USE OF AN ELECTRONIC FINGER DOSIMETER IN OPTIMISATION OF FINGER DOSES

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1. ABSTRACT
Optimisation of radiation doses to the hands is problematic. Doses recorded by passive dosimeters include contributions from many different manipulations, so it is difficult to ascertain which actions make significant contributions to the doses received. A device for electronic monitoring of finger doses called an Advanced Extremity Gamma Instrumentation System (AEGIS), which records instantaneous dose rates at the finger, can assist in providing this information. AEGIS has been employed in a number of hospital departments where radionuclides are used, including a large hospital radionuclide dispensary and nuclear medicine departments. Data were recorded throughout complete sessions and analysed to identify the actions which made the most significant contributions to doses. Study of the patterns of radiation dose rate has enabled finger doses in the radionuclide dispensary to be optimised through raising staff awareness of doses from each manipulation. Optimisation has been achieved through changes following evaluation of alternative manipulation techniques and use of shielding devices. AEGIS has also been used to determine dose distributions across the hand and establish a relationship between the dose to the most exposed part and that at the monitoring position. For radionuclide dispensary staff, the tip of the index finger on the dominant hand receives the highest dose. Studies carried out in nuclear medicine departments have shown that withdrawals of radiopharmaceutical into a syringe, where a shield is not used routinely, tend to make the largest contribution to the dose. This can vary from 5 to 500 μGy per manipulation. Doses for injections varied from 1.5 to 300 μGy.

2. INTRODUCTION
Hospital staff involved in the preparation of radiopharmaceuticals and their administration to patients may receive significant radiation doses to their hands. Thus it is important that techniques are optimised in order to keep these doses to a minimum. Assessment of finger doses has, in the past, involved lengthy studies of accumulated doses measured using thermoluminescent dosimeters (TLDs), which were the only type of dosimeter small enough to be accommodated on a finger. TLDs provide an integrated dose often covering several different operations from which it may not be possible to separate the dose contribution from the procedure of interest. This has presented difficulties in optimisation of procedures in order to minimise the dose received by the hands. A new electronic dosemeter for detecting and recording dose rates at the finger tip has been developed which allows extremity dose rates to be monitored continually throughout a procedure. This instrument, called an Automated Extremity Gamma Instrumentation System (AEGIS), has been designed to provide a continuous readout of dose-rate from a small probe, which can be attached to a finger. It is small, lightweight and relatively simple to use. AEGIS allows doses received from individual operations and from actions within a particular procedure to be recorded, so that the pattern of dose accumulation can be analysed immediately at the end of a session. This facility for rapid feedback is valuable in the optimisation of techniques for dose reduction. AEGIS has been employed to measure the doses received by the hands from individual actions during the dispensing and administration of radiopharmaceuticals. Dose rate patterns associated with a variety of procedures have been analysed and doses assessed for individual manipulations. Electronic finger dosimetry systems such as AEGIS have the potential to become a valuable radiation protection tool which should allow a greater degree of optimisation of finger doses than has previously been possible.

3. METHODS
The Advanced Extremity Gamma Instrumentation System (AEGIS)
AEGIS has been developed by CIL (Barrow in Furness, UK), in order to record the instantaneous dose rate from a probe which is small enough to be attached to a finger. The probe is connected to a signal amplifier, which can be worn on the wrist, and from there the signal is passed to a lightweight data logger, which can fit in a pocket (figure 1). The logger stores the counts registered each second, which can be related to dose rate, and these data can be downloaded onto a PC via windows based software. The data is available for analysis as soon as the procedure has been completed, allowing the pattern of exposure from individual actions to be examined. The system is powered by a PP3 Alkaline 9V battery which will provide 300 h of use. Data can be stored for up to 10 h of continuous monitoring.

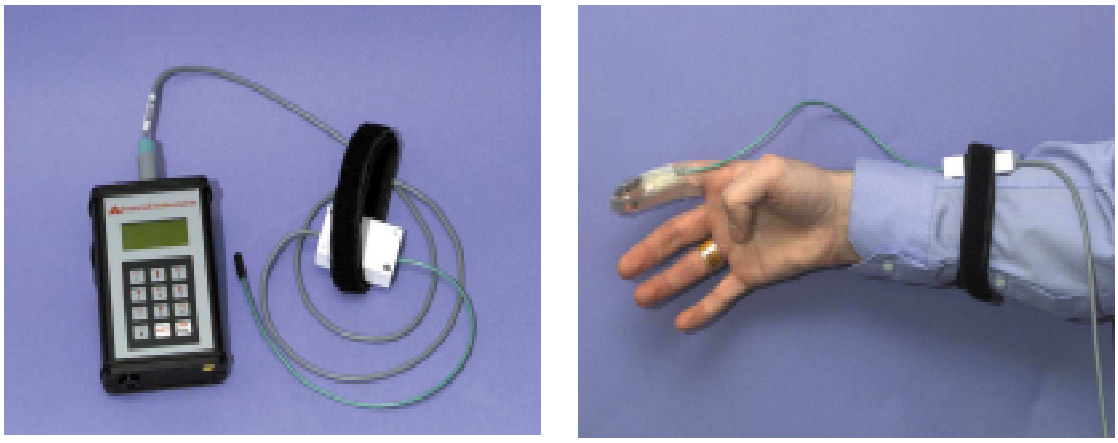


Figure 1 Picture of AEGIS, showing the probe, and the typical position in which it is worn, the amplifier and logging unit.

