d (from 23 September at 12:45 until 28 September at 11:15) in the security personnel's office inside the airport building, far away from the X-ray units. The average BG ambient equivalent dose rate in that area was measured using a calibrated survey meter Thermo Eberline FH 40 G. During these 5 d, AEDs measured a time-independent count rate (number of counts accumulated during 1 h) which revealed usual BG dose rate variations ranging from 10 to 20 %. The average BG ambient equivalent dose rate was 120 nSv $h^{-1}$.

Since a GM tube records ionisation events, the shortest time of integration for which the relative uncertainty appeared to be acceptable was selected—<20 %, which was a compromise between the number of expected counts (higher number of counts requires longer integration time which decreases time resolution) and the BG radiation variations. The average number of counts within 1 h (during BG measurements) was 29.35 with standard deviations from 2.87 to 5.51, so we decided to set the time of integration to be 1 h.

Responses of all AEDs were first normalised to the average ambient dose equivalent rate until the moment of their transfer from the security personnel's office to the X-ray control area. The correction coefficients varied from 0.70 to 1.43 and were applied to all the AEDs tuning their sensitivities. Although without particular data of BG's energy spectrum, it was assumed that the method of sensitivity correction is valid for the X-ray energies, <200 kV, as well. Therefore, it was not possible to apply the same coefficients to all the data measured during the X-ray unit working time (from 28 September at 12.13 until 29 September 29 at 15.13). It was important to apply the correction in order to have a set of AEDs which, when put on various locations in scattered radiation field, give consistent results.

Energy response curve of GM tube[4] shows a steep increase in sensitivity below ~250 keV, cabinet X-ray energies (140-kV peak voltage), relative to $^{137}$Cs. Especially for this purpose, AEDs against calibrated Thermo FHZ 612 external probe, connected to a Thermo Eberline FH 40 G survey meter and a PC, by taping them on the inner side of the plexiglass tunnel at the entrance to the X-ray unit was calibrated. The measurement set was left to measure the scattered radiation for 2 h during rush hours. Calibration factor was then calculated using total accumulated values.

Tuned and calibrated AEDs on positions were put at a selected X-ray cabinet system, as depicted in Figure 1, where breaches of scattered radiation towards security personnel's usual working positions were expected. In order to simulate the maximum workload (worst-case scenario), all the passengers who were undergoing security screening were forced to use that X-ray unit.

The measurement was carried out on a Smiths Heimann HS 6046 si unit[6]. They are used for the scanning of hand luggage and personal items and for any illegal or forbidden objects (weapons, explosives, drugs, etc.). The cabinet X-ray system consists of an X-ray unit with an X-ray tube operating at 140 kV, with a 0.2-mA tube current, in a fan beam geometry, a detector line (semiconductor detectors), a conveyer belt which transports (at 0.2 m $s^{-1}$) object to be scanned into the inspection tunnel ($L$=1.15 m) and a monitor displaying high-contrast image of the object is displayed. Pseudo-colour mode allows for the distinction of objects with different densities, thus enabling detection of hidden forbidden items. The X-ray tube is placed on the operator side close to the floor directing extremely thin

