ISSN - 0250 - 5010

ANNALEN VAN DE BELGISCHE VERENIGING VOOR STRALINGSBESCHERMING

==========
VOL. 28, N°1, 2003, 2e trim. 2003

Nieuwe toepassingen van radionucliden in de geneeskunde
Nouvelles applications des radionuclides en médecine

Workshop : Dosimetry in hospitals

Driemaandelijkse periodiek Périodique trimestriel
2400 MOL 1 2400 MOL 1
==========

ANNALES DE L'ASSOCIATION BELGE DE RADIOPROTECTION

Hoofdredacteur Mr C. Steinkuhler Rédacteur en chef
Rue de la Station 15
B- 1325 Longueville

Redactiesecretariaat Mme Cl. Stiévenart Secrétaire de Rédaction
Av. Armand Huysmans 206, bte 10
B- 1050 Bruxelles - Brussel

Ce numéro contient les textes d'exposés présentés lors de la réunion organisée par l'Association belge de Radioprotection à Bruxelles, le 13 décembre 2002 et ceux du workshop sur la dosimétrie en milieu hospitalier organisé par SCK•CEN, le 13 mars 2003

Dit nummer bevat de teksten van de uiteenzettingen ter gelegenheid van de vergadering van de Belgische Vereniging voor Stralingsbescherming in Brussel, op 13 december 2002 en deze van de workshop over dosimetrie in ziekenhuis omgeving georganiseerd door het SCK•CEN op 13 maart 2003

SOMMAIRE **INHOUD**

Nieuwe toepassingen van radionucliden in de geneeskunde
Nouvelles applications des radionuclides en médecine
BVSABR, 13.12.2002

K. BACHER
Application of alpha emitters in nuclear medicine : facts and fictions **1**

R. HUSTINX
Radiotherapie métabolique des douleurs osseuse d'origine métastatique : Nouveaux traitements, nouvelles pratiques **9**

Workshop : Dosimetry in hospitals
SCK•CEN, 13.03.2003

P. GOVAERTS
Welkomstwoord **23**

M. SONCK
Survey of occupational dose results and analysis of constraints for implementation of regulations **25**

F. VANHAVERE
Quantities and units in personal dosimetry, principles of thermoluminescent dosimetry **33**

J. CAUSSIN
Aspects pratiques de la dosimétrie du personnel dans les laboratoires et les cliniques universitaires de l'UCL **41**

J. VAN DAM, B. NOWAK, R. BOGAERTS
Personendosimetrie in een ziekenhuisomgeving **51**

P. COVENS, D. BERUS, N. BULS
Extremity doses in nuclear medicine **55**

N. BULS, P. COVENS, M. OSTEAUX
Estimating occupational effective dose of lead apron protected workers in radiology **69**

APPLICATION OF ALPHA EMITTERS IN NUCLEAR MEDICINE: FACTS AND FICTIONS

Klaus Bacher[1], Katia Vandenbulcke[2], Filip De Vos[3], Jan Philippé[4], Guido Slegers[2], Fritz Offner[5], Rudi Dierckx[2], Hubert Thierens[1]

(1) Ghent University, Department of Medical Physics and Radiation Protection
Proeftuinstraat 86, 9000 Gent
(2) Ghent University, Department of Radiopharmacy
Harelbekestraat 72, 9000 Gent
(3) Ghent University Hospital, Division of Nuclear Medicine
De Pintelaan 185, 9000 Gent
(4) Ghent University Hospital, Department of Clinical Chemistry
De Pintelaan 185, 9000 Gent
(5) Ghent University Hospital, Department of Internal Medicine
De Pintelaan 185, 9000 Gent

Abstract
Radioimmunotherapy (RIT) with therapeutic doses of radionuclides conjugated to monoclonal antibodies is gaining importance in cancer therapy. Nowadays, new isotopes for the application in RIT are investigated. Because of their high potential efficacy, alpha emitters are of particular interest in different research programs.
To comply with the radiation protection legislation, a special laboratory was set up at the Ghent University Hospital for handling alpha isotopes. Special attention was paid to avoid cross-contamination in other rooms of the department.
Due to the stochastic nature, alpha-RIT requires microdosimetric calculations with Monte Carlo on a realistic model of the source and target cells at the micrometer level.
Despite the high LET of alpha-emitters, *in vitro* radiotoxicity experiments showed a biological efficacy that was lower than generally assumed. In addition, the *in vitro* experiments could not prove a better efficacy for radioresistant patients with alpha-RIT compared to external gamma irradiation. Therefore, patient studies will not be performed with alpha-RIT.

Introduction

The clinical application of radiolabeled antibodies is becoming an important tool in cancer treatment. Radioimmunotherapy (RIT) with therapeutic doses of beta-emitters conjugated to monoclonal antibodies has produced promising results in the treatment of lymphoma (1). Since beta-emitters have a path length in the millimeter range, they can also kill cancer cells in the vicinity that are either epitope negative or cannot be reached by the antibody. On the other hand, this ‘crossfire effect’ can cause undesired radiation damage to surrounding healthy tissues (Figure 1). Moreover, an increasing resistance to chemotherapy and radiation is observed in many patients with B-cell lymphoid malignancies (2)

Alpha-RIT could provide a solution for the limitations of beta-RIT. Alphas are high LET radiation in contrast to the low LET nature of betas: the ionization density along the path of the particle is about 1000 times larger for alphas than for betas (3) In addition, alpha-emitters have very short path lengths (50-90μm). The high LET allows a tumor cell to be killed by only a few nuclear hits, while the short path length reduces the toxicity to surrounding tissues.

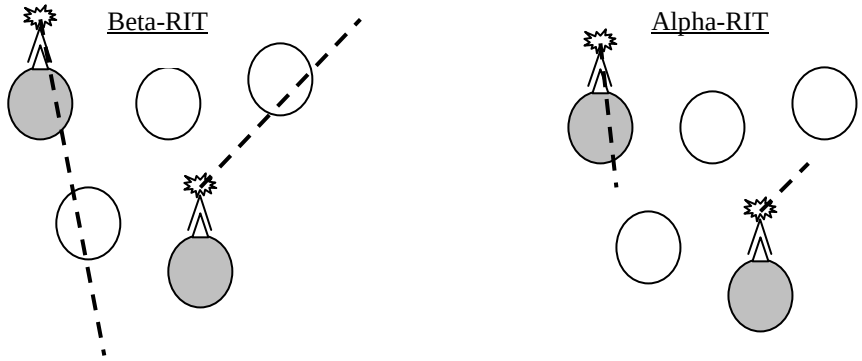


Figure 1: Schematic representation of the 'crossfire effect' in beta-RIT. Due to the very short path length, there will be no 'crossfire effect' in alpha-RIT.

Different alpha-emitters are under investigation in a large variety of research programs: ^{211}At, ^{212}Bi, ^{213}Bi, ^{225}Ac (4). In the framework of the European program of treatment of B-chronic lymphocytic leukemia (B-CLL), the possibilities of alpha-RIT using ^{213}B-anti-CD20 were examined in a multidisciplinary collaboration at the Ghent University and the Ghent University Hospital.

The 'alpha-lab'

To comply with the radiation protection legislation, a special laboratory was set up at the Ghent University Hospital for handling alpha isotopes (Figure 2). All measures were taken to keep the radiation exposure as low as possible.

Inside the laboratory, ^{213}Bi is produced from a ^{225}Ac/^{213}Bi generator, placed in a glove box with the purpose of confining the higher radio-toxic ^{225}Ac (half-life 10 d). The glove box is connected by a double-valve system with a central laminar airflow cabinet (Biohazard IIa), in which ^{213}Bi can be processed for *in vitro* experiments. An incubator is build-in on the other side of the Biohazard.

Special attention was paid to avoid cross-contamination in other rooms of the department. This could be achieved by a stepwise negative pressure gradient in the laboratory and up to 15 room refreshments per hour by a filtered ventilator. In addition, the closed circuit of the glove box, Biohazard and the incubator makes it possible to perform an experiment without leaving the air flow system (Figure 3). Moreover, a hand-foot-clothing monitor is available to avoid export of contaminated materials.

Figure 2: The 'alpha-lab' with a closed-circuit of the glove box, Biohazard and the incubator.

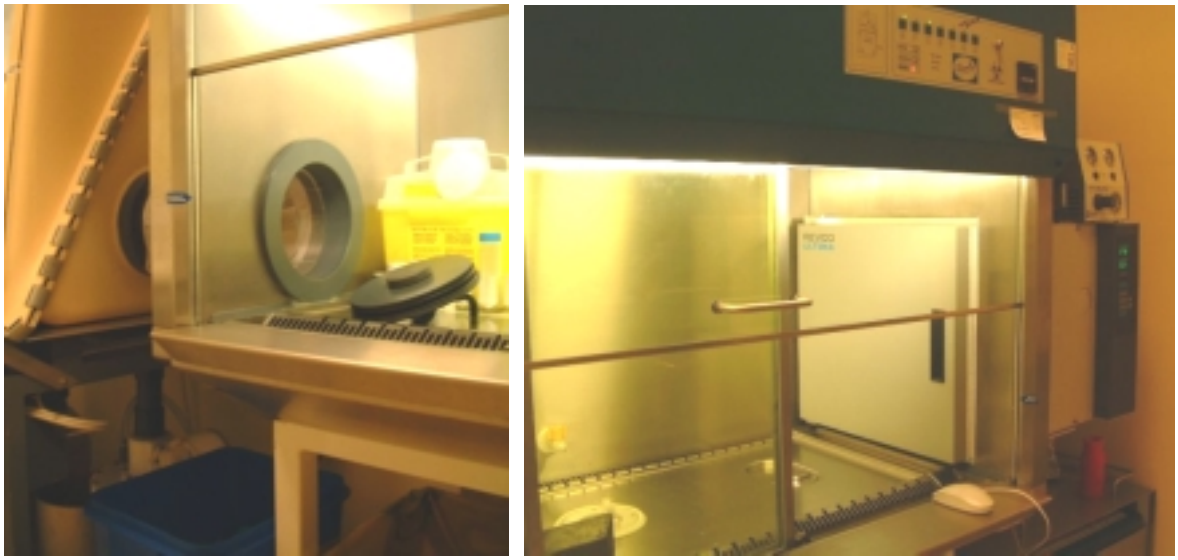


Figure 3: The double-valve connection between the glove box and the Biohazard (left) and the build-in incubator on the other side of the Biohazard (right) make it possible to perform an experiment without leaving the air flow system.

^{213}Bi for alpha-RIT

^{213}Bi is a decay product of ^{225}Ac (Figure 4). It can be eluted from a ^{213}Bi/^{225}Ac generator system. At present it is possible to produce up to 1 GBq of pure chemically reactive ^{213}Bi (4). However, one of the major limitations to constructing alpha particle-emitting generators is their rapid failure due to radiation damage.

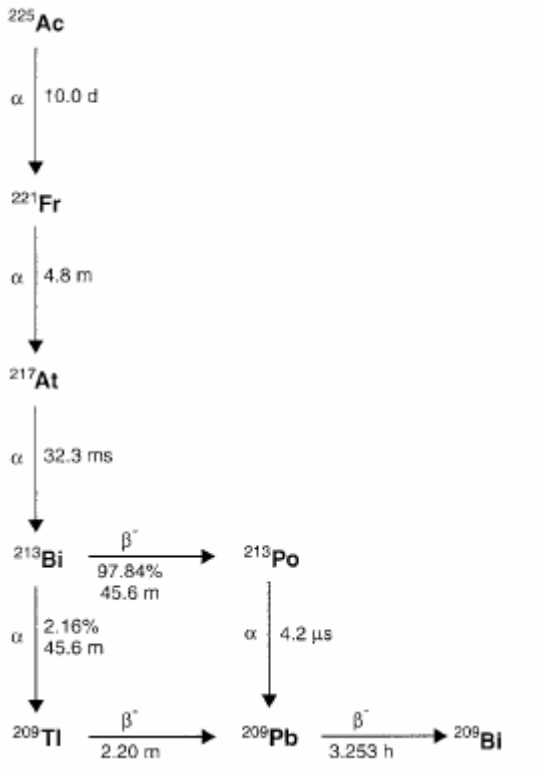


Figure 4: Decay scheme of ^{225}Ac and ^{213}Bi [4].

The half-life of ^{213}Bi is short (45.6 min). This has the consequence that it is not feasible to use ^{213}Bi in combination with monoclonal antibodies that need hours or even days to target tumor sites which are not immediately accessible (1) In addition, the processing time required to achieve elution of the radionuclide in the proper chemical form and to label it with the desired compound, must be short (4).

Microdosimetry [3]

Due to the high LET, complex DNA damage will occur after traverse of the cell nucleus by an alpha particle. As a consequence of this, single cells are sterilized by only two or three traverses of the cell nucleus. Due to this low number, the stochastic nature of the energy deposition has to be taken into account. Therefore prediction of the biological effects of alpha therapy by average quantities of energy deposition as the absorbed dose need to be replaced by simulations of alpha tracks by Monte Carlo simulations, which is the domain of microdosimetry.

Microdosimetry for alpha-RIT should be based on a realistic model of the source and target cells at micrometer level. The source compartment consists of monoclonal antibodies at the source cell membranes. The target compartment consists of the nuclei of the target cells. Using Monte Carlo simulations, hit distributions can be calculated and a prediction of the amount of surviving target cells can be made and can be compared with *in vitro* experiments.

In vitro comparison of alpha-RIT with external gamma irradiation

One of the questions to be answered was whether the alpha-emitters are capable of killing tumor cells that are resistant to conventional gamma radiation in a dose range that can be reached with similar or less toxicity. Therefore the relative biological efficacy (RBE) of equal absorbed doses of gamma versus alpha-RIT was measured for 2 biological endpoints: apoptosis induction in tumour cells and long-term chromosomal damage in non-tumoral cells (5) (6).

The alpha-particle exposure killed B-CLL cells more effectively than external gamma irradiation at low dose (RBE = 2), but a (similar) plateau was reached at high dose. Long-term toxicity on healthy B and T lymphocytes was systematically higher for the alpha emitter (RBE = 5 to 2) (5) (6). However, the *in vitro* experiments could not prove a significant better efficacy for radio-resistant and chemo-resistant patients with alpha-RIT compared to external gamma irradiation.