An early version of electronic finger dosimeter called a Gamma Extremity Monitoring System (GEMS) used a cadmium telluride detector crystal in an aluminium sheath (Montgomery et al 1997). However, because the crystal was more sensitive to lower energy X- and gamma-radiation a calibration factor had to be applied related to the particular radiation energy being studied. In AEGIS, filters have been applied to provide energy compensation. Design of the probe has involved achieving a balance between the competing requirements of the incorporation of the energy compensating filters and construction of a probe small enough to be worn comfortably on a finger. Two versions of AEGIS were used in this study. One had a cadmium telluride detector crystal, measuring 5 mm x 1 mm x 1 mm, which was surrounded by cylindrical metal filters, giving the probe an outer diameter of 4 mm. The filters are designed to give an energy response in the side-on orientation within ±25% over the energy range 80-160 keV. The second version of AEGIS had a flat silicon detector 5 mm x 5 mm x 1 mm filtered by 0.4 mm of tin to provide an energy response within ±12% between 70 keV and 1 MeV. The output from this probe could be combined with that from a second unfiltered silicon detector, which has a greater response to radiation between 20 keV and 60 keV to give a measure of dose which is relatively independent of energy over the range 24 keV to 1 MeV (±28%) (figure 2) and so can potentially be used to monitor radiology procedures.

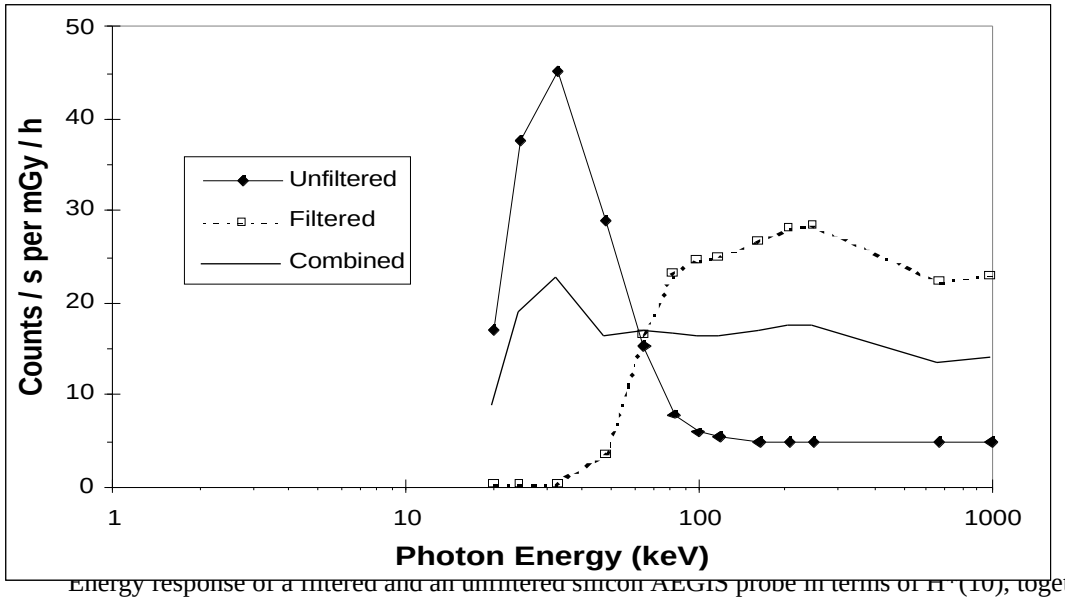


Figure 2 Energy response of a filtered and an unfiltered silicon AEGIS probe in terms of $H^*(10)$, together with the more uniform energy response obtained by combining the response from the two detectors.

Individual AEGIS probes and loggers were calibrated using sources of approximately 10 GBq of ^{99m}Tc in the form of 2 ml of liquid in glass vials. Measurements were made in the radiation field at distances between 50 mm and 3 m from the ^{99m}Tc sources. The count rates recorded were compared with the air kerma rate derived both by calculation and by measurement with a 6 cc ionisation chamber and MDH 9010 dosimeter (Radcal

Corporation, Monroveau, USA), whose calibration was traceable to National Standards. A purpose built jig was used to allow accurate positioning of the probe for measurements at distances from 50 to 300 mm from the source. In order to enable readings made in different positions to be separated and identified, AEGIS was placed in each position for 20-30 s. After this a lead shield was put in front of the probe for 5-10 s to give a low dose rate marker and the probe moved to another position. The whole process was repeated to give a series of exposures at different dose rates. Corrections were applied to each measurement to allow for decay of ^{99m}Tc. In order to confirm the linearity of the instruments at high dose rates, periodic measurements were also performed over periods of 4-5 radionuclide half-lives with the detector in a fixed geometry 80 mm from the source allowing natural decay of the ^{99m}Tc source activity to provide the range of dose rates required. The prototype version of AEGIS, called Gamma Extremity Monitoring System (GEMS) had saturated at dose rates of 2 mGy h^{-1} (Montgomery et al 1997), but the dose rate response of AEGIS with a cadmium telluride probe was linear up to 20 mGy h^{-1}, while that for the silicon probe was linear up to at least 80 mGy h^{-1}.