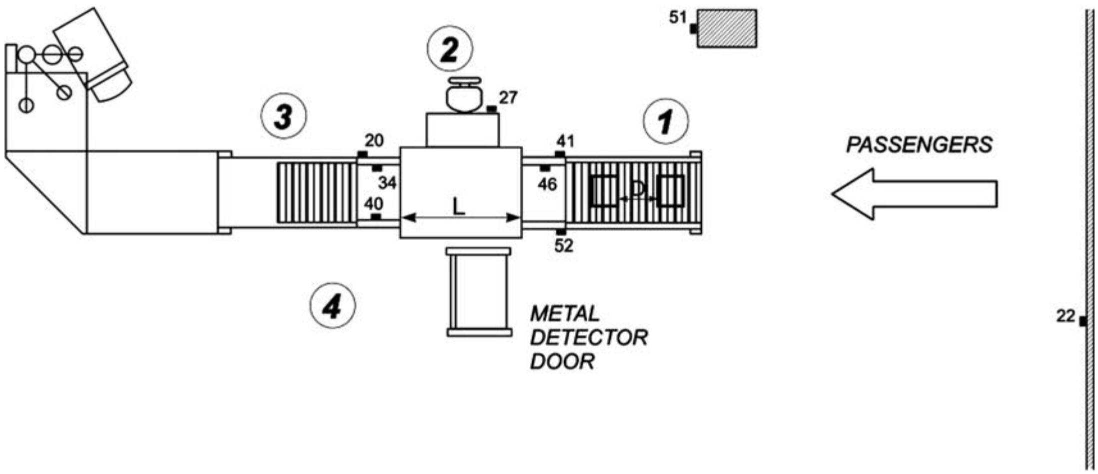


Figure 1. Positions of AEDs (closed squares), marked by their serial numbers, around a selected X-ray unit. The usual standing positions of security workers are marked 1–4. AEDs 51 and 22 were located at 3.2 and 10 m from the X-ray tube, respectively. Length of the inspection tunnel (*L*) and distance (*D*) between two consecutive objects are indicated.

fan-shaped X-ray beam diagonally towards the detector line.

The X-ray unit used in the experiment had passed regular quality control procedures and had a legal operating license.

The X-ray radiation measurement started on 28 September at 12.13 and finished on September 29 at 15.13. Duration time of the measurement was limited by security protocols.

The usual working positions of security workers are marked 1–4 in Figure 1. A group that operates one X-ray cabinet system usually consists of four people:

- 1: puts items to be irradiated on the conveyer belt,
- 2: operates the X-ray machine, analyses image on the monitor,
- 3: takes items that are exiting from the inspection tunnel, inspects luggage for suspicious contents, takes away illegal objects,
- 4: performs passenger checks with a metal detector, helps worker on 3.

Data readouts from the AEDs were downloaded to a PC and processed using ALARA OD software.

## RESULTS AND DISCUSSION

Results of the count rate versus time measurements (expressed as number of counts in preselected integration interval of 1 h) using AEDs are presented in Figure 2. Original measured data multiplied with the correction factor are presented. The considerable increase in the count rate detected close to the end

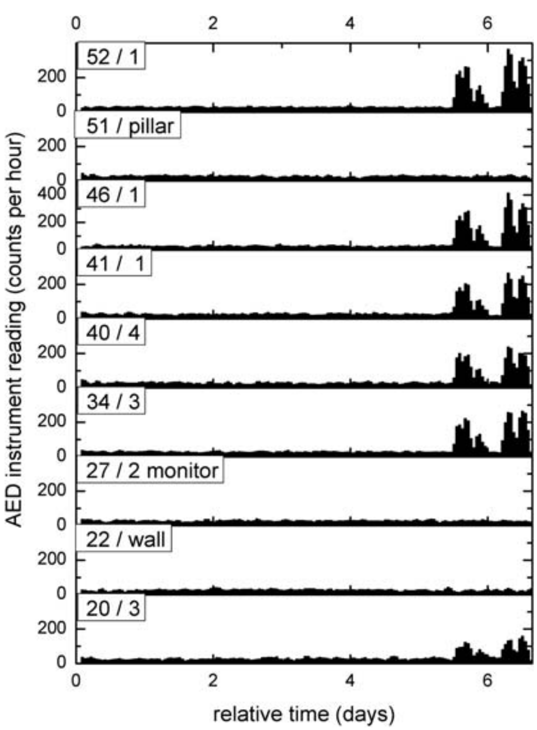


Figure 2. Count rate measured by AEDs as number of counts accumulated per 1 h versus relative time. Original measured data multiplied with the correction factor are presented. Serial number of AED/nearest workplace position is marked in the upper left corner of each plot. The zero of the time scale refers to September 23 at 12:45.