Conclusion

Because of their high potential efficacy, alpha emitters are of particular interest in different research programs. When taking the appropriate radiation protection measures, it is possible to handle alpha emitters safely for *in vitro* experiments.

Despite the high LET of alpha-emitters, *in vitro* radiotoxicity experiments showed a biological efficacy that was lower than generally assumed. In addition, the *in vitro* experiments could not prove a better efficacy for radioresistant patients with alpha-RIT compared to external gamma irradiation. Therefore, patient studies will not be performed with alpha-RIT.

References

[1] Postema E, Boerman O, Oyen W, Raemaekers J, Corstens F. Radioimmunotherapy of B-cell non-Hodgkin's lymphoma. Eur J Nucl Med 2001; 28: 1725-1735.

[2] Johnson T, Press O. Therapy of B-cell lymphomas with monoclonal antibodies and radioimmuniconjugates: the Seattle experience. Annals Heamatol 2000; 79: 175-182.

[3] Thierens H, Monsieurs M, Brans B, Van Driessche T, Christiaens I., Dierckx RA. Dosimetry from organ to cellular dimensions. Computerized medical Imaging and Graphics 2001; 25: 187-193.

[4] MucDevitt MR, Sgouros G, Finn RD, Humm, JL, Jurcic JG, Larson SM, Scheinberg DA. Radioimmunotherapy with alpha-emitting nuclides. Eur J Nucl Med 1998; 25: 1341-1351.

[5] De Vos F, Vandenbulcke K, Offner F, Thierens H, Philippe J, Slegers G, Dierckx RA. In vitro evaluation of anti-CD20 conjugated to 213 Bi versus external 60Co irradiation in apoptosis induction in B-CLL. J Nucl Med 2002; 43: 314P.

[6] De Vos F, Vandenbulcke K, Offner F, Brans B, Thierens H, Philippe J, Slegers G, Dierckx RA. Alpha-immunotherapy with 213Bi-Rituximab compared to external gamma irradiation and chemotherapy in B-CLL in vitro: correlation with clinical chemotherapy sensitivity. Eur J Nucl Med 2002, 29: 312.

RADIOTHÉRAPIE MÉTABOLIQUE DES DOULEURS OSSEUSES D'ORIGINE MÉTASTATIQUE: NOUVEAUX TRAITEMENTS, NOUVELLES PRATIQUES

Dr Roland Hustinx
Service de Médecine Nucléaire
CHU Liège

Dr Patrick Paulus
Service de Médecine Nucléaire
CHR Liège

Résumé

Le traitement palliatif des douleurs osseuses liées à la dissémination métastatique s'est récemment enrichi d'une molécule, le ^{153}Sm-EDTMP (Quadramet®). Le traitement classique faisait appel au Strontium-89 (Métastron®). Alors que ce dernier est un émetteur Beta pur, de longue demi-vie (50.5 jours), le ^{153}Sm émet également un rayonnement Gamma de 103 keV, et sa période physique est de 1,95 jours. Dans cet exposé nous envisagerons, du point de vue de la radioprotection, les propriétés pharmacocinétiques du radiopharmaceutique et les caractéristiques physiques du ^{153}Sm. Nous relaterons également l'expérience acquise dans notre centre avec le ^{186}Re-HEDP.

Les métastases osseuses

Le squelette constitue une localisation secondaire fréquente dans une grande variété de maladies néoplasiques. La prostate, le sein, le poumon, la thyroïde et le rein sont des tumeurs primitives particulièrement ostéophiles. De façon schématique, on distingue deux types de métastases osseuses : les lésions ostéocondensantes ou ostéoblastiques, et les lésions ostéolytiques. Quel que soit le mode prépondérant, le turn-over résorption/adsorption est accru d'un facteur multiple du turn-over physiologique. Les premières présentent un remodelage accru avec une prépondérance de la néo-formation osseuse. Elles accumulent les diphosphonates marqués et sont donc aisément visualisées en scintigraphie osseuse. Les secondes présentent essentiellement, voire quasi exclusivement une ostéolyse périlésionelle de telle sorte que la scintigraphie squelettique peut-être négative par défaut relatif d'accumulation du traceur, si la vitesse de croisade de la métastase est très élevé. Le caractère lytique ou condensant des lésions est un paramètre essentiel, qui va conditionner l'accessibilité de la maladie à une éventuelle radiothérapie métabolique. Mentionnons également que les lésions lytiques présentent un risque fracturaire, qui nécessite un traitement tumoricide spécifique. La fréquence d'apparition des métastases osseuses et leur distribution, lytiques ou condensantes, en fonction des tumeurs primitives les plus ostéophiles sont représentées dans le tableau 1. Les cancers de la prostate et du sein retiendront particulièrement notre attention. Il s'agit en effet de pathologies fréquentes qui présentent la

particularité d'évoluer sur un mode chronique. Très souvent, le patient répondra initialement à une première ligne de traitement, puis présentera un échappement thérapeutique. Une seconde ligne sera alors instaurée, d'efficacité plus limitée et ainsi de suite. Le résultat est qu'un nombre significatif de ces patients bénéficient d'une survie prolongée, malgré la présence d'une dissémination métastatique osseuse. L'intervention thérapeutique présente alors deux buts primaires : d'une part contrôler l'évolution de la maladie (plutôt que la guérir) et d'autre part maintenir une qualité de vie aussi bonne que possible. C'est dans ce schéma que s'inscrit la radiothérapie métabolique, palliative certes mais néanmoins cruciale pour le vécu quotidien du patient.

Les traitements classiques de la douleur osseuse métastatique

Jusqu'à la fin des années 80, les options thérapeutiques se limitaient aux traitements symptomatiques systémiques (antidouleurs, anti-inflammatoires), aux agents limitant le remodelage osseux (diphosphonates) et à la radiothérapie externe. Cette dernière est très efficace mais ne peut être appliquée qu'à un nombre limité de lésions. La seule possibilité de traitement d'une maladie disséminée est l'irradiation hémicorporelle, efficace mais dont la toxicité limite la répétition. La radiothérapie externe conserve néanmoins une place essentielle, dans des indications bien définies.

La radiothérapie métabolique

Les différents radiopharmaceutiques proposés dans la palliation des algies osseuses secondaires sont exposés dans le tableau 2, avec leurs caractéristiques physiques. Le P-32 n'est plus utilisé depuis longtemps, et n'est mentionné qu'à titre anecdotique. Tous reposent sur le même principe : il s'agit d'administrer par voie intraveineuse un radio-isotope émetteur de rayonnement β et présentant un tropisme ostéoblastique propre (le chlorure de Sr-89) ou couplé à un pharmaceutique dont l'accumulation est directement proportionnelle à l'activité ostéoblastique. Ainsi, les lésions secondaires osseuses seront irradiées préférentiellement, avec l'effet biologique attendu. On comprend qu'en fait, ce ne sont pas les cellules néoplasiques qui sont la cible principale, mais bien la zone de remaniement osseux péritumorale, responsable des douleurs osseuses. S' il existe un effet tumoricide, celui-ci n'est qu'un bénéfice collatéral, ces traitements n'ont pas la capacité de contrôler l'évolution tumorale.

Le radiopharmaceutique idéal peut être défini en termes physiques et biologiques :

- l'énergie du rayonnement β doit permettre un effet thérapeutique, mais puisqu'elle conditionne le parcours moyen, elle doit être limitée de manière à réduire l'irradiation des tissus sains périlésionnels, en l'occurrence les cellules souches et la moelle hématopoïétique.
- La biodistribution du radiopharmaceutique doit permettre un bon rapport cible/bruit de fond, avec une élimination urinaire rapide de la fraction libre.

- La période effective doit réaliser le compromis entre un débit de dose efficace, des mesures de radioprotection limitées et une toxicité modérée compatibles en pratique avec une activité et un mode de vie aussi normaux que possible.
- L'émission d'un rayonnement γ concomitant est un atout supplémentaire, car il permet la réalisation d'une imagerie.

Nous allons envisager les diverses molécules proposées, en nous attardant sur les deux d'entre elles qui sont disponibles sur le marché belge.

Le Sr-89 (Métastron®)

Il s'agit d'un émetteur β pur, d'une période physique de 50,5 jours. La dose administrée est standard (150 MBq) et n'est pas adaptée au poids du patient. La captation relative de la cible est très variable, estimée entre 11 et 88% de la dose injectée. Elle dépend du volume métastatique global (importance de la dissémination métastatique). Dans le même ordre d'idée, la dose administrée à la moelle osseuse varie de 0,9 à 9 Gy. Ce traitement est efficace, avec un effet antalgique dans 50 à 96% des cas, le plus souvent partiel mais améliorant significativement la qualité de vie. Le taux de réponse complète est de l'ordre de 10 à 20%. Compte tenu de la période physique, relativement longue, l'amélioration clinique n'intervient que 2 à 4 semaines après l'injection. En corollaire, l'effet thérapeutique, lorsqu'il existe peut persister de 3 à 6 mois.
Sur le plan de la radioprotection, les mesures appliquées après un tel traitement sont réduites. L'administration est réalisée en ambulatoire. L'absence de rayonnement γ limite le potentiel d'exposition de la population générale et de l'entourage du patient. Les précautions sont essentiellement destinées à éviter les contaminations. En effet, le sang, les fèces et l'urine restent modérément radioactives en particulier la semaine après l'injection. Pour autant que le patient ne soit pas incontinent, aucune collecte des déchets n'est nécessaire. Il n'existe pas de recommandations strictes concernant l'isolement des patients, mais d'une manière générale les mesures de radioprotection appliquées s'inspirent de celles en usage après un traitement par I-131 pour hyperthyroïdie. Le délai permettant la crémation de sujets décédés peu après l'injection de Sr-89, avec la libération dans l'atmosphère de traces d'isotopes à longue période (Sr-90), est un problème particulier non résolu.

Le Sm-153-EDTMP (Quadramet®)

Il s'agit d'un atome de Sm-153 couplé à une molécule d'acide éthylènediamine-tetraméthylènephosphonique. Le Sm-153 présente une période physique de 46,3 heures. Il émet des rayonnements β dont les énergies maximales sont de 810 keV (20%), de 710 keV (50%) et de 640 keV (30%). L'énergie moyenne de l'émission β est de 233 keV. En outre, le Sm-153 émet un rayonnement γ de 103 keV, permettant une imagerie de bonne qualité. La biodistribution du radiopharmaceutique dépend des propriétés de l'agent chélateur (EDTMP).

Celui-ci possède une haute affinité pour le squelette, se concentrant dans les régions à forte activité ostéoblastique, en ce compris les lésions métastatiques ostéocondensantes. La distribution du Sm-153-EDTMP est en fait en tous points comparable à celle des agents diagnostiques utilisés en scintigraphie osseuse. Les études de pharmacocinétique montrent une clairance sanguine rapide, de l'ordre de 85% de l'activité injectée en 30 minutes. L'élimination est exclusivement rénale avec 35% environ de l'activité retrouvée dans l'urine dans les 6 heures suivant l'injection. Le squelette concentre deux tiers environ de l'activité injectée.

Sur un plan thérapeutique, la courte période physique de l'isotope associée aux propriétés pharmacocinétiques, assurent des débits de dose à la cible plus élevés qu'avec le Sr-89, mais pendant une période de temps plus limitée. L'efficacité sur le contrôle de la douleur est assez similaire à celle du Sr-89, avec une toxicité médullaire réputée moindre, liée à la plus faible énergie du rayonnement β et à son parcours plus court. Notre expérience personnelle reste cependant trop limitée pour conclure de façon formelle. Lorsqu'il est efficace, le traitement produit ses effets plus précocement, 2-4 jours après l'injection. Ses effets sont cependant partiellement plus limités dans le temps (2-7 mois). En fait, des administrations itératives, toutes les 8-10 semaines ou en fonction de l'évolution clinique donnent le plus souvent des résultats cliniques très satisfaisants. Relevons que la dose administrée est fonction du poids du patient. La dose de 37 MBq/kg est celle qui fournit le meilleur compromis entre toxicité médullaire et efficacité thérapeutique.

Les doses absorbées par les différents organes sont mentionnées dans le tableau 3. La présence d'un rayonnement γ et les doses totales administrées, relativement élevées vont évidemment modifier les règles de radioprotection par rapport à celles appliquées pour le Sr-89. L'irradiation γ du personnel médical, une heure après l'injection de 3,7 GBq a été estimée à 300 μSv/h au contact de la poitrine du patient, 20 μSv/h à un mètre et 1 μSv/h à 3 mètres. Les mêmes études réalisées chez 16 patients ayant reçu 37 MBq/kg ont montré des débits de dose à 1 mètre, mesurés 6 heures après l'injection, qui varient entre 2 et 15 μSv/h. Le Service Universitaire de Contrôle Physique des Radiations (Pr. Smons) a effectué de nombreuses mesures lors des premiers traitements réalisés au CHU de Liège, afin de valider localement les mesures de radioprotection recommandées par la société commercialisant le Quadramet®. A titre d'illustration, nous donnons ici les valeurs obtenues pour deux traitements :

- Patient 1 : l'activité reçue était de 2 GBq, dont seulement 1,48 ont été injectés à la patiente (réserve médullaire limitée). Les débits de dose mesurés sont les suivants :
  - Au niveau du flacon, (2 GBq) :
    - 5000 μSv/h à 2 cm
    - 80 μSv/h à 1 m
    - 1,5 μSv/h contre la vitre plombée
  - Au niveau de la patiente, à hauteur du thorax, vessie vide, 6 H PIV :
    - 50 μSv/h à 5 cm
    - 10 μSv/h à 1 m

- Patient 2 : activité reçue 2,9 GBq , dont 2,7 GBq ont été injectés.
    - ❖ Pendant le transfert du laboratoire « chaud », émission à partir du conteneur plombé :
        - 2000 µSv/h à 5 cm, conteneur ouvert
        - 18 µSv/h à 5 cm, conteneur fermé
    - ❖ Patient, 5 minutes après l'injection :
        - 250 µSv/h à 5 cm
        - 33 µSv/h à 1 m
    - ❖ Patient, 5,5 heures après l'injection :
        - 100 µSv/h à 5 cm
        - 18 µSv/h à 1 m
    - ❖ Urines collectées pendant 6 heures, dans deux conteneurs :
        - 1500 µSv/h dans le premier
        - 250 µSv/h dans le second
    - ❖ Dose totale enregistrée sur un film-badge placé sur un mur à 180 cm du patient :
        - 40 µSv

Les mesures effectuées chez les autres patients étaient du même ordre de grandeur. Nous n'avons pas observé de débit de dose supérieur à 20 µSv/h à 1 m du patient, 6 heures après l'injection. Par conséquent, les mesures de radioprotection sont assez simples. Préalablement à l'administration du radiopharmaceutique et après celle-ci, il convient d'assurer une bonne hydratation du patient, favorisant l'élimination urinaire. L'injection est réalisée dans un local isolé, dans le service de médecine nucléaire, le patient utilise des WC réservés à son usage pour toute la journée. Il reste dans ce local pendant 5 heures 30 environ. Une scintigraphie corps entier est ensuite réalisée et le patient est alors autorisé à quitter le service, 6 heures après l'injection. Aucune consigne particulière n'est donnée pour son retour au domicile.