Variations in the response of the probe with orientation to the radiation source will affect the dose measurement. Therefore the response to ^{99m}Tc γ-rays in different orientations was evaluated for both types of probe using a purpose built jig. The lowest responses for both probes were in the 'end on' position in which the detector presented a smaller cross sectional area towards the radiation source, so that there was a higher self absorption (figure 3). However, the ends of the detector crystals were not shielded by the compensating filters for either probe and this enhanced the response in this direction, giving an overall uniformity in angular response to ^{99m}Tc γ-rays of ± 34% for the cadmium telluride probe over the range of orientations encountered and ± 32% for the silicon one. When the probe was strapped to the side of the finger in the position used for monitoring, the end of the probe pointed in the same direction as the finger and so could have a range of orientations with respect to the radiation sources of between end on and side on as the fingers moved. A calibration factor which was an average of the responses measured at 15^{o} intervals over the arc from 'side on' in one direction through 'end on' to ' side on ' in the other direction was applied to data derived from monitoring. The instantaneous dose rate response should be within ±27% of the actual value for the cadmium telluride probe and ±25% for the silicon probe. It is estimated that the mean result over a series of manipulations in which a range of finger orientations are involved should be within ±20% of the true value for the cadmium telluride probe and ±15% for the silicon one.

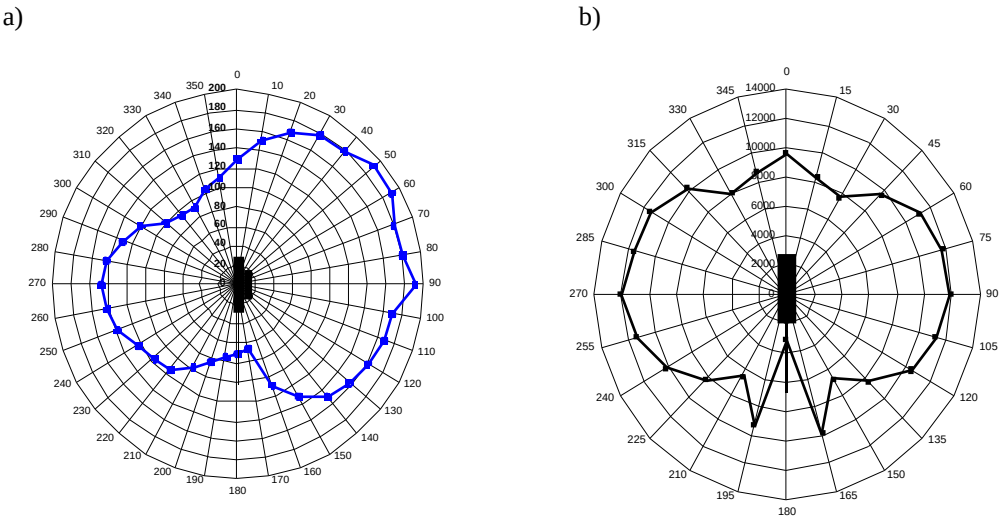


Figure 3 Angular response of AEGIS probes: a) Cadmium telluride with cylindrical compensating filter and b) silicon with flat compensating filter.

Monitoring radionuclide dispensing and administration procedures

In a hospital, radiopharmaceuticals are prepared in a radiopharmacy or radionuclide dispensary. They are then administered to patients for a variety of diagnostic procedures in nuclear medicine departments. Individual radionuclide dispensaries may serve several nuclear medicine departments, and as a result substantial activities may be handled. Nuclear medicine departments inject lower levels of activity, but the procedures are often longer, as they involve injection of the activity into patients, so exposures may still be significant.

The radiopharmaceuticals that are administered in twelve nuclear medicine departments in the West of Scotland are all prepared in the radionuclide dispensary at the Western Infirmary, Glasgow. They are dispensed in three

shielded laminar flow cabinets by six technicians. Different groups of radiopharmaceuticals are dispensed in each cabinet. One cabinet is devoted primarily to the dispensing of Methylene Diphosphonate (MDP), one to pertechnatate and the third to a variety of other radiopharmaceuticals. The MDP activities prepared are all within the range 800-1300 MBq, so the dispensing process consists of a series of repetitive actions using similar activities. At the start of each dispensing session, between 100 and 180 GBq of ^{99m}Tc is eluted from a ^{99}Mo generator and collected in a single 'elution' vial. This activity is dispensed into three or four 'kit' vials, each containing 15-17 GBq from which activity is later sub-dispensed into individual 'patient' vials.

All manipulations in the radionuclide dispensary are carried out using 1 ml syringes. Technicians undergo a period of intensive training in order to enable them to perform manipulations rapidly, relying primarily on reducing exposure time to minimise dose. A syringe shield made from high density leaded glass (6.2 g cm^{-2}) (Bright Technologies Ltd., Sheffield, UK), which allows good visibility, is sometimes used. However, standard practice has been for a shield not to be used, as staff find manipulations with the shield awkward to carry out. Monitoring was undertaken during dispensing sessions where a syringe shield was in use, as well as ones when no shield was used (Whitby and Martin 2002). The patient vials prepared in the dispensary are sent out to nuclear medicine departments in individual hospitals. Here radiopharmaceuticals are drawn up by nuclear medicine technicians and injected into patients. Images showing the accumulation of activity are obtained using gamma cameras. The injections may be performed by technicians, doctors or nurses. Syringe shields are not used routinely for drawing up radiopharmaceutical, but are used for giving injections.