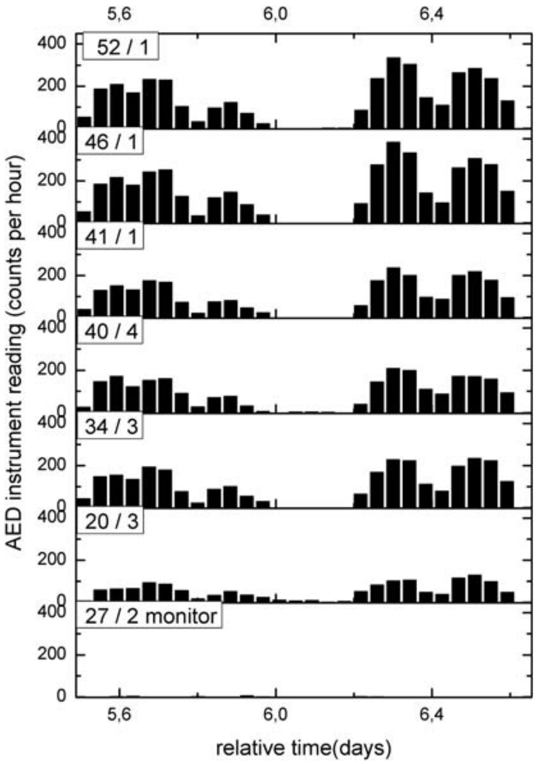


Figure 3. Scattered X-ray radiation count rate versus time (BG count rate is subtracted) measured by the AEDs only during measurements on the X-ray unit. Serial number of AED/nearest workplace position is marked in the upper left corner of each plot.

of the time interval coincided with putting the AEDs onto measuring positions next to the active X-ray unit, 28 September at 12.13—5.5 on relative time scale.

AEDs No. 51 (3.2 m from the X-ray tube) and No. 22 (~10 m from the X-ray tube) were placed on the pillar and the wall, respectively. These two AEDs recorded BG radiation only, i.e. scattered radiation was too low to be distinguished from BG variations. The absence of the dose rate recorded above the BG can be expected by taking into account the absorption in the air.

Figure 3 displays a detail of Figure 2, namely it zooms into the time interval from 28 September at 12.13 to 29 September at 15.13 (working period), BG ambient dose equivalent rate being subtracted. For all the AEDs, the enhanced dose rate coincided with the activity of the X-ray tube. During the night (approximately from Day 6.0 to 6.2) there was no activity (flights) and hence no detectible increase in the dose rate above the BG.

AED with serial number 27 placed on the monitor next to the operator (working position 2) recorded barely noticeable radiation (above the BG radiation), see Figures 2 and 3, since it was shielded by the housing of the X-ray unit.

The shapes of the time-dependent count rate during the working period were different comparing two successive days, 28 and 29 September, which is ascribed to different daily workloads (see Fig. 3). Within a single day, the count rate pattern is obviously very similar for all the AEDs which implies the reliability of the calibration and measurement procedure. However, count rates are different for differently located AEDs. There is a clear difference between the rates recorded by two equivalent sets of AEDs put at the entrance to and exit from the inspection tunnel (Fig. 1 and Fig. 3). Approximately 50 % higher count rates were recorded on AEDs placed at the entrance to the inspection tunnel, close to working position 1 (AEDs Nos. 46, 52 and 41). This could have been expected knowing the mode of the operation of the X-ray unit. When an object is transported to inspection tunnel through lead curtains, the front side interrupts the infrared beam of the light barriers (located at the input side of the tunnel, right behind the lead curtains) and the X-ray generator is switched on simultaneously. The irradiation lasts until the end of the object passes the detector line in the middle of the inspection tunnel ($L/2$). Since it was practically impossible to take into account the shape of an irradiated object and detailed arrangement of objects entering the inspection tunnel, the authors based the discussion on the distance between consecutive objects and its influence on the difference (entrance/exit) of the measured scattered count rate.