Le Re-186-HEDP et le Sn-117m-DTPA sont des composés en évaluation clinique, dont les propriétés s'avèrent intéressantes, mais qui ne sont pas disponibles sur le marché belge. Par conséquent nous ne les envisagerons pas dans cette discussion.

CONCLUSIONS

La radiothérapie métabolique des douleurs osseuses métastatiques est une méthode à la fois sûre et efficace, pourvu que les cas cliniques soient bien sélectionnées. La mise sur le marché d'une seconde molécule, le Quadramet® , qui vient s'ajouter au Métastron® disponible de longue date, devrait en élargir le champs d'application. En effet la molécule est reconnue pour le traitement de toutes les lésions osseuses métastatiques ostéocondensantes, quelle qu'en soit l'origine. Elle n'est donc pas limitée aux néoplasies prostatiques comme le prévoit les autorisation de remboursement pour la première molécule. Les données scientifiques publiées, confirmées par les mesures dosimétriques réalisées sur le terrain, démontrent l'innocuité du

traitement pour la population générale, au prix de mesures de radioprotection simples à appliquer, peu contraignantes pour le patient, et n'entraînant aucun surcoût en santé publique.

TABLEAU 1 :

Métastases osseuses

Tumeurs ostéophyliques primaires	Fréquence des métastases osseuses	Tumeurs ostéoblastiques ou mixtes
Prostate	**33-85**	**80%**
Seins	**47-85**	**40%**
Poumon	**30-55**	**< 8%**
Thyroïde	**28-60**	**≈ 0%**
Reins	**33-40**	**≈ 0%**

TABLEAU 2 :

Radiothérapie métabolique des métastases osseuses douloureuses

	^{32}P	^{89}Sr	^{186}Re	^{153}Sm	$^{117}mSn^{(4+)}$
Demi-vie (jours)	**14.3**	**50 .5**	**3.77**	**1.95**	**13.6**
Energie β max (MeV)	**171**	**1.49**	**1.08**	**0.81**	**0.152**
Energie β moyenne	**0.70**	**0.58**	**0.33**	**0.22**	**---**
Parcours moyen (mm)	**8.7**	**8**	**5**	**3**	**0.3**
Energie γ (KeV)	**-**	**-**	**137**	**103**	**159**
Traceur	**Phosphate**	**Chlorure**	**HEDP**	**EDTMP**	**DTPA**

TABLEAU 3 :

Dosimétrie du Quadramet®

Organe cible	Dose absorbée (mGy/MBq)
Surface osseuse	**6.76**
Moelle osseuse	**1.54**
Paroi vésicale	**0.973**
Reins	**0.018**
Ovaires	**0.009**
Testicules	**0.005**
Foie	**0.005**
Rate	**0.005**
Corps entier	**0.011**

Bibliographie

Galasko CSB. The anatomy and pathways of skeletal metastases. In : Weiss L, Gilbert AH. (Eds) Bone metastasis. GK Hall, Boston, 49-63, 1981.

Bone Metastases. Diagnosis and Treatment. In Rubens RD and Fogelman I. (Eds). Springer – Verlag 1991

Guise TA. The vicious cycle of bone metastases J Musculoskel Neuron Interact 2002;2(6):570-572

Giammarile F, Mognetti T, Blondet C, Desuzinges C, Chauvot P. Bone pain palliation with 85Sr therapy. J Nucl Med. 1999 Apr;40(4):585-90.

Berna L, Carrio I, Alonso C, Ferre J, Estorch M, Torres G. Bone pain palliation with strontium-89 in breast cancer patients with bone metastases and refractory bone pain. Eur J Nucl Med. 1995 Oct;22(10):1101-4.

Pons F, Herranz R, Garcia A, Vidal-Sicart S, Conill C, Grau JJ, Alcover J, Fuster D, Setoain J. Strontium-89 for palliation of pain from bone metastases in patients with prostate and breast cancer. Eur J Nucl Med. 1997 Oct;24(10):1210-4.

Ackery D, Yardley J. Radionuclide-targeted therapy for the management of metastatic bone pain. Semin Oncol. 1993 Jun;20(3 Suppl 2):27-31.

Serafini AN. Systemic metabolic radiotherapy with samarium-153 EDTMP for the treatment of painful bone metastasis. Q J Nucl Med. 2001 Mar;45(1):91-9.

Eary JF, Collins C, Stabin M, Vernon C, Petersdorf S, Baker M, Hartnett S, Ferency S, Addison SJ, Appelbaum F, et al. Samarium-153-EDTMP biodistribution and dosimetry estimation. J Nucl Med. 1993 Jul;34(7):1031-6.

Anderson PM, Wiseman GA, Dispenzieri A, Arndt CA, Hartmann LC, Smithson WA, Mullan BP, Bruland OS. High-dose samarium-153 ethylene diamine tetramethylene phosphonate: low toxicity of skeletal irradiation in patients with osteosarcoma and bone metastases. J Clin Oncol. 2002 Jan 1;20(1):189-96

Serafini AN. Samarium Sm-153 lexidronam for the palliation of bone pain associated with metastases. Cancer. 2000 Jun 15;88(12 Suppl):2934-9.

Lewington VJ. Targeted radionuclide therapy for bone metastases. Eur J Nucl Med. 1993 Jan;20(1):66-74.

Krishnamurthy GT, Krishnamurthy S. Radionuclides for metastatic bone pain palliation: a need for rational re-evaluation in the new millennium. J Nucl Med. 2000 Apr;41(4):688-91.

Samenvatting

Metabolische radiotherapie van metastatische osteoalgie. Nieuwe behandelingen en werkwijzen.

Kortgeleden is een nieuwe molecule, ^{153}Sm-EDTMP(Quadramet®), in gebruik genomen voor de palliatieve behandeling van botpijn veroorzaakt door het uitzaaien van metastasen. De klassieke behandeling doet beroep op Strontium-89 (Metastron®), een zuiver β-straler met een natuurkundige halfwaardetijd van 50,5 dagen. ^{153}Sm straalt naast een β van 0,7 Mev ook een γ van 103 keV uit en zijn natuurkundige halfwaardetijd bedraagt 1,95 dagen. Hier worden de farmacokinetische eigenschappen van de radiofarmaceuticum en de natuurkundige eigenschappen van ^{153}Sm besproken. De ervaring opgedaan in de dienst met ^{186}Re-HEDP wordt ook toegelicht.

Abstract

Metabolic radiotherapy of bone pain of metastatic origin: new treatments and practice.

Shortly a new molecule, ^{153}Sm-EDTMP(Quadramet®), has been used for the palliative treatment of osteal pain caused by the metastases. The classical treatment makes use of strontium-89 (Metastron®), a pure β-emitter with a physical half-life of 50.5days. ^{153}Sm emits both a β radiation of 0.7 MeV and a γ radiation of 103 keV with a half-life of 1.95 days. The pharmacocinetic properties of this pharmaceutical and the physical properties of samarium-153 are presented. Experience gained in this department with ^{186}Re-HEDP, is commented upon.

WORKSHOP

DOSIMETRY IN HOSPITALS

SCK-CEN 1 3 maart 2003

Voorwoord

Het Studie Centrum voor Kernenergie (SCK•CEN) organiseerde op 13 maart 2003 te Mol een seminarie over d*osimetrie in ziekenhuisomgeving* ***: 'Workshop on Personal Dosimetry in Hospitals : practical considerations and difficulties'***. Verscheidene uiteenzettingen met waardevolle informatie werden voorgesteld en de Belgische vereniging voor Stralingsbescherming is daarom met het SCK overeengekomen de teksten te publiceren in haar Annalen.

Wij danken organisator Filip Vanhavere voor deze medewerking. Wij wensen eveneens de gastsprekers te bedanken voor hun bijdrage.

Préface

Le Centre d'Etude pour l'énergie Nucléaire (SCK•CEN) a organisé le 13 mars 2003 à Mol un séminaire sur la *dosimétrie dans le milieu hospitalier :* ***'Workshop on Personal Dosimetry in Hospitals : practical considerations and difficulties'***. Plusieurs exposés contenant de l'information de valeur furent présentés et de ce fait l'Association Belge de Radioprotection s'est proposée en accord avec le CEN de publier les textes dans ses Annales.

Nous remercions l'organisateur Filip Vanhavere pour cette collaboration. Nous souhaitons également remercier les orateurs pour leur contribution.

Workshop
Dosimetry in hospitals
SCK•CEN, 13 maart 2003

Welkomstwoord
Paul Govaerts
Directeur-generaal van het SCK•CEN

Mevrouwen, Mijne heren

Het is voor mij een groot genoegen u te verwelkomen op deze studiedag over "Dosimetrie in hospitalen". Ik hoef u er niet van te overtuigen dat het gebruik van ioniserende stralingen in de medische sector steeds toeneemt, dit zowel voor diagnostische, therapeutische, interventionele als palliatieve doeleinden.

In tegenstelling tot wat men zou kunnen verwachten daalt de collectieve dosis ten gevolge van de blootstellingen van patiënten en personeel lichtjes sinds enkele jaren, zoals blijkt uit het overzicht gepubliceerd door UNSCEAR. Dit is het gevolg van een drastische verbetering van de kwaliteitsbeheersing. Kwaliteitsbeheersing is echter onmogelijk zonder betrouwbare en realistische meetmethodes. De dosimetrische technieken bij medische toepassingen wijken nogal af van deze bij de bewaking van de blootstellingen in de industriële sector. Vandaar het belang van deze studiedag.

Ondanks de voortdurende verbetering van de gemiddelde blootstelling weten wij dat sommige toepassingen zeer hoge dosissen vereisen van patiënt of personeel, zoals CT-scanning en interventionele radiografie. Een goede dosimetrie bij deze praktijken is essentieel om ALARA geoptimaliseerde procedures op te stellen.

Het SCK•CEN is een studiecentrum dat opgericht werd met het oog op onderzoek rond nucleaire energetische toepassingen. Sinds 1991 werden de onderzoeksthema's met betrekking tot nucleaire veiligheid prioritair gesteld. Het betreft hier de veiligheid van nucleaire installaties, het afvalbeleid, de bescherming tegen de blootstelling aan ioniserende stralingen en het onderzoek rond het beletten van de proliferatie van strategische materialen. Veel van deze expertise kan ook nuttig gebruikt worden in de medische sector. Het strategisch plan van 1999 weerhield dan ook deze sector als een opportuniteit voor maatschappelijk relevant onderzoek. Het SCK•CEN kent vandaag activiteiten rond de productie van medische radio-isotopen in de BR2-reactor, het onderzoek naar nieuwe toepassingen van radio-isotopen en hun productie, de optimalisatie van de blootstellingen bij diagnostische en interventionele blootstellingen, met inbegrip van dosimetrieproblemen. Daarnaast is ook het onderzoek rond biologische effecten op moleculaire schaal belangrijk voor de beheersing van de secundaire risico's van therapeutische bestralingen.

Geachte aanwezigen, ik dank u voor uw deelname en ben ervan overtuigd dat u een boeiende namiddag zal beleven.

Annales de l'Association Belge de Radioprotection Vol. 28,n°1,2003

SURVEY OF OCCUPATIONAL DOSE RESULTS AND ANALYSIS OF CONSTRAINTS FOR IMPLEMENTATION OF REGULATIONS

Michel Sonck

Associatie Vinçotte Nucleair
Walcourtstraat 148, B-1070 Brussel, BELGIUM

1. Introduction

Routine monitoring of occupational exposure to ionising radiation is performed for different reasons. The most obvious reason is of course to verify and to demonstrate compliance with the regulatory dose limits. Other applications of monitoring radiation doses include indicating good radiation protection practices, identifying new risks and implementing ALARA policies.
The results of this routine monitoring are grouped into individual dose records for all professionally exposed workers. These individual dose records are stored for 30 years and can be used to document professional radiation disease cases, epidemiological studies and for medico-legal reasons.

2. Dosimetry in medical practice

As generally is known, ionising radiation is used extensively in medical practice. The most obvious applications of ionising radiations in hospitals are diagnostic radiology, diagnostic or therapeutic metabolic use of radionuclides in nuclear medicine departments and external radiation therapy or brachytherapy in radiotherapy departments. Other medical applications of ionising radiation include also cardiac catheterisation under radioscopy, in-vitro biomedical research and also radionuclide and radiopharmaceutical production around cyclotrons and associated laboratories.
Hospital workers in these departments are liable to be exposed to ionising radiation and are hence prone to routine monitoring of professional radiation exposures. When taking a look at a typical distribution of the number of monitored workers in a large hospital over the different departments, as shown in Figure 1, the large importance of the subgroup formed by the workers of the diagnostic radiology department is noticed immediately. These include radiologists, X-ray technicians and dedicated nurses of the radiology department. We also notice that the subgroup of general nurses form an important fraction of all monitored workers. These nurses are typically monitored because it cannot be excluded that they come into contact with hospitalised patients who received nuclear medicine procedures. Their doses can in general be expected to be low to very low.

3. Doses received

The distribution of the number of monitored people over the departments of a hospital of course holds no information on the registered doses for these workers. Table 1 gives the annual dose distribution for a medium-sized hospital for the period between 1998 and 2002 and this for the departments Radiology, Nuclear Medicine and Radiotherapy. These are the most important departments where ionising radiation is used and that we can find in most hospitals. It has to be mentioned that the workers of the cardiac catheterisation department are included in the dose distribution for the radiology department.
The total distribution for these 3 departments together is shown in Figure 2. These results are based on dosimeters that are replaced every month and that allow for natural background correction. Furthermore, the limit of detection for these dosimeters is 50 µSv for every month. Hence workers with an annual dose below 0.05 mSv are workers for whom no dose was recorded above the limit of detection for any of the months. In other words, these workers are not measurably exposed to ionising radiation.