In the radionuclide dispensary, where standard procedures are repeated many times and can be well practised, dose levels are similar for each manipulation, but in a nuclear medicine department where manipulations depend on individual patients, doses vary significantly. In this study doses received by radionuclide dispensary and nuclear medicine technicians during single manipulations of MDP have been determined. An AEGIS probe was worn along the side of a finger for most monitoring. Attempts to attach a probe to the back of a finger gave an unacceptable restriction in bending of the finger and attaching to the front was impractical. The index finger on the dominant hand was used for the majority of the monitoring for radionuclide dispensary technicians, but some measurements were made in other locations on either hand. Various locations on both hands were used for monitoring nuclear medicine technicians. Data were recorded throughout complete sessions and analysed at the end of each session. The variation in dose rate was displayed in real time on a laptop PC during some dispensing and injection sessions in nuclear medicine in order to enable doses to be linked to particular actions. Staff in the radionuclide dispensary were filmed using a video camera for several sessions, while they were being monitored and review of the video allowed the dose that was accumulated to be linked to the manipulations performed. These techniques enabled the actions which made the most significant contributions to the dose to be identified.

4. RESULTS

Patterns of exposure in a Radionuclide Dispensary

Results obtained using AEGIS show how the dose rate at the finger tip varies during manipulations of radionuclides. Figure 4 shows a typical example of the variations in dose rate recorded at the tip of the index finger of the hand holding the syringe during a complete dispensing session. The plots contain sets of peaks in dose rate each of which correspond to the dispensing of a volume of radioactive solution. Actions involved in dispensing of activity from the elution vial into kit vials and from a kit vial into patient vials are similar, but use different activity levels. Each manipulation during dispensing involves two basic actions; the withdrawal of radioactive solution from an inverted vial into a syringe and the injection of that solution into another vial. The most time consuming part, which gives rise to the majority of the dose, is the withdrawal of solution from the inverted vial. At the start of a session 100-180 GBq of eluted ^{99m}Tc is dispensed into individual kit vials. This appears in the trace as a period with peaks in dose rate of 20 - 200 mGy h^{-1}, which lasts for about two minutes (figure 4). Between four and six kit vials are prepared according to the requirements for that day. Each contains 15-17 GBq of ^{99m}Tc, and this requires one or two manipulations to transfer the activity. Sets of patient vials are then made up by sub-dispensing radioactive solution from the kit vials. The dose rate pattern for this part of the procedure shows 1-2 minute periods of exposure, made up of a series of peaks in dose rate of several mGy h^{-1}, each of which corresponds to the dispensing of 800 - 1300 MBq of ^{99m}Tc (figure 4).

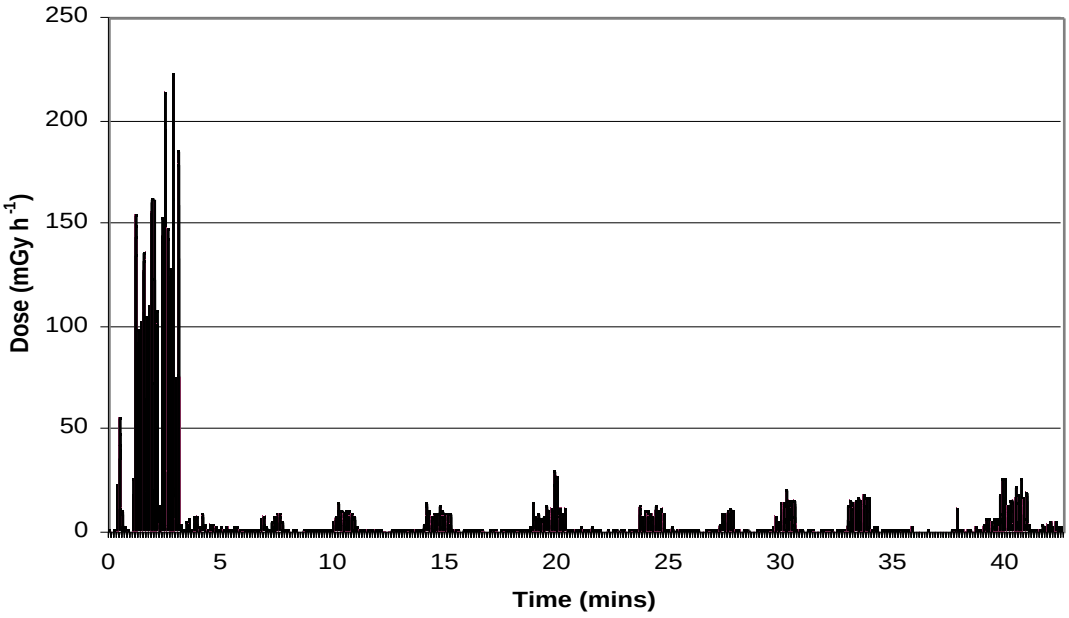


Figure 4 Variation in dose rate at the index finger during a complete session of dispensing MDPs without a syringe shield, recorded by AEGIS in the radionuclide dispensary.

When shielding devices are employed for parts of a procedure, the electronic dosimeter allows that dose reduction for those parts to be assessed more readily. Use of a syringe shield for making up the kit vials at the start of each session reduced the dose to the tip of the index finger from 1.9 ± 0.9 mGy to 0.24 ± 0.18 mGy for that part of the procedure and this is now used routinely (figure 5).