In case of a single object (distance $D$ between two consecutive objects $D \geq L$), scattered radiation leaks through opened entrance lead curtains from the moment of turning the X-ray tube on until the curtains are properly closed. For objects whose length is $d < L/2$ lead curtains on the exit side are closed during the whole time of irradiation and no scattered radiation can be recorded on the exit from the inspection tunnel. For objects whose length is $d \geq L/2$ the lead curtains on the exit side are opened (scattered radiation can leak) only when the object's leading side exits from the inspection tunnel lasting $(d-L/2)/0.2$ m s$^{-1}$. The share of such long objects is very low so their contribution to the difference in the count rates at the entrance and the exit side is minimal.

However, a line of objects which is usually formed during rush hours generally favours the difference in leakage of scattered radiation between the entrance and the exit. It is especially enhanced for dense lines ($D < L/2$). Exceptions to this expectation are the case when objects are distanced by $D=L/2$, and the line of objects without gaps. In these cases there is no difference in entrance/exit scattered radiation dose rate.

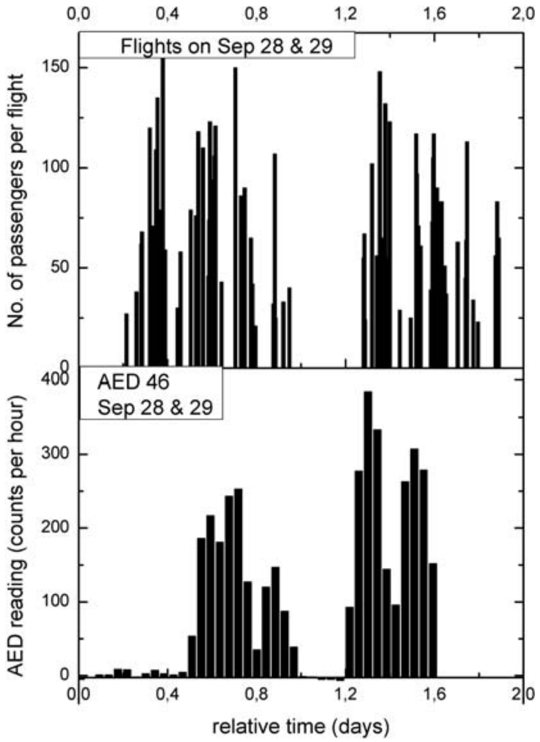


Figure 4. Sum of passengers per flight, within 1 h time interval, versus time and AED reading versus time for AED 46 placed at the entrance to the inspection tunnel.

Note that the predominant source of scattered radiation measured on the exit side is the pile up of objects entering the inspection tunnel during rush hours.

Among AEDs placed close to working position 1, the highest total number of counts was recorded by AED 46 which was taped inside the plexiglass tunnel closer to the lead curtains. AEDs 52 and 41 were placed on the outer side of the plexiglass tunnel (Fig. 1).

The evaluated radiation shielding provided by the plexiglass tunnel by the attenuation law, using mass attenuation coefficient of 0.15 $cm^2$ $g^{-1}$[7], density 1,19 g $cm^{-3}$[8] and effective plexiglass thickness of 1 cm (security worker's positions 1 and 3), gives a reduction in the scattered radiation intensity of 15 %. The plexiglass tunnel was 40 cm long with walls of 0.5 cm thick. Usual working positions 1 and 3, near the X-ray unit with or without a plexiglass tunnel are 70 or 30 cm from the lead curtains, respectively.

As the results clearly indicate a strong connection between the number of passengers undergoing security control (particularly their luggage) and the increase in the measured count rate, in Figure 4 the count rate time pattern, measured by a representative AED, with a sum of passengers per flight within 1 h intervals was compared. Passenger flow versus time and count rate versus time (BG count rate subtracted) measured at the entrance to the inspection tunnel (AED No. 46) were investigated and put on the same time scale, which is shown in Figure 4 (zero on relative time scale coincides with 28 September at 0:00 h, measurements by AED No. 46 on the selected X-ray unit started at 0.50971 on relative time scale).

During the measurement period, a total number of 3600 passengers passed through security control at the selected cabinet X-ray system. In order to present passengers flow versus time dependence correctly, a plausible assumption has been used in which all the passengers of an airplane pass the security control in from 2 to 0.5 h before boarding. Results in Figure 4 visually show a good time correlation between these two sets of data.