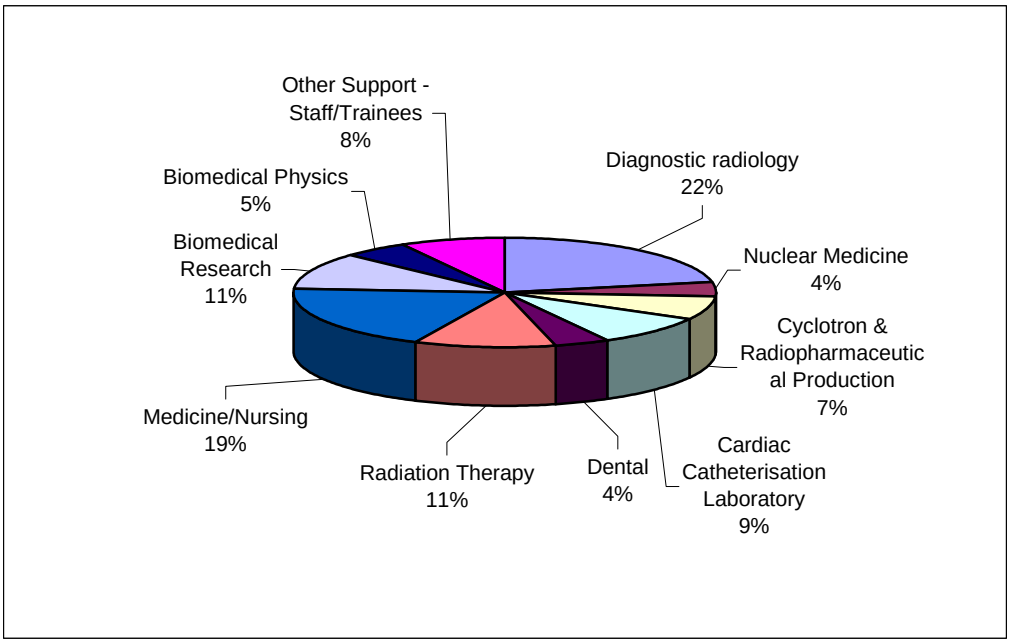


Figure 1. Typical distribution of monitored workers in hospitals

Table 1. Annual dose distribution for medium-sized hospital (1998-2002)

	Radiology	Nuclear Medicine	Radio therapy	Total	%
< 0.05 mSv/y	178	38	149	365	58.8
0.05 < 1 mSv/y	103	23	34	160	25.8
1 < 5 mSv/y	34	26	3	63	10.1
5 < 10 mSv/y	6	20	0	26	4.19
> 10 mSv/y	7	0	0	7	1.13
Total	328	107	186	621	100

From Table 1 and Figure 2 it can be concluded that the total dose distribution is very skewed towards low doses, with almost 60% of these workers being not measurably exposed and 85% exposed to levels below the dose limit for the general public. Roughly 1% of the workers in radiology, nuclear medicine and radiotherapy are exposed to levels above 10 mSv/year.

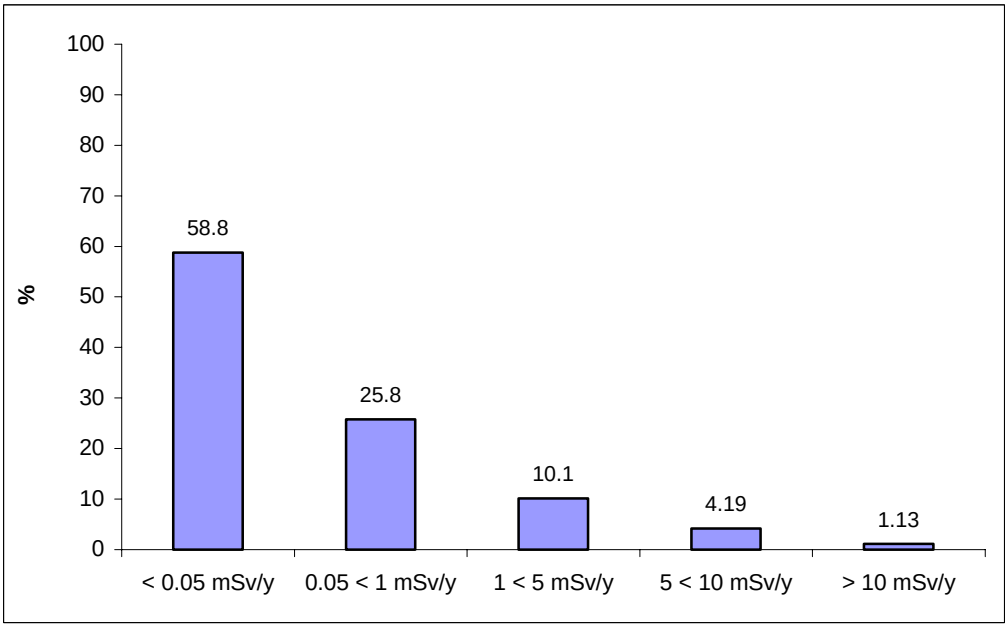


Figure 2. Total dose distribution for 3 departments of medium-sized hospital (1998-2002)

From Table 1 it is seen that in radiotherapy workers are mainly exposed to low doses, below 1 mSv/year. Doses in nuclear medicine are practically equally distributed in the moderate dose range between 1 and 10 mSv/year. In radiology, mainly low doses below 1 mSv/year are found, but the workers who are being exposed to high levels of ionising radiation, above 10mSv/year, are also found here. The highest annual dose recorded for this hospital for this period 1998-2002 was 17.5 mSv/year for a cardiologist. It should also be mentioned all workers in Table 1 exposed to annual doses above 10 mSv/year work in interventional radiology and that doses for the diagnostic radiology applications form the lower part of the distribution.
In conclusion it can hence be stated that in general low doses or no occupational doses at all are recorded for hospital workers. However there is a wide variation between the different departments and even within the same department in the exposures recorded. Some subgroups are exposed to important doses. This is especially the case for workers in interventional radiology.

4. Mean annual dose

Figure 3 represents the mean annual dose in the period 1998 to 2002 for several hospitals of different sizes. A total of 8850 dose records are included.
The graph shows that the mean annual occupational dose over the period 1998-2002 remains more or less constant, with a certain tendency to fall at the end of the period. When taking a look at the annual doses for the measurably exposed workers, in other words those workers with at least one recorded monthly dose over the limit of detection of 50µSv, significantly higher doses are noted, which is consistent with the fact that a large amount of the monitored workers in hospitals are not measurably exposed. Furthermore it is noticed that the mean annual dose of the measurably exposed workers has a tendency to rise for 2002, there where the overall mean annual dose has a tendency to fall.
Comparing these mean annual doses with the UNSCEAR values for measurably exposed hospital workers, which report for the period 1990-1994 an annual dose of 1.38 mSv (radionuclide production not included), a rather good agreement is observed between the values reported here and the UNSEAR values.

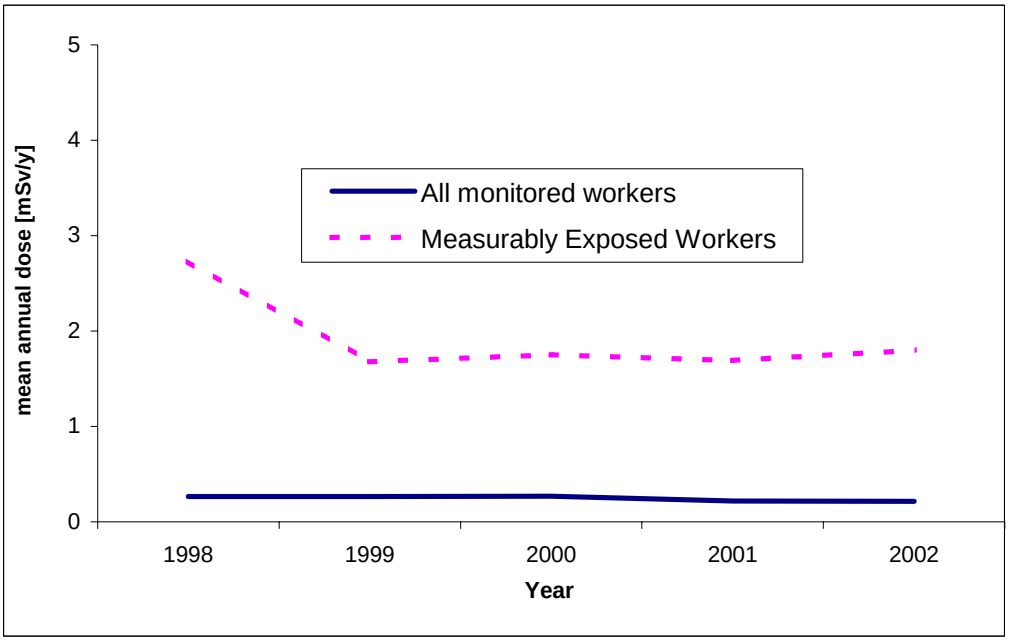


Figure 3. Mean annual dose for several hospitals (1998-2002)

5. Usage of dosimeter

That in a medium sized hospital a very large portion of the monitored workers in hospitals are not measurably exposed and that a majority of the registered doses is below the dose limit for the general public were already mentioned. A possible reason for this can be found in our legislation, which imposes the use of a dosimeter in all cases where there is a risk of being professionally exposed. Being effectively exposed is of course a different thing. It also indicates that employers tend to interpret this rule rather strict.

Another possible reason could of course also be that the dosimeters are not worn systematically or even not worn at all.

Figure 4 shows the dose distribution for hospital workers as registered by the dosimetric service of the Belgian research centre SCK•CEN for the period 1998-2002. This graph shows that 87% of all workers are not measurably exposed while the registered dose for 96% of them remains below the dose limits for the public. Comparing these results with the ones found earlier for one particular medium sized hospital, shows that there are large differences for the dose distributions for workers doing the same type of work. This leads to the conclusion that the dosimeters are effectively not worn systematically. This conclusion corresponds furthermore to personal observations made during routine inspections in hospitals.

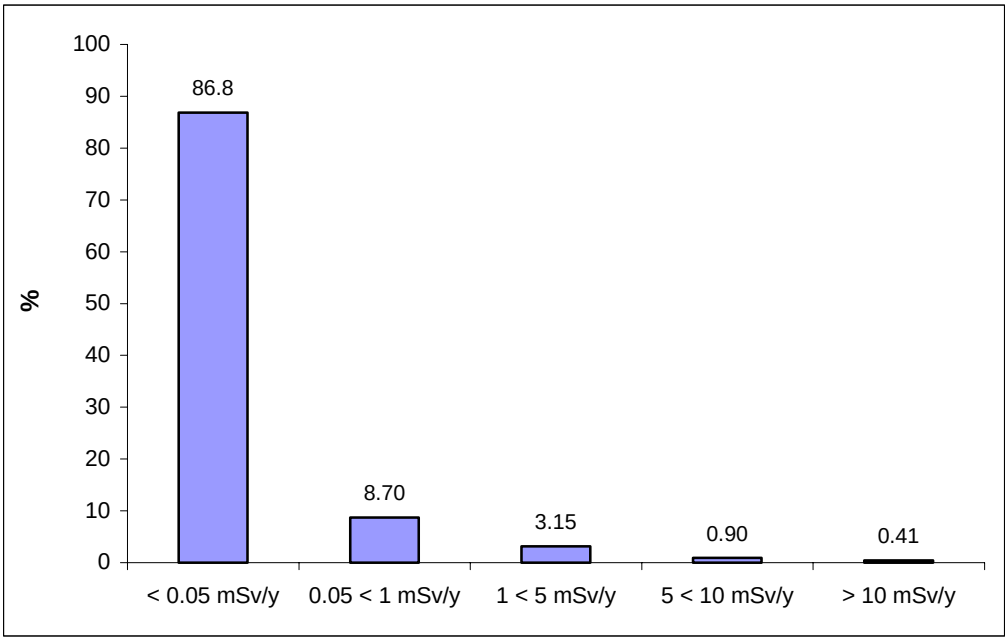


Figure 4. Dose distribution for hospital workers registered by SCK•CEN (1998-2002)

6. Quality of dose assessment

The effective dose, the property we need to measure, hides in fact a very abstract concept. It is a physical property that cannot be measured directly. It involves a weighted summation over the different parts of the body exposed to radiation and over the different types of radiation.

Typically the workers wear one dosimeter on the chest. If we want to calculate the effective dose received by the person wearing the dosimeter, the exposure of this dosimeter somehow needs to be characteristic for the exposure off all parts of the body. This is hence only possible in case the body is exposed to a homogeneous or quasi-homogeneous radiation field.

Examples of homogeneous or quasi-homogeneous exposure include exposures at large distances from an X-ray tube or behind a protective screen, exposures outside a linear accelerator room for external beam therapy and exposure at a sufficiently large distance from a radioactive patient some time after injection of a radio-pharmaceutical.

The assumption of a quasi-homogeneous exposure is not valid in these cases: exposure near, or even in, the primary beam of an X-ray tube, exposure while manipulation radionuclides (preparation, injection, …) and exposures near or at a moderate distance from an X-ray tube while wearing a protective lead apron.