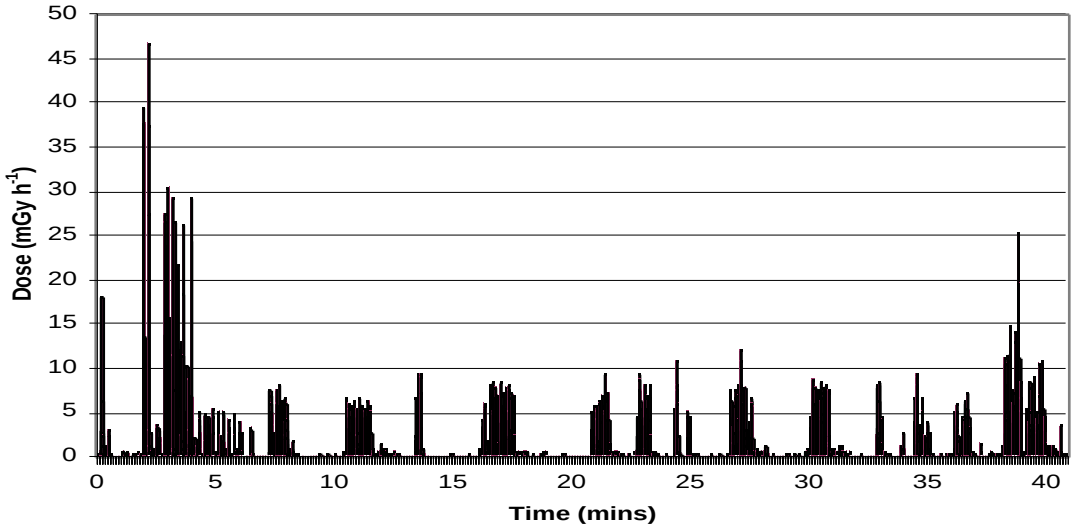
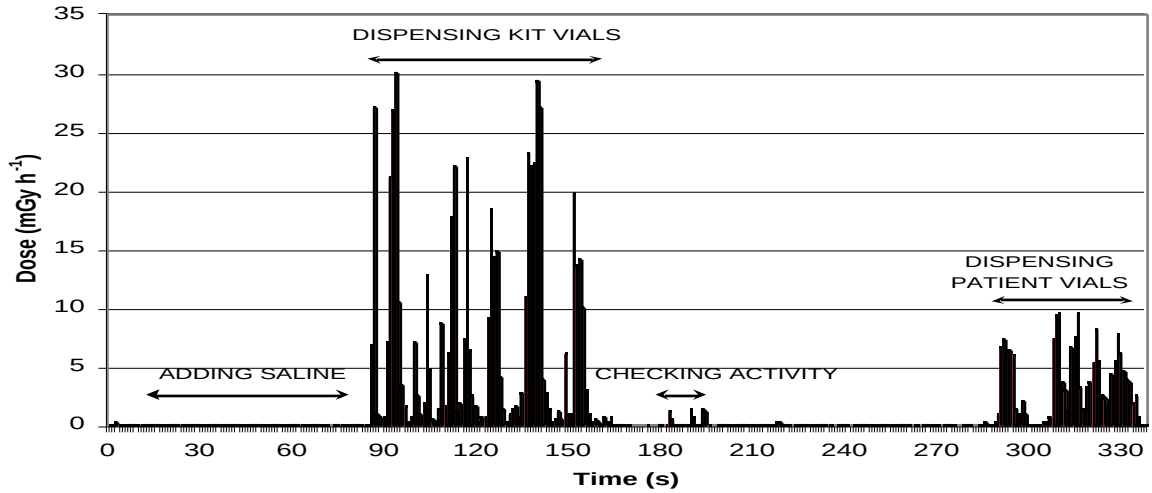


Figure 5 Variation in dose rate at the index finger during a complete session of dispensing MDPs in the radionuclide dispensary, recorded by AEGIS with a syringe shield used for the dispensing of kit vials at the start of the session.

An electronic dosimeter allows parts of a procedure to be identified where changes in technique may make only small reductions in dose and so enables dose optimisation. In order to achieve this it is necessary to be familiar with all the operations carried out. An example is shown in figure 6. The dispensing of a set of kit or patient vials consists of three types of manipulation. Standard practice is that first the vials into which radiopharmaceutical is to be dispensed are set out and volumes of saline added to each. Next about 1000 MBq of radioactive solution is dispensed into each vial giving a series of peaks in dose rate of 20-30 mGy h^{-1}. In the

example in figure 6a there are eight peaks corresponding to the dispensing of radioactivity into four vials. Finally the amount of activity in each vial is measured resulting in a period with small peaks in exposure. The sets of peaks in dose rate at the end of the procedure are from dispensing of the first few patient vials and are included for comparison. One technician in the radionuclide dispensary added the radioactive solution first, so that the high dose rate peaks are seen at the start of the manipulation. As a result, while saline was being added, her hand was exposed from the radioactive solution already in the vial (figure 6b). This shows up as a series of eight small peaks of about 5 mGy h^{-1} as two lots of saline are added to each of the vials. As the dose rate from adding the saline was only about 20% of that for dispensing radioactivity into the kit vials, the exposure would not have been apparent without the electronic dosimeter. Since the order in which solution was added to the vials does not affect the radiopharmaceutical preparation, it was changed and saline added to each vial at the start. Parts of a procedure where small dose savings can be made through a small change in a procedure are readily identifiable when an electronic dosimeter is used, so that the ability to optimise finger doses starts to become a reality.

a)