Calibration coefficients for both BG and scattered X-ray radiation energies were calculated using results from ambient dose equivalent rate measurements performed by a survey meter Thermo Eberline FH 40 G. The average BG ambient dose equivalent rate was 120 nSv $h^{-1}$ with the average AEDs number of impulses of 29.35 imp $h^{-1}$ so the calibration coefficient for BG energies was 4.08 nSv $imp^{-1}$. Due to the very steep energy response curve of GM tube[4] for X-ray energies, it is expected to obtain much lower calibration coefficient. It was calculated using the survey meter scatter radiation ambient dose equivalent rate averaged over 2 h, as follows. The total average ambient dose equivalent rate was ~249 nSv $h^{-1}$, hence by subtracting the average BG ambient dose equivalent rate the net value amounts to 129 nSv $h^{-1}$. A similar procedure was carried out for AED, the average BG (29.35 counts $h^{-1}$) was subtracted from the total average number of counts (237 counts $h^{-1}$), giving 208 counts $h^{-1}$ for scattered X-ray radiation. Therefore, the calibration coefficient 0.62 nSv $count^{-1}$ was calculated. The ratio of the calibration factors shows that the sensitivity of AEDs GM tube is enhanced by more than six times, which is in agreement with the expectation that 140-kV peak voltage X-ray tube reveals just about this factor due to the GM tube energy characteristics[4]. Using the calibration coefficient of 0.62 nSv $count^{-1}$ maximal ambient dose equivalent rates, from X-ray radiation only, were calculated (Table 1).

Based on the data in Table 1, the annual doses from scattered X-ray radiation for working positions 1–4, were calculated. Based on 1800 working hours per year (8 h working day), the annual doses would be up to 430 μSv for a worker standing exclusively at workplace 1. Since neither 1800 h of effective (while X-ray is on) working hours per security officer annually is obviously a realistic assumption nor that anyone occupies a single standing position

**Table 1. Maximum ambient dose equivalent rates estimated from scattered X-ray radiation only, measured by AEDs.**

| AED no./position | Maximum ambient dose equivalent rate (nSv $h^{-1}$) |
|---|---|
| 41/1 | 238 |
| 27/2 | Below measurement threshold |
| 20/3 | 80 |
| 40/4 | 130 |

during the whole workday (usually there are 20 min rotations among working positions) and the actual standing positions are always further away from the positions where AEDs were put, the real doses must be much lower from the worst-case scenario values estimated above.

## CONCLUSIONS

A measurement set consisting of number of AEDs has proved to be a good choice for measuring instrument in cases where simultaneous measurements of radiation field at various positions is required with minimal disturbance of working processes. The use of such a set positioned in the area close to a cabinet X-ray system has enabled an insight into the time-dependent dose rate providing spatial information on scattered radiation in that area.

Properly calibrated AED with time-resolution capability allows for a new approach in workplace monitoring, especially those with variable workloads.

Measurements have shown that all recorded count rates above BG have come from leakage radiation through partially opened lead curtains and that the number of counts recorded by AEDs placed at the entrance to the inspection tunnel were significantly higher (50 %) than the doses recorded at the exit from inspection tunnel. A simple analysis has shown that for a very intense flow of objects being inspected (objects in contact—continuous activity of the X-ray tube) or for small objects separated by $D=L/2$ there should have been no difference in the total scattered radiation dose measured at the entrance and at the exit. In all other cases, dose at the entrance dominates over that at the exit.

Presumption on a time correlation between the number of passengers undergoing security control and the coinciding increase in the dose rate has been confirmed.

Estimation of the maximum ambient dose equivalent rates from the exposure to scattered radiation for workplaces 1–4 has been done. The calculation has proved that the highest annual occupational doses could be received on workplace 1 (up to 430 μSv) but, taking into account the real working routine of security officers, the real occupational doses are several times lower. Therefore, it can be concluded that, if obeying working protocol, security officers that operate X-ray cabinet systems for the control of hand luggage and personal items, even in the case of a very intense workload, should not be under dosimetric surveillance[9].

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