Hence it can be stated that in clinical practice it is often not possible to determine the effective dose with only one dosimeter due to the use of directional radiation fields or because of the short distance between sources of ionising radiation and particular parts of the body like fingers and hands.
Consequently high to very high local dose may result to particular parts of the body for which even the dose limits may be exceeded. It should be noted that these limits prevent deterministic radiation effects in contrast to the 20 mSv/year effective dose limit, which is a stochastic dose limit.
To augment the quality of dose assessments, typically the use of additional dosimeters to measure the local doses is needed. This includes the use of dosimeters worn at the fingers or at the wrist, but also the use of a dosimeter above and under the lead apron and of course wearing dosimeters at all relevant places where high local exposure can be expected.
According to Belgian legislation, the use of additional dosimeters is mandatory in all cases where the local exposure could exceed 3/10 of the deterministic dose limit for these parts of the body. If in this case a lead apron is being used, the use of dosimeters above and under the lead apron is also mandatory. This is commonly referred to as double dosimetry.
The use of additional dosimeters can solve some of the operational problems with determining the effective exposures of hospital workers due to non-homogeneous radiation fields. However some problems remain. These include for instance the need for neutron dosimetry due to the increasing use of cyclotrons in hospitals for the production of short-lived radionuclides and because of the increasing use of high-energy linear accelerators for external radiotherapy. It should however be mentioned that more recent trends in radiotherapy tend to use lower energy particle beams, for which considerable less or even no production of neutrons exists. Contrary to their increasing use in the nuclear industry, practically no neutron dosimeters are being used in medical installations. Another remaining problem is of course the need for internal dosimetry due to the increasing use of radionuclides and radiopharmaceuticals in hospitals. The lack of a system for internal dosimetry is a general problem also known in nuclear industry.

QUANTITIES AND UNITS IN PERSONAL DOSIMETRY, PRINCIPLES OF THERMOLUMINESCENT DOSIMETRY

Filip Vanhavere

Instrumentation, Calibration and Dosimetry
SCK-CEN, Belgian Nuclear Research Centre
Boeretang 200, 2400 Mol, Belgium

Introduction

In radiation protection we want to prevent deterministic effects of ionising radiation, and limit the stochastic effects to acceptable risks. Radiation protection is based on three principles: ALARA(= As Low As Reasonably Achievable), justification and dose limits. Dosimetry is necessary to control these dose limits and to help applying the ALARA principle, so it is an essential part of the radiation protection field.

Quantities and units

Fundamental quantities:

Exposure (X): the number of X- or gamma-rays necessary to form 2 x 10^9 ions in air. The unit is the Rö ntgen (R): 1 R = 2,58 x 10^4 C/kg air.
Air Kerma (K_a): the sum of the kinetic energy of all particles created in air by the incoming particle. The unit is Gray (Gy): 1 Gy= 1 J/kg. Air kerma replaces exposure as fundamental quantity because it is valid for all energies and particles. For photon energies below 1500 keV the ratio between K_a/X is fixed (=8,76 mGy/R)
Absorbed Dose (D): the energy absorbed in a certain mass of a material. The unit is Gray (Gy): 1 Gy= 1 J/kg. The old unit was the rad (1 Gy = 100 rad)
Equivalent dose (H): different types of radiation can give different biological effects, even for identical absorbed doses. To take this into account, the absorbed doses are multiplied with a weighting factor W_R. The result is called equivalent dose: $H = W_R \cdot D$ The unit is called Sievert (Sv). This is also J/kg, but is given a new name to make the distinction with absorbed dose.

Protection quantities:

The protection quantities are defined such that they form the link with the biological effects on humans. For deterministic effects the protection quantity is the organ equivalent dose H_T. A certain organ will show a deterministic effect when H_T is higher than a certain limit. For stochastic effects, the protection quantity is the effective dose E. E is defined as the sum of the equivalent doses in a selected number of organs, multiplied by a weighting factor W_T for every organ. The effective dose is a measure for the risk to stochastic effects.

$$E = \sum_R \sum_T \quad w_R \; w_T \; D_{T,R}$$

The yearly dose limits are expressed in effective dose and organ equivalent dose[(1)]. The dose limits for effective dose are low enough to exclude deterministic effects. Two exceptions are the dose to the eye lens (no contribution to effective dose) and localised exposures to the skin. So, next to a whole body dosemeter to estimate E, extremity dosemeters for these two cases can be necessary.

Operational quantities

In practice it is not possible to measure the absorbed dose in every organ, so the effective dose is a non-measurable quantity. To solve this, the operational quantities have been introduced. These are defined to give a good but conservative estimate of the effective dose, and are easy to measure.
Ambient dose equivalent H* (d): equivalent dose at *d* mm depth in an ICRU sphere (tissue equivalent, 30 cm diameter)
Personal dose equivalent $H_p(d)$: equivalent dose at *d* mm depth at a place on the body, mostly the chest.
There are also the angular dependent operational quantities $H'(d,\alpha)$ and $H_p(d,\alpha)$. For the depth *d* two values are taken: *d* = 10 mm for strongly penetrating radiation; and *d* = 0,07 mm for weakly penetrating radiation. Through calculations on standardised human phantoms of different irradiation geometries, it was checked that the operational quantities are a good conservative estimate of E[(2)]for all energies. Only when the irradiation comes predominantly from the back and the dosemeter is worn on the chest, an underestimation can take place. Also for some intermediate neutron energies an underestimation can occur.

Calibration of personal dosemeters

The calibration of personal dosemeters is described in the ISO 4037 series[(3)]. Personal dosemeters need to be calibrated in $H_p(10)$. This is done by bringing the dosemeter in a radiation field with a known spectrum. The air kerma value is first determined in free air with a reference ionisation chamber. From this K_a value the reference $H_p(10)$ value is calculated using tabulated conversion factors[(2)]. For irradiation, the dosemeter is mounted on a 30 x 30 x 15 cm PMMA phantom filled with water. The result of the dosemeter can than be related to the reference value.

The thermoluminescent dosemeter of the SCK-CEN

As we saw before, the intention of dosimetry is to measure $H_p(10)$ and $H_p(0.07)$ with a dosemeter. This dosemeter is worn, mostly during 1 month, at chest height. For dose equivalent detectors (which is more or less the case for LiF:Mg,Ti thermoluminescent dosemeters) it is enough to put a 10 mm tissue equivalent filter in front of the detector. Because of the finite thickness of the detector itself, in reality the filter should be less than 10 mm. The TL-dosimeter of the SCK•CEN has 3 detectors behind different filters with thicknesses: (A)13 mg/cm², (B) 400 mg/cm², (C) 710 mg/cm². The B-detector of this dosemeter has an almost flat energy response (max deviation 20%) compared to $H_p(10)$, as was shown by measurements. The A-detector measures $H_p(0.07)$, the C-detector is used as a back-up. For every read-out the glow curve is automatically checked on irregularities, and the ratios of the different detectors are checked to be within standard intervals.

Uncertainties in personal dosimetry

The basic requirement for personal dosemeters is to provide a reliable measurement of $H_p(10)$ and $H_p(0.07)$ for almost all practical situations with a prescribed overall accuracy. In the ICRP 35 publication[4] following recommendation can be found for the overall accuracy:
"The uncertainties in the measurement of the annual value of the operational quantities should be reduced as far as reasonably achievable. If these quantities are of the order of the relevant annual limits, the uncertainties should not exceed a factor of 1.5 at the 95% confidence level. Where they amount to less than 10 mSv an uncertainty of a factor 2 is acceptable. This uncertainty includes errors due to variations in the dosemeter sensitivity with incident energy and direction of incidence, as well as intrinsic errors in the dosemeter and its calibration. It does not include uncertainties in deriving organ dose equivalent or effective dose values from the dosemeter results."
It is accepted that for neutrons and low energy betas these requirements can not be achieved.
The ICRP have recommended that the level of doses, above which recording of the doses is required (recording level), should be set to $1/10^{th}$ of the fraction of the annual limit, corresponding to the issuing period of the dosemeter. If the dosemeter is used for 1 month, this means that the recording level should be at least 1 mSv/12 or 85 µSv per month.
The overall accuracy of a dosimetric system is determined from the combined effects of a number of systematic and random errors. The following sources are usually considered to cause systematic uncertainties: energy dependence, directional dependence, non-linearity, fading, effects from exposure to light, effects from exposure to other types of ionising radiation, calibration errors, variation in local natural background. Typical sources of random uncertainties are inhomogeneity of detector sensitivity and zero dose, and fluctuations in reading parameters including reader sensitivity.
The lowest limit of detection (LLD) of the detectors is mostly defined as 2 times the standard deviation on non-irradiated detectors, that have run through the whole procedure. At the SCK-CEN we have determined the detection level together with a customer dependent background value. This is done by plotting all results from a specific customer, background not subtracted. An example can be seen in figure 1. As most doses are always zero, the plot shows a peak which should have a normal distribution. To the high dose side there is a tail that shows the non-zero doses. By fitting a normal distribution to the data, the background value and detection limit can be determined. We have done that for all customers, and a specific background is now subtracted.
More information on uncertainties and standards for personal dosimetry can be found in (5) en (6).

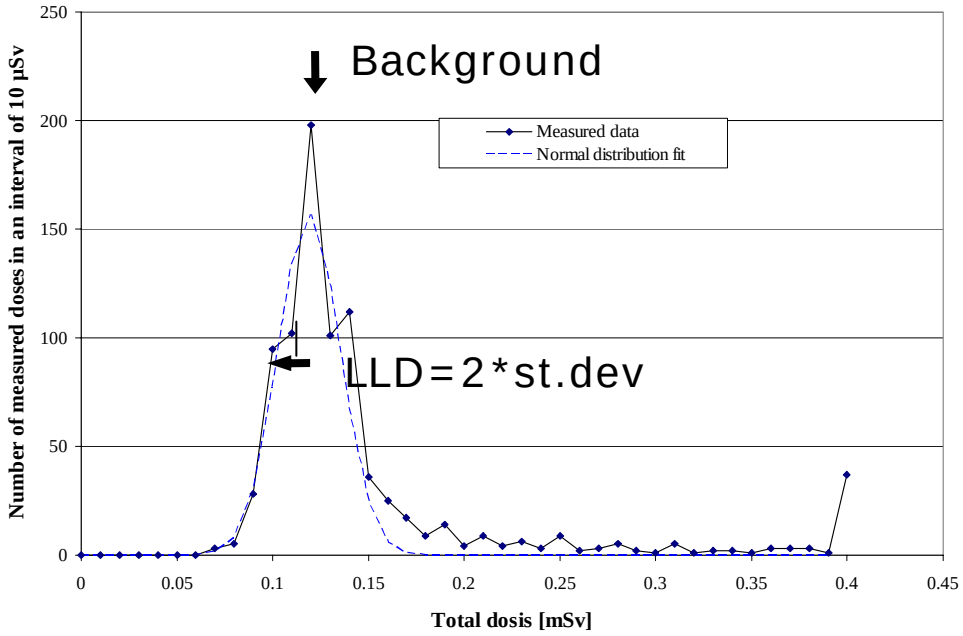


Figure 1: How to determine the background value and detection level.

Quality Assurance and Quality Control procedures

A quality assurance program should be an integral part of a dosimetry service. Although quality assurance is often a matter of common sense, the development of a formal QA program and implementing it in the service requires considerable thought. At the SCK-CEN a QA structure is implemented at the level of the whole organisation, with a general quality manual. There are numerous procedures (e.g. rules for purchasing and suppliers) that are valid for the whole SCK-CEN. At the next level, there is a quality manual specific for every service. All methods used and all procedures set up to control the various processes ought to be well documented. The practical work of the dosimetry service is described in procedures and instructions, explaining step by step what is to be done. The heart of the service depends upon the personnel, so it is important that they are adequately trained and motivated. Also this training and education, and the various responsibilities are documented. For all equipment used, there exist calibration instructions, and all relevant characteristics are checked in control charts. The technical parameters are described in validation manuals, where the type tests and scientific bases of the method are explained. Here, among others, the uncertainties, the lowest limit of detection and the traceability are shown. The most visible of the QA actions, are the quality control measurements that have to be done very frequently. TL readout instruments, although they are reasonably stable these days, need to be checked at least daily using a set of known dosemeters. At the SCK-CEN control charts exist for the calibration values and the daily control of the TL reader. Another QC measure that we have introduced is the "dummy" customer. These dosemeters runs through the entire routine procedure, except for the irradiation, which is done at a calibration service with a known dose. Real and measured values are being compared and the results interpreted. Last but not least it is important to have access to a well equipped and traceable calibration service. Ideally they should have their own QA system implemented, as is the case at the SCK-CEN.

References

(1) ICRP (1990) 1990 recommendations of the international commission on radiological protection. *Annals of the ICRP* 21, 1-3, Publication 60.

(2) ICRP (1996) Conversion coefficients for use in radiological protection against external radiation. *Annals of the ICRP* 26, 3/4, Publication 74.

(3) International Standard Organisation: X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of energy, Part 1, 2 and 3: ISO 4037 series.

(4) ICRP (1982) General principles of monitoring for radiation protection of workers. *Annals of the ICRP* 9, 4, Publication 35.

(5) D.T. Bartlett, P. Ambrosi, J.M. Bordy and J.W.E. van Dijk, Harmonisation and dosimetric quality assurance in individual monitoring for external radiation, Rad. Prot. Dosim. 89, 1-2 (2000).

(6) P. Christensen, H.W. Julius and T.O. Marshall (1994), Technical recommendations for monitoring individuals occupationally exposed to external radiation. European Commission Radiation Protection 73, EUR 14852 EN

Annales de l'Association Belge de Radioprotection Vol. 28, n°1,2003

ASPECTS PRATIQUES DE LA DOSIMETRIE DU PERSONNEL DANS LES LABORATOIRES ET LES CLINIQUES UNIVERSITAIRES DE L'UCL

J. CAUSSIN
Service de radioprotection UCL

I. Introduction

Au sein d'une institution hospitalière un nombre important de diagnostics et traitements nécessitent l'utilisation de radiations ionisantes. De ce fait, de nombreux travailleurs sont susceptibles d'être exposés à ce risque. Ces personnes travaillent essentiellement dans des services de radiologie (diagnostic), de radiologie interventionnelle (cardiologie, vasculaire, gastro-entérologie, urologie,…), de médecine nucléaire, ainsi que dans les départements où sont utilisés des appareils de RX mobiles (quartier opératoire, service d'urgence, service de soins intensifs,..).

Le risque "radiations ionisantes" peut également se présenter dans certaines chambres où sont hospitalisés des patients porteurs de quantités importantes de radio-isotopes dans un but thérapeutique. Quelques laboratoires de recherche ou « in vitro » peuvent également être concernés.

II. Dosimètre utilisé par l'UCL

Le dosimètre Panasonic type UD-802 est utilisé par l'UCL pour évaluer la dose efficace du personnel. Ce dosimètre est constitué de quatre éléments thermoluminescents placés dans un boîtier en plastique. Ces éléments sont composés de :

- borate de lithium, ($Li_2B4O_{7)}$ pour les éléments 1 et 2,
- sulfate de calcium ($CaSO_4$) pour les éléments 3 et 4..