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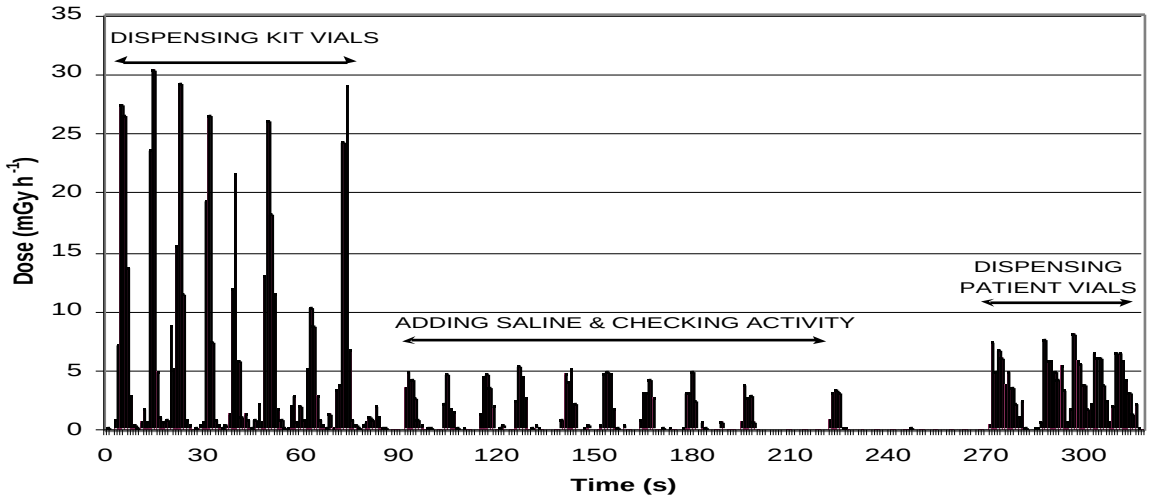


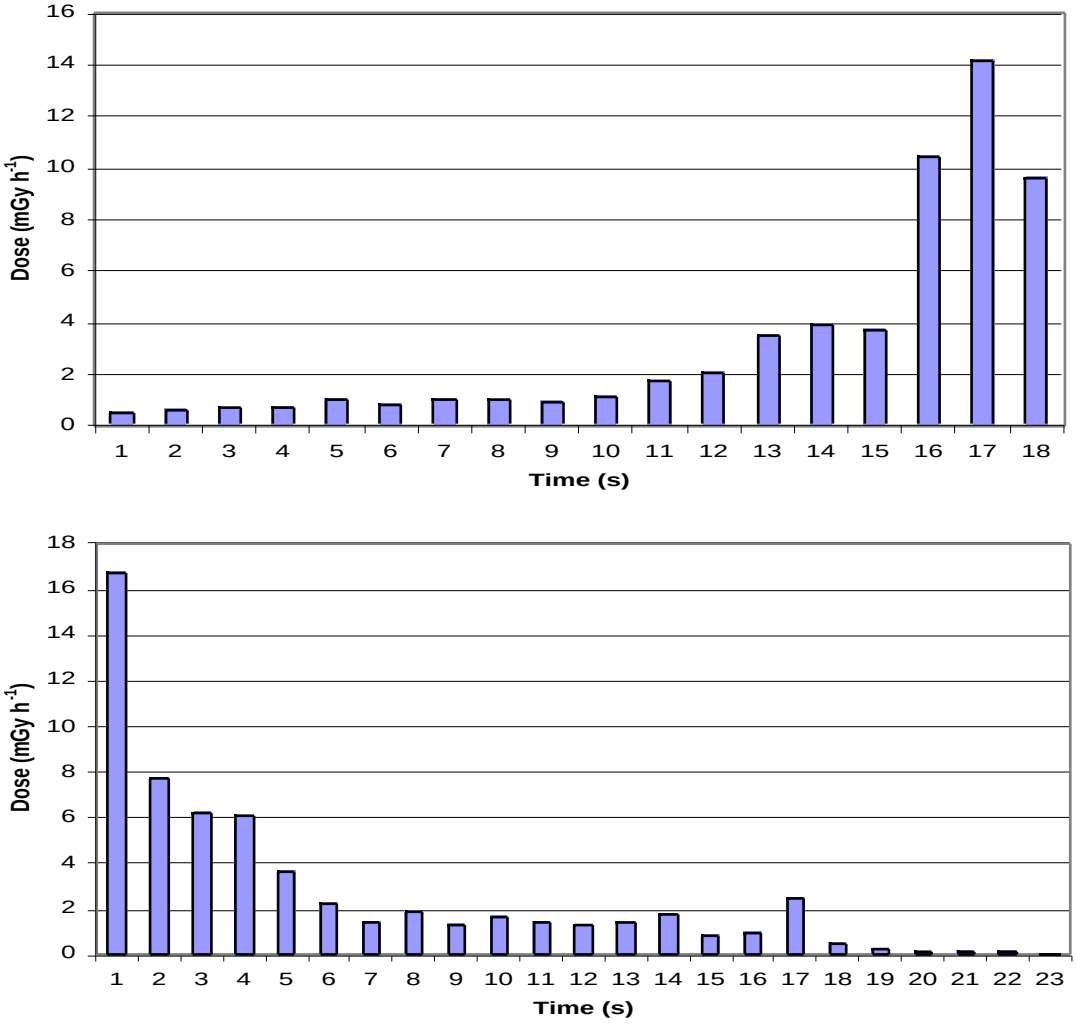
Figure 6 Variations in dose rate at the index finger during the preparation of kit vials using syringe shields in two separate dispensing sessions, with different sequences of operation: a) order of manipulations; dispensing of saline, dispensing of radiopharmaceutical and checking activity, and b) dispensing the radiopharmaceutical, followed by addition of saline and checking activity.