L'élément 1 est placé derrière une fenêtre de faible épaisseur (15 mg/cm^2) afin d'évaluer la dose au niveau de la peau, les éléments 2 et 3 sont placés derrière une fenêtre d'épaisseur de 340 mg/cm^2. L'élément 2 permet de déterminer la dose en profondeur.

Contrairement aux éléments 1 et 2 qui présentent une sensibilité quasi identique aux photons dont l'énergie est inférieure à 10 Mev, les éléments 3 et 4 sont plus sensibles aux photons dont l'énergie est inférieure à 100 keV. En comparant les valeurs enregistrées par les éléments 2 et 3, il sera possible de disposer de données concernant l'énergie du rayonnement.

Pour que le dosimètre puisse être lu dans un lecteur automatique, il est constitué de trois parties:

- la partie 1 contient les 4 éléments thermoluminescents qui sont présentés un à un à l'effet du flash d'une lampe halogène. C'est le flash de cette lampe qui assure le chauffage de l'élément thermoluminescent indispensable à la détermination de la

dose reçue par le dosimètre. En fait, par élément trois flashes sont produits un pour le préchauffage, un pour la lecture proprement dite et un pour l'opération d'"annealing". Un flash supplémentaire est produit avant la lecture de chaque dosimètre, afin de contrôler le bon fonctionnement du lecteur.

- la partie 2 contient l'identification du dosimètre (perforations codant le numéro de série du dosimètre et étiquette avec le nom du porteur). Les parties 1 et 2 ne sont séparées que dans le lecteur de dosimètre au moment de la lecture.

- La partie 3 est un boîtier portant le système de fixation sur le vêtement de travail du porteur du dosimètre. Si ce boîtier est transparent, il n'est pas nécessaire d'y placer une étiquette d'identification. Cela évite les erreurs d'affectation du dosimètre.

Ce dosimètre ne peut pas être placé dans un four externe à haute température vu que les éléments sont fixés sur des pièces en plastique. La remise à zéro ne peut donc se faire que par les flashes de la lampe halogène du lecteur automatique, ce qui est suffisant pour les doses d'irradiation reçues normalement par le personnel. Si un dosimètre reçoit une dose élevée, elle sera correctement lue mais la remise à zéro ne sera pas toujours possible. Dans ce cas, le dosimètre devra être remplacé.

Le dosimètre ne pourra donc pas servir à l'évaluation de doses de patients si celles-ci sont importantes (par exemple en radiothérapie). Il est spécialement adapté à une lecture automatique de doses reçues par le personnel.

La nouvelle législation prévoit le port d'un deuxième dosimètre au-dessus d'un tablier plombé. La mise en pratique de cette nouvelle obligation peut présenter quelques difficultés:

- la fixation du dosimètre sur le tablier plombé n'est pas toujours aisée,

- en vue d'éviter l'oubli du port de ce dosimètre, certains travailleurs le laisse délibérément sur leur tablier de protection. Dans ce cas, il s'agit de tablier portant le nom de l'utilisateur et dont le port lui est réservé. Cependant, il arrive qu'une autre personne le porte par erreur ou tout simplement parce qu'il manque un tablier. A ce moment, des doses supplémentaires sont enregistrées à mauvais escient par le dosimètre.

- dans le cas mentionné à l'alinéa précédent, le lieu de stockage du tablier lorsqu'il n'est pas porté est important. Si le tablier est stocké dans la salle de radiologie, il peut enregistrer une dose supplémentaire.

- l'inversion du dosimètre au-dessus et en dessous du tablier doit absolument être évitée, car dans un tel cas une évaluation correcte de la dose efficace peut s'avérer impossible. Pour éviter cela, il faut différencier visuellement les deux dosimètres, soit par des étiquettes de couleurs différentes soit par des boîtiers différents .

L'évaluation des doses reçues au niveau des doigts doit parfois être effectuée. Le matériau thermoluminescent utilisé à cette occasion est constitué de fluorure de lithium (LiF - TLD100 Harshaw). Celui-ci est placé dans des bagues en plastique.

La lecture de ce type de dosimètre est difficilement automatisable. Une évaluation correcte des doses, au niveau des doigts, demande une grande discipline de la part de la personne qui porte ce type de dosimètre. En effet, si le travailleur ne peut le porter constamment, il ne doit pas oublier de le mettre lorsqu'il va effectuer un travail pour lequel se présente un risque important de radiations. De même s'il porte des gants, au moment où il les enlève, il doit prendre garde à ne pas perdre ce dosimètre.

En ce qui concerne la valeur des doses mesurées, citons comme exemple la médecine nucléaire, service pour lequel la moyenne des doses annuelles mesurées se situe entre 50 et 60 mSv. Cette moyenne a été établie pour les années 2000 à 2002, en ne considérant que les doses au-dessus de 10 mSv. La valeur maximale a été de 110 mSv pour un an.

III. Statistiques

L'étude des doses efficaces reçues par le personnel sur une période de 13 ans (entre 1990 et 2002 inclus) montre que 95 % des doses annuelles sont inférieures à 5 mSv.. Pour l'ensemble de la clinique, l'étude de la dose collective après avoir diminué de façon significative jusque 1995 environ a tendance à augmenter (environ 60 mSv) depuis l'année 2000. Il est évidemment intéressant d'essayer de comprendre la raison de cette augmentation. Différents paramètres peuvent avoir été modifiés. Citons comme exemple le nombre et le type d'examens, les radionucléides utilisés, le type d'appareil, le nombre de personnes portant un dosimètre (suite par exemple à la modification de la législation), les procédures, les blindages (Fig.1).

Pour mieux isoler chacun de ces paramètres nous avons défini plusieurs groupes de personnes pour qui nous allons étudier l'évolution de la dose collective. Ces groupes sont:

- la médecine nucléaire,
- la radiologie (diagnostic),
- la radiologie interventionnelle,
- la radiothérapie,
- les services où sont utilisés des appareils de RX mobiles.

En médecine nucléaire (fig. 2) nous constatons entre 1990 et 1996, une diminution de la dose collective due à des améliorations des blindages de protection, à la modification de certaines procédures et à l'utilisation de dosimètres électroniques en complément des dosimètres thermoluminescents. Cette démarche avait été provoquée par la publication du rapport n° 60 de la CIPR. Malheureusement depuis l'année 2000 nous assistons à une augmentation de cette dose collective. La valeur de cette augmentation est approximativement de 45 mSv. Nous essayons de déterminer la cause de cette augmentation de la dose collective.

En radiologie (diagnostics), nous observons également une diminution de la dose collective des années comprises entre 1990 et 1995 (Fig.3). C'est le résultat d'une campagne de sensibilisation en radioprotection. Depuis 1997 la dose collective fluctue, une ou deux années elle augmente puis elle diminue. Ces fluctuations la font varier d'une vingtaine de mSv au cours de cette période.

En ce qui concerne la radiologie interventionnelle, (fig.3) la dose collective a tendance à augmenter. Ceci pourrait être dû à une augmentation du nombre d'actes effectués dans ce

secteur. Afin de préciser notre analyse, nous avons créé au sein du groupe radiologie interventionnelle différents sous-groupes:

- sous groupe 1 : évolution de la dose collective des personnes ayant reçu une dose efficace inférieure à 0,5 mSv,
- sous-groupe 2 : évolution de la dose collective des personnes ayant reçu une dose efficace comprise entre 0,5 et 5 mSv
- sous-groupe 2 : évolution de la dose collective des personnes ayant reçu une dose efficace comprise entre 5 et 15 mSv
- sous-groupe 2 : évolution de la dose collective des personnes ayant reçu une dose efficace comprise entre 15 et 50 mSv

Nous pouvons remarquer que seul le sous-groupe constitué des personnes ayant reçu une dose efficace annuelle comprise 15 et 50 mSv voit sa dose collective augmenter (sauf en 2002). Cela pourrait signifier que certaines personnes ont peu la possibilité d'améliorer leur protection, par contre cela s'avère plus complexe pour quelques personnes qui ne peuvent s'écarter de la source de rayonnement, ni utiliser des blindages. Il est également possible que la qualification de certains médecins, infirmières ou technologues les spécialise dans la réalisation des interventions les plus irradiantes (Fig.5).

En radiothérapie la dose collective diminue et tend actuellement à se stabiliser (Fig.4).

IV. Conclusion

Tous les efforts doivent évidemment être consentis pour que les dosimètres soient correctement portés, collectés, lus. Il est essentiel et obligatoire que les résultats des doses enregistrées soient communiqués au personnel professionnellement exposé. En effet, l'examen des résultats par le porteur du dosimètre et par le service de contrôle physique permettra de disposer d'éléments nécessaires à l'amélioration de la radioprotection.

La dose collective peut se révéler être un bon outil pour tester l'efficacité de modifications de procédure, de blindages.

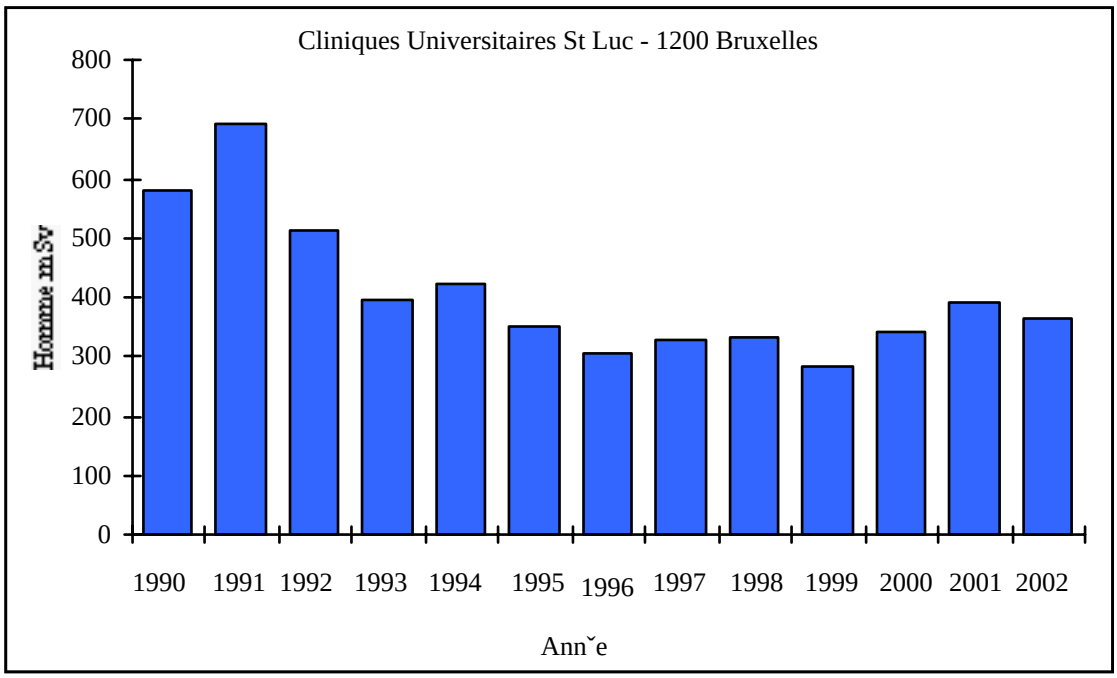


Fig. 1 Evolution de la dose collective

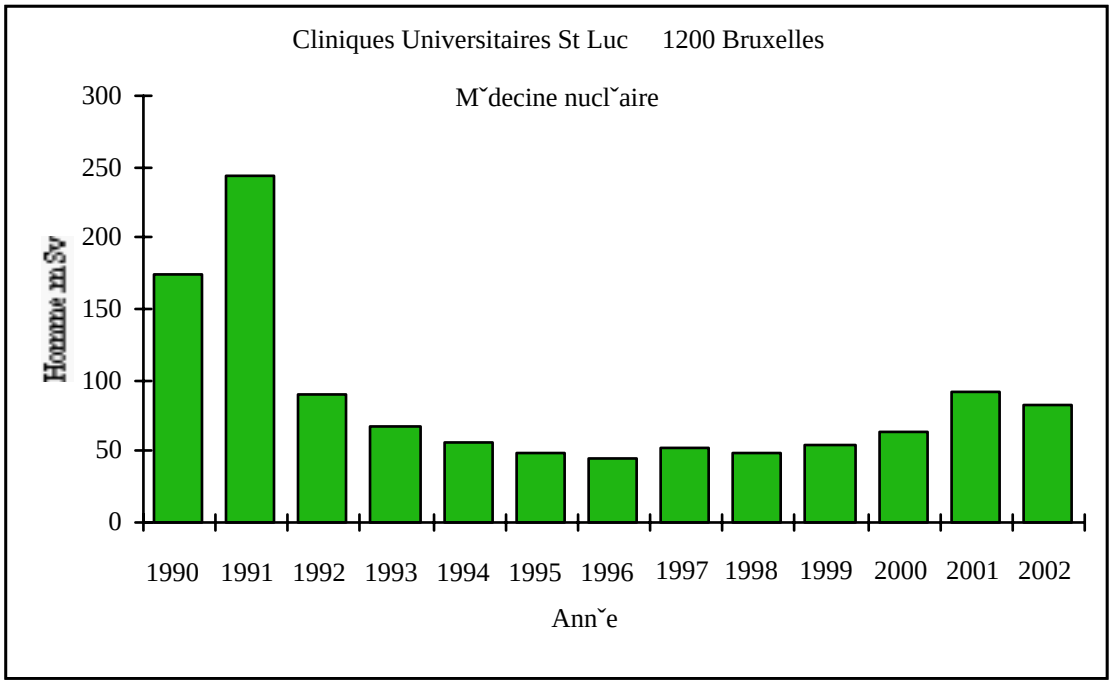


Fig. 2 Evolution de la dose collective

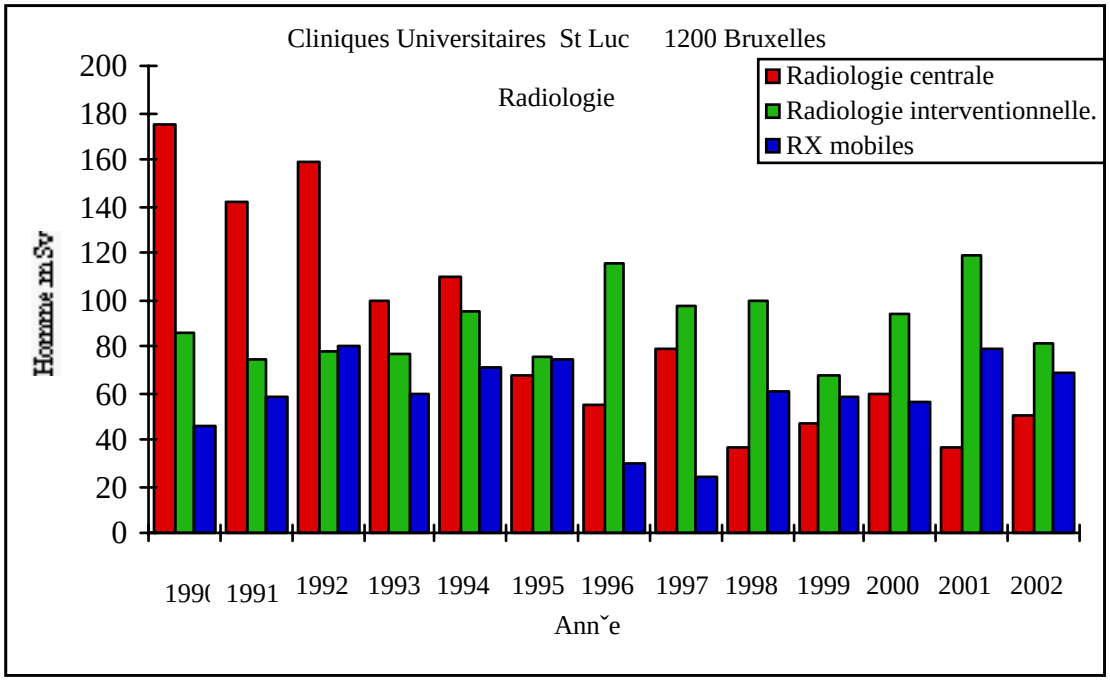


Fig. 3 Evolution de la dose collective

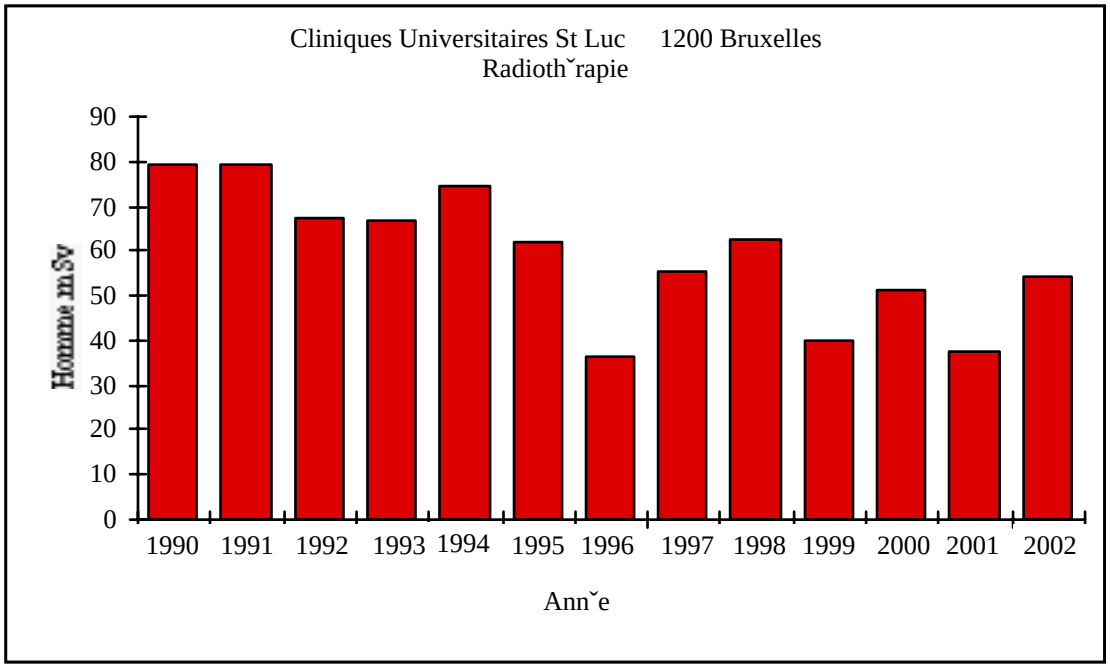


Fig.4 Evolution de dose collective

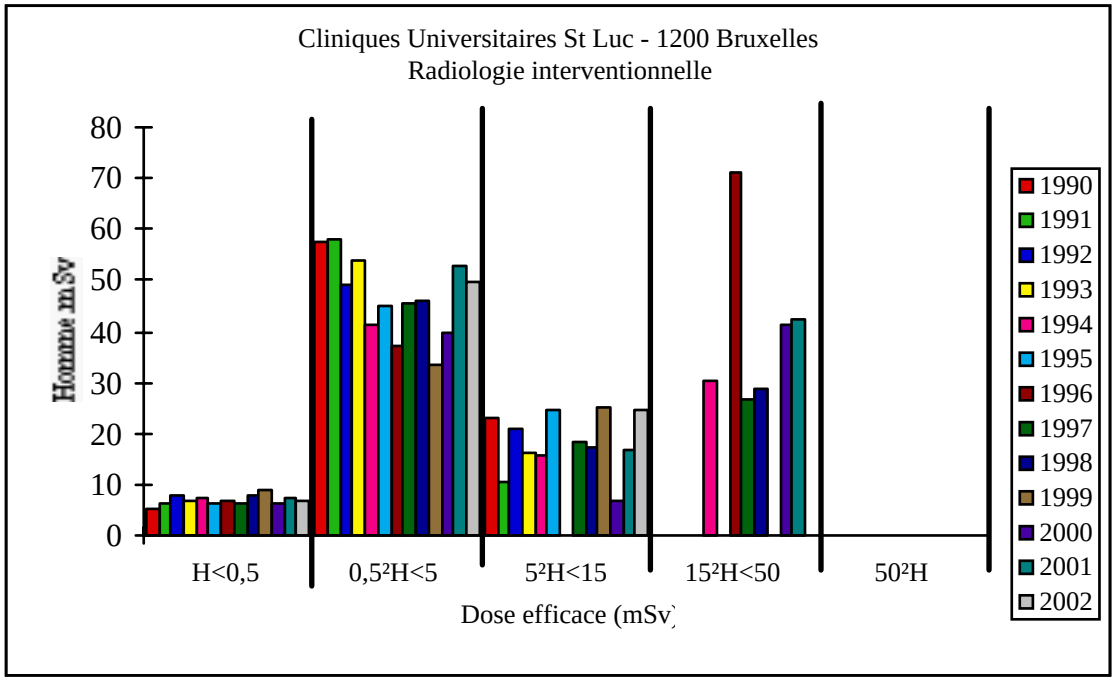


Fig. 5 Evolution de la dose collective

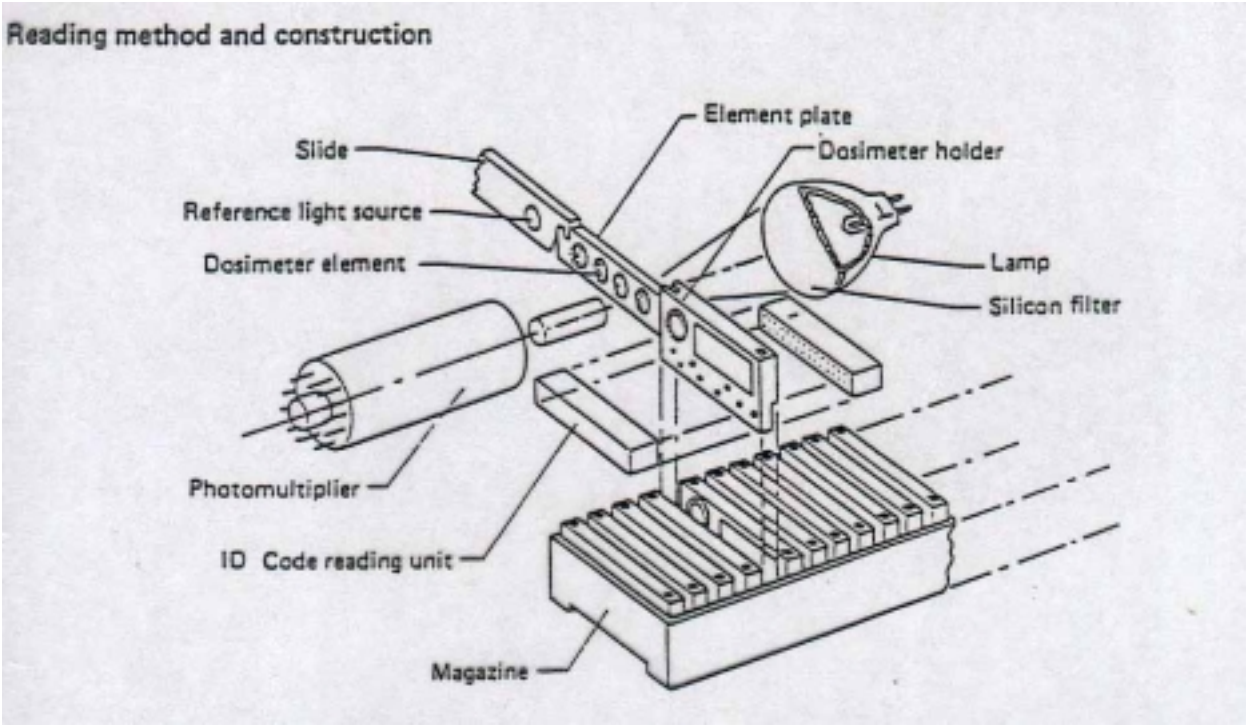


Fig 6. Principe de fonctionnement (document Panasonic)

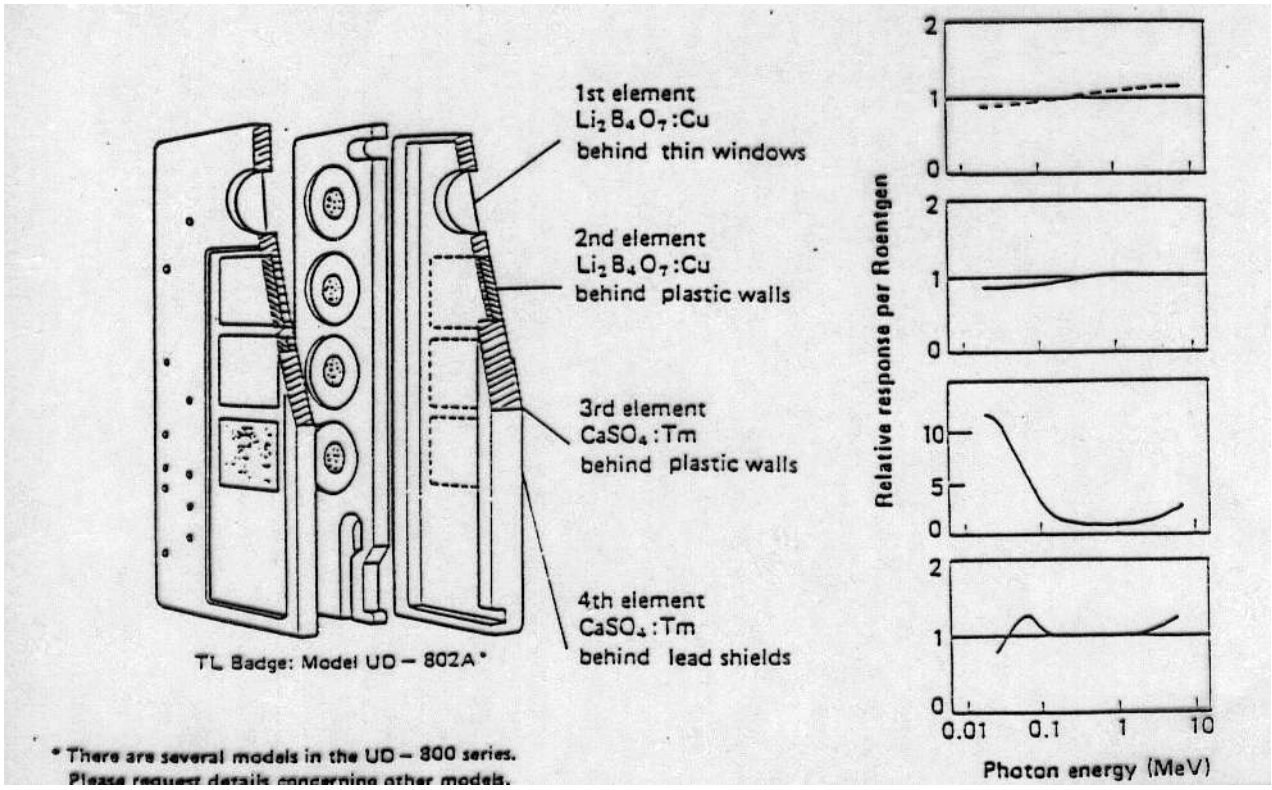


Fig. Description et réponse du dosimètre UD-802AS (document Panasonic

Annales de l'Association Belge de Radioprotection Vol. 28,n°1,2003

PERSONENDOSIMETRIE IN EEN ZIEKENHUISOMGEVING

J. Van Dam[*°], B. Nowak[*] en R. Bogaerts[*]
[*]Dienst Gezwelziekten, Afdeling Radiofysica (hoofd: D. Huyskens)
[°]hoofd Fysische Controle
Katholieke Universiteit Leuven

De personendosimetrie in de Universitaire Z iekenhuizen Leuven is toevertrouwd aan de afdeling Radiofysica van de dienst Gezwelziekten. Naast de voornaamste resultaten van de laatste 5 jaar handelt deze bijdrage eveneens over de basismetrologie en geassocieerde kwaliteitsverzekering.