Patterns of exposure in Nuclear Medicine

There are significant differences in the technique of drawing up radiopharmaceuticals and of injecting into patients both between individual operators and between patients. Examples of some of the patterns of exposure, that can occur are given in figures 7 and 8. Figure 7a shows an example of the dose rate to the index finger of the hand holding the syringe as radiopharmaceutical is withdrawn. The dose increases as radiopharmaceutical enters the barrel of the syringe and moves closer to the fingers. When the withdrawal is almost complete, the

fingers are moved to nearer the end of the plunger as the final drops of liquid are carefully drawn up. This gives rise to a longer period of slightly lower dose rate exposure. Doses to the index finger are usually 5-20 μGy per withdrawal, but can be up to 500 μGy if the vial is not held in a lead pot. Figure 7b shows the variation in dose rate to the hand holding the vial. The dose is shown for the base of the little finger, as this is the part of the hand closest to the cap of the vial and the syringe. The dose rate starts off much higher as the activity is close to the hand, and then falls. There is again a longer period of lower dose rate exposure as the last drop of radiopharmaceutical is withdrawn. Doses to the hand holding the vial were generally slightly lower than those to the hand holding the syringe, being between 2 and 15 μGy per withdrawal. However, they could be as high as 100 μGy.

a)



b)

Figure 7 Examples of the variation in dose rate during drawing up of 600 MBq of ^{99m}Tc into a syringe in a nuclear medicine department for a) the index finger of the hand holding the syringe and b) the base of the little finger of the hand holding the vial.

The pattern of dose rate during injection is more variable than the drawing up as this is affected by the ease with which a vein can be located in a patient. In most departments a syringe shield is used for the injection. The index finger of the dominant hand is usually placed at the base of the needle in order to secure the position of the needle in the patient and as a result this finger usually receives the highest dose. Figure 8 shows examples of different dose rate patterns for the index finger of the dominant hand. In figure 8a insertion of the needle took only a few seconds, and the radiopharmaceutical was injected into the patient in a single discharge. The finger was placed higher up on the barrel of the syringe, and was therefore protected by the shield, so giving a smaller dose. There is a short period of exposure prior to the injection, which results from replacement of the needle on the syringe. This practice is undertaken in some departments prior to injection in order to ensure that the needle to be inserted into the patient has not been damaged by insertion into the rubber vial cap. In the example shown in figure 8b, the index finger was placed close to the base of the needle to facilitate insertion and injection of the

radiopharmaceutical into the vein, injection of the radiopharmaceutical extended over about a minute as the member of staff ensured a viable vein had been punctured. These examples provide an indication of how the dose can vary significantly between ostensibly similar operations with different patients. The range of doses to the hand per injection that was recorded during this study was typically 1.5 - 15 μGy, but could be up to 300 μGy.

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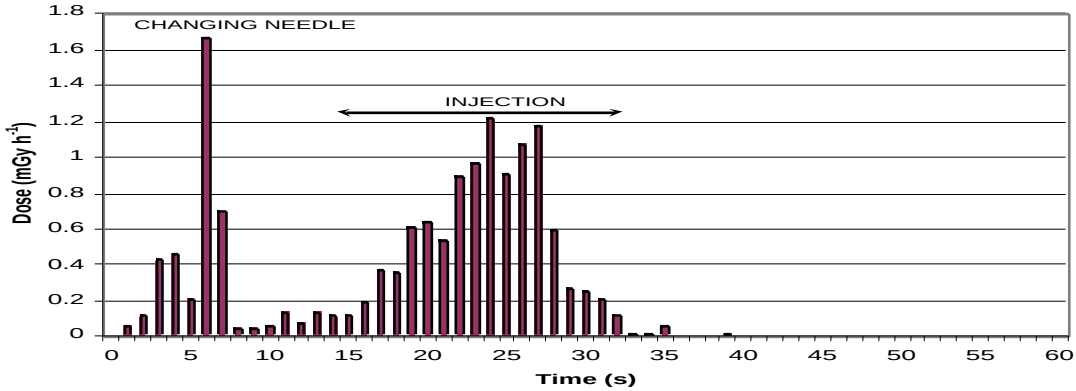

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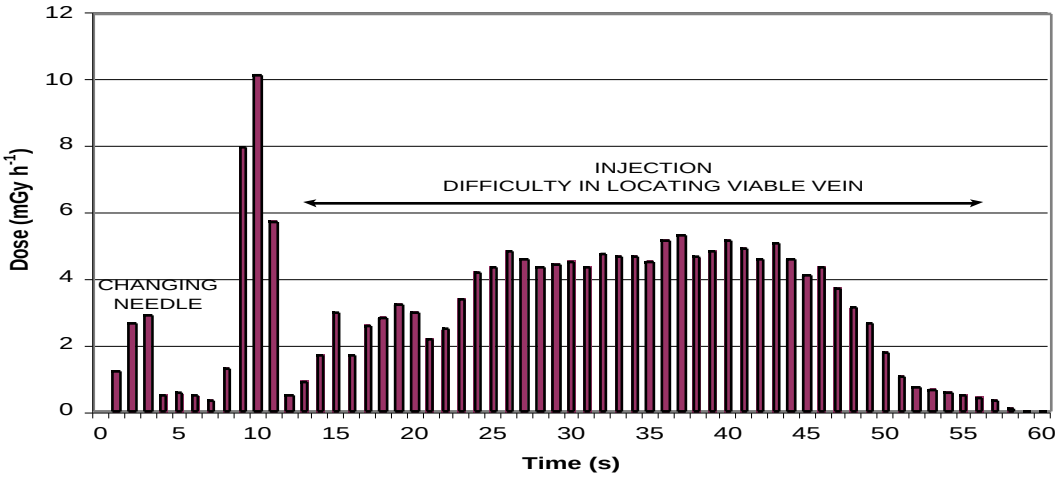

Figure 8 Examples of the variation in dose rate at the index finger during injection of 600 MBq of ^{99m}Tc labelled radiopharmaceutical into a nuclear medicine patients, showing differences that can occur in exposure.

Assessing the distribution of dose across the hand.
Use of an electronic dosimeter probe in different positions on the hand allows the parts receiving the highest dose to be identified more quickly than by conventional methods using TLDs. In the radionuclide dispensary and nuclear medicine the tips of the index fingers of the hands holding the syringe were found to receive the highest doses and this position was monitored for most of the study. Measurements with an electronic dosimeter also allow the relationship between the dose to the most exposed part and those to positions which might be used for monitoring to be studied.

5. DISCUSSION
An electronic finger dosimeter is a useful tool for dose assessment. Its primary role lies in dose optimisation rather than routine monitoring. The advantages of electronic dosimeters are that they enable the pattern of exposure throughout a session to be viewed, so that the procedures which give rise to the highest doses can be identified and doses for individual manipulations can be quantified. The dose received from each withdrawal of radiopharmaceutical can in principle be assessed and mean doses determined from a set of manipulations

performed in one session. Thus AEGIS is a tool which will be valuable to radiation protection practitioners, who can apply it in a variety of situations in order to optimise procedures.

The tasks that can be performed using an electronic finger dosimeter are:

- identification of parts of a procedure giving higher doses to the hands
- identification of areas of the hand receiving the highest dose
- identification of components of a procedure where changes in technique might be made to reduce doses from analysis of the patterns of dose delivered
- assessment of reductions in dose that can be achieved from changes in technique or use of dose reduction devices
- assessment of the relationship between the dose to the most exposed part of the hand and the position used for routine monitoring

In order for such a dosimeter to be used successfully, results need to be interpreted with the aid of persons familiar with the operations monitored. The best way of accomplishing this is for a radiation protection staff member to observe the procedures during the monitoring. Recording of a video of the manipulations during monitoring can also be a valuable aid in interpretation of results.

One major advantage of the technique is that doses can be assessed following changes in small parts of a procedure. For example the reduction in dose resulting from the use of a syringe shield for some of the manipulations within a dispensing session could be evaluated (figure 5). The syringe shields gave a significant reduction in finger dose, but made manipulations more difficult to carry out. As a result, use of a syringe shield was adopted for dispensing of the higher activity kit vials, where there was a high dose saving from a limited period of use, but not for sub-dispensing to patient vials. In addition, when an alteration was made in the order in which manipulations were performed in the radionuclide dispensary, with the insertion of saline into vials being made at the start rather than the end of the dispensing process, the removal of the component of the dose received from the vial into which liquid was being dispensed was immediately apparent and the resulting reduction in dose could readily be assessed (figure 6). Reductions in dose of this type would be difficult to assess using integrating dosimeters such as TLDs, as they would have been masked by statistical variation in measurements.

In nuclear medicine AEGIS traces clearly show where the most significant contributions to doses arise. Staff only handle vials containing single patient administrations and draw up almost all the radioactive liquid from the vial into a syringe for injection. For the majority of the drawing up procedure the dominant hand is closer to the activity in the syringe. AEGIS results showed that this drawing up procedure contributed more to the radiation dose than the injection, as a syringe shield was not used routinely for drawing up, but was for giving injections. Staff need to draw up as much of the activity from the vial as possible, while avoiding taking any air bubbles into the needle. The inverted vial is supported by the syringe needle, which is inserted through the rubber cap. The technician must ensure that the needle tip is always within the radiopharmaceutical when liquid is being withdrawn. It is this process which makes the manipulation more difficult and lengthy. In some cases technicians find that it is necessary to remove the vial from the lead pot to dispense the complete volume in order to obtain sufficiently good visibility to ensure that the tip of the needle stays beneath the surface. The doses received when injecting radiopharmaceuticals tend to be lower because syringe shields are used. However, there is a wide range in the doses received, which depends on the technique of the operator and the veins in individual patients. The main difficulty was in locating and puncturing a viable vein.

6. CONCLUSION

AEGIS is a new type of electronic dosemeter for recording dose rates at the finger. It has been used to analyse doses to the finger tips of hospital staff manipulating radiopharmaceuticals. The pattern of exposure from individual actions can be examined and the data is available for analysis as soon as the procedure has been completed. In this study doses received by radionuclide dispensary and nuclear medicine technicians during single manipulations of MDP have been determined. Although the numbers of vials handled by nuclear medicine departments is small, compared to the number handled by the radionuclide dispensary, finger doses received by staff may be significant, because staff need to view the radiopharmaceutical during the drawing up process to ensure that no air bubbles are taken into the syringe and injected into patients. The manipulation time cannot be reduced to the same degree as in a radionuclide dispensary by having a well practised technique and the injection procedure varies with individual patients. Electronic finger dosimetry systems such as AEGIS have the potential to become a valuable radiation protection tool which should allow a greater degree of optimisation of finger doses than has previously been possible. In addition to helping to identify actions giving rise to higher doses, AEGIS also enables the reduction in dose from changes in technique to be evaluated. AEGIS also allows doses for different parts of the hand to be determined to assess the best strategy for dose monitoring.

7. ACKNOWLEDGEMENTS
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