Apparatuur, procedures en kwaliteitsverzekering

De Personendosimetrie van het UZ Leuven maakt gebruik van het Harshaw 6600 volautomatisch afleesapparaat. Als thermoluminescent materiaal wordt het Harshaw " TLD 100" (natuurlijk mengsel ^{6}LiF en ^{7}LiF) gebruikt.
De kwaliteitsverzekering van het systeem steunt op een aantal procedures op het vlak van ijking en responsemonitoring. IJking van de thermoluminescente dosimeters gebeurt met ionisatiekamer dosimetrie in de bundel van een cobalttoestel gebruikt voor radiotherapie (in de toekomst wordt echter overgegaan op een cesium-137 straling, wegens ontmanteling van het cobalttoestel). Hiertoe werden een vingerhoedskamer gebruikt, die eveneens voor radiotherapie dosimetrie gebruikt wordt, en een ionisatiekamer van het type " radiation survey meter" . Deze kamers werden geijkt in resp. het Laboratorium voor Standaarddosimetrie van de R.U. Gent en in de SSDL van het Atoomenergie Agentschap te Wenen. Dit agentschap heeft verder de ganse ijkprocedure aan een audit onderworpen met behulp van postale dosimetrie. Ook werd met het SCK te Mol een intervergelijking opgezet, eveneens gebaseerd op postale dosimetrie.
Voor de maandelijkse kwaliteitscontrole wordt gebruik gemaakt van de 120 kVp X-stralenbundel van een radiotherapie simulator. Hierbij worden een aantal badges bestraald tot een met een ionisatiekamer bepaalde dosis en samen afgelezen met de personenbadges. De verhouding van bepaalde over reële dosis varieert tussen 1,03 en 0,94.

Resultaten en bespreking

De uitgevoerde dosimetrie betreft hoofdzakelijk dieptedosissen $H_p(10)$. In een paar diensten, waar manipulaties van open en/of gesloten bronnen worden uitgevoerd, worden bij een aantal personeelsleden ook vingerdosissen bepaald.

$H_p(10)$

De resultaten behaald in de diverse diensten tussen 1998 en 2002 werden gegroepeerd (Tabel I) in 3 clusters: deze van de diagnose met open bronnen, deze van de algemene en interventionele radiologie (incluis de chirurgie), en deze van de radiotherapie. Het aantal gevolgde personeelsleden nam toe van 482 in 1998 tot 964 in 2002. De toename het laatste jaar is vooral veroorzaakt door het veralgemenen van de personendosimetrie op niveau van de operatiezalen. Er werd geopteerd om telkens de jaardosis aan te geven van het personeelslid

met de hoogste dosis van de betrokken dienst. Vanaf het jaar 2002 worden de resultaten aangegeven na achtergrondsubtractie (0,6 mSv op jaarbasis).

Diagnose met open bronnen
De resultaten voor Nucleaire geneeskunde en Radiofarmacie zijn totaal vergelijkbaar, wat uiteraard te verwachten is. Wanneer we deze resultaten vergelijken met deze aangehaald in het NCRP rapport 124[1] dan vinden wij een dosis die tot 2 maal hoger ligt dan de in dit handboek vermelde 4 mSv: dit is echter te verklaren door het gebruik van PET isotopen.

Tabel I - Resultaten personendosimetrie U.Z. Leuven
(max. jaardosis in millisievert)

Dienst	1998	1999	2000	2001	2002
nucl. geneesk.	7,2	8,5	8,5	7,0	4,7
radiofarmacie	5,2	7,4	5,2	5,5	6,0
radiologie	3,5	2,1	2,9	3,3	1,8
pediat. radiol.	3,4	2,5	2,3	1,8	1,5
angiografie	1,9	1,8	2,2	2,0	0,9
hartcathet.	9,7	5,6	5,9	4,0	4,7
endoscopie	12,4	2,8	5,7	5,7	9,4
chirurgie - orthopedie - andere	 3,5 -	 6,3 -	 2,2 -	 4,4 -	 1,0 1,1
radiotherapie	1,6	1,7	1,8	1,7	1,0

Algemene en interventionele radiologie
De maximale personeelsdosissen gemeten in algemene radiologie liggen tussen 2 tot 3,5 mSv, wat volgens de verwachtingen is. Deze van kinderradiologie zijn iets lager, wat uiteraard te maken heeft met de dosisreducties toegepast op de patiëntjes. In de interventionele sfeer vinden wij in de afdeling hartcatheterisatie de verwachte hoge dosissen die tot 10 mSv per jaar kunnen oplopen. Bij endoscopie zien wij een drastische dosisvermindering in 1999 t.o.v. het jaar ervó ó r. Dit is een typisch gevolg van ALARA: in 1999 werd het systematisch dragen van een loodschort tijdens de procedures ingevoerd. De graduele stijging van de dosis op deze

[1] NCRP 124: Sources and magnitude of occupational and public exposures from nuclear medicine procedures. National Council on Radiation Protection and Measurements, Bethesda, USA, 1996

dienst tijdens de volgende jaren illustreert het nadeel van de maximale jaardosis als monitoring parameter: deze terug verhoogde dosissen werden telkens gemeten bij hetzelfde personeelslid met een weinig gedisciplineerd gedragspatroon voor radioprotectie. In de chirurgie werd enkel op orthopedie sinds 1998 personendosimetrie bedreven. Voor wat betreft de rest van de ingrepen werd pas in 2002 systematische dosimetrie ingevoerd. De erg lage maximale dosis die gemeten werd stemt tot een zeker scepticisme met betrekking tot het consequent dragen van de dosimeter door sommige chirurgen.

Radiotherapie
Radiotherapie behelst zowel de externe als de curietherapie. Bij deze laatste is ook de hospitalisatie begrepen van patiënten behandeld met iodium-131 voor schildklierkanker. De relatief lage dosissen die in deze discipline optreden zijn welgekend en zijn het resultaat van adequate afschermingen en correcte procedures. De hoogste dosis wordt meestal opgelopen door de assistent die de curietherapeutische applicaties mee uitvoert, waarbij de manuele afterloading met iridium-192 de hoogste dosisbijdrage levert.

Vingerdosissen
Vingerdosimetrie wordt gedaan op de diensten Nucleaire Geneeskunde en Radiofarmacie, bij de meest geëxposeerde personeelsleden, en op de dienst Radiotherapie, bij de assistent in opleiding voor curietherapie. Enkel op radiofarmacie wordt bij één (en altijd hetzelfde) personeelslid vingerdosissen gemeten die erop wijzen dat het overschrijden van de wettelijke jaarlimiet van 500 mSv niet ondenkbeeldig is.

Besluit

De bekomen resultaten bevestigen dat in sommige klinische diensten zeer significante dosissen worden gemeten. Onder voorbehoud dat ook in de chirurgie de dosimeters consequent gedragen worden, blijven, mogelijks op één uitzondering na, ook de hoogste dosissen comfortabel onder de wettelijke limieten. Deze vaststelling doet evenwel niets af van de noodzaak tot verdere optimalisatie van de radioprotectie in de U.Z . Leuven.

Annales de l'Association Belge de Radioprotection Vol. 28,n°1,2003

EXTREMITY DOSES IN NUCLEAR MEDICINE

P. Covens, D. Berus an N. Buls*

Radiation Protection Department University of Brussels (VUB)
and Academic Hospital AZ -VUB
*Department of Radiology and Medical Imaging Academic Hospital AZ -VUB

Abstract

Due to increasing number of medical procedures in nuclear medicine, interventional radiology and brachytherapy, it's necessary to give more and more attention to extremity doses as an particular aspect of dose monitoring. The radiation dose to the hands of staff members in nuclear medicine is mainly received during 3 different manipulations of radiopharmaceuticals: preparation, dispensing and intravenous administration. In the nuclear medicine department of the Academic Hospital VUB (AZ -VUB), extremity doses have been monitored during several years by means of wristdosemeters. The significant results of this monitoring urged the introduction of ringdosemeters for radiopharmacy staff members. The recorded doses at the base of the middle finger showed the need of radiation protection measures to assure compliance with the dose limit of 500mSv/year. The use of new vial containers and new syringe shields has reduced these fingerdoses by 30%. Nevertheless, some staff members are still exposed to values of 250mSv/year. Since much higher dose is expected at the fingertips, further radiation protection measures have to be imposed. By measuring the specific dose at the base of middle finger it's possible to calculate the contribution of each manipulation to the collective dose at this location. Further measurements will be carried out in order to search for the highest dose location on the hand. The ratio between the dose at this location and the dose at a convenient location can be used to correct results after routine monitoring.

Introduction

The two main sources of external radiation exposure to workers in a nuclear medicine department are from radioactivity in patients, and from preparation, dispensing and administration of radiopharmaceuticals. Personal dose monitoring has been carried out for many years by means of personal dosemeters, worn at chest level. The relatively high radiation dose, which can be received by the hands, asks for extremity dose monitoring in many departments. It is important that techniques are optimised in order to keep these doses to a minimum and to assure that the dose limits are respected.

Extremity dose versus skin dose

The Directive 96/29/Euratom **[1]** and the Belgian regulations **[2]** stipulate separate dose limits for the equivalent dose (H_T) to the lens of the eye and H_T for the extremities (hands, forearms, feet and ankles) following the recommendations of ICRP60 **[3]**. In most practical radiation fields the true equivalent dose to the extremity will be less than the equivalent dose to the skin

of the extremity. The relevant dose quantity for extremity measurement is therefore usually $H_P(0.07)$. Assessment of $H_P(d)$ using other values of " d" may be appropriate since data on the standard man **[4]** indicate greater depths over some parts of the extremities. These depths range from 0.2mm to 0.5mm (thickness of the epidermis) over the palmer surfaces of the hands. However, the depth over the wrist, the sides and back of the hands is nearly 0.07mm. Therefore it is recommended that assessment for extremity monitoring for dose from beta and gamma radiation fields should be made at a depth of 0.07mm.
The occupational dose limits concerning the extremities are included in Art. 20.1.3 of the Belgian regulations:

- The equivalent dose limit for the hands, forearms, feet and ankles is set to 500mSv for 12 gliding months.
- The equivalent dose limit for skin is set to 500mSv for 12 gliding months averaged over any area of $1cm^2$.

Material and location of extremity dosemeters

Extremity dose assessments are usually carried out using thermoluminescent dosemeters (TLDs) because of their convenient size. For accurate measurement of $H_P(0.07)$ the dosemeter must be physically thin to avoid significant attenuation of the radiation. The dosemeter also needs to be robust because it may be placed on the hands carrying out manual work.
The position on the hand at which a dosemeter is worn and the choice of hand on which it is placed both have a large influence on the value of the assessed dose, especially when working with localised sources. Since the dose limit to skin applies to the dose averaged over any area of $1cm^2$, it is necessary to identify, as accurately as possible, the location of the highest dose. Ideally a dosemeter should be used to monitor the part of the extremity receiving the highest dose. If this is impractical, it may be necessary to monitor a different part in which case a factor may be employed to ensure dose limits are not being exceeded. The type of dosemeter, used for routine extremity dose monitoring, varies in nuclear medicine departments. Generally we can distinguish three basic types.

- A wristdosemeter is convenient during manipulations but results in a underestimation of the dose due to the distance between the wrist and the possible highest dose location (fingertip).
- A better estimation of the dose can be obtained by using a ringdosemeter. This type is usually worn at the base of the middle finger and is quite convenient during manipulations. However, these dosemeters have the disadvantage of contamination risk since the protective gloves can be damaged.
- Extremity dose monitoring can also be carried out by TLD-tapes or finger stalls which enable doses at the tip of the finger to be measured. However, these dosemeters are often inconvenient during manipulations, which can result in longer exposure time. Additionally, the use of this type also involves contamination risk.

Contamination of the hands during manipulations can occur and therefore a regular check-up is important. The doses to the skin and possible subsequent ingestion are particular hazards that can be reduced if decontamination measures are taken as soon as contamination is detected. A contaminated dosemeter will measure an elevated dose if the contamination remains on the surface of the dosemeter. The actual skin dose received will be lower and irradiation of the dosemeter will continue after work with radiation has ceased. This can lead to a dose limit being exceeded and a incorrect report to a regulatory body.

Workload of the nuclear medicine department

Besides some therapeutic procedures, a nuclear medicine department can be generally characterised by various diagnostic examinations involving intravenous administration of radiopharmaceuticals. These pharmaceuticals are usually labelled with ^{99m}Tc and among the more common are also ^{18}F, ^{201}Tl, ^{123}I, ^{51}Cr and ^{67}Ga. Current trends in clinical nuclear medicine include an emphasis on radioimmunodiagnosis, single photon emission tomography (SPECT) and positron emission tomography (PET). This PET involves mainly the use of ^{18}F-labelled fluorodeoxyglucose (^{18}FDG) and is now available in many major hospitals.
Most diagnostic examinations in a nuclear medicine department involve the use of ^{99m}Tc-labelled radiopharmaceuticals. PET (^{18}FDG) is also well represented and still increasing. The distribution shown in Table 1 clearly indicates the principal radiopharmaceuticals, which contribute to extremity doses in AZ -VUB.

	Distribution of diagnostic examinations with different radiopharmaceuticals(%)		
Month	**^{99m}Tc-labelled**	**^{18}FDG**	**Other (labelled with ^{123}I, ^{201}Tl, ^{51}Cr…)**
1	88	7	5
2	84	10	6
3	85	9	6
4	86	9	5
5	89	7	4
6	86	10	4
7	85	11	4
8	87	9	4
9	85	10	5
10	85	11	4
11	83	14	3
12	85	10	5

Table 1: Distribution of diagnostic examinations in AZ -VUB (2002)

Manipulation of radiopharmaceuticals

Before the imaging of the patient with SPECT or PET, the radiopharmaceutical causes radiation exposure during a number of manipulations. Generally we can consider three basic manipulations (fig. 1):

- The first manipulation is the kit preparation during which multidose kit vials of different radiopharmaceuticals are prepared. The preparation of ^{18}FDG occurs generally by fully automated modules in heavy shielded ‘hot cells’ and is not considered as a significant source of exposure to the extremities. This is however not the case during ^{99m}Tc-labelling where the manipulation starts with the elution of the ^{99}Mo-^{99m}Tc generator into an elution vial and ends up with the injection of a typical activity into a multidose kit vial.
- These kit vials have to be dispensed into syringes after which the individual patient activity is checked in the dose (activity) calibrator and the syringe is transferred with a shielded transport box to the administration room.

- The third manipulation is the administration to the patient. The insertion of a butterfly cannula into a vein, prior to the radiopharmaceutical administration, is prevalent in many hospitals in terms of dose reduction effect **[5]** to the staff members performing this task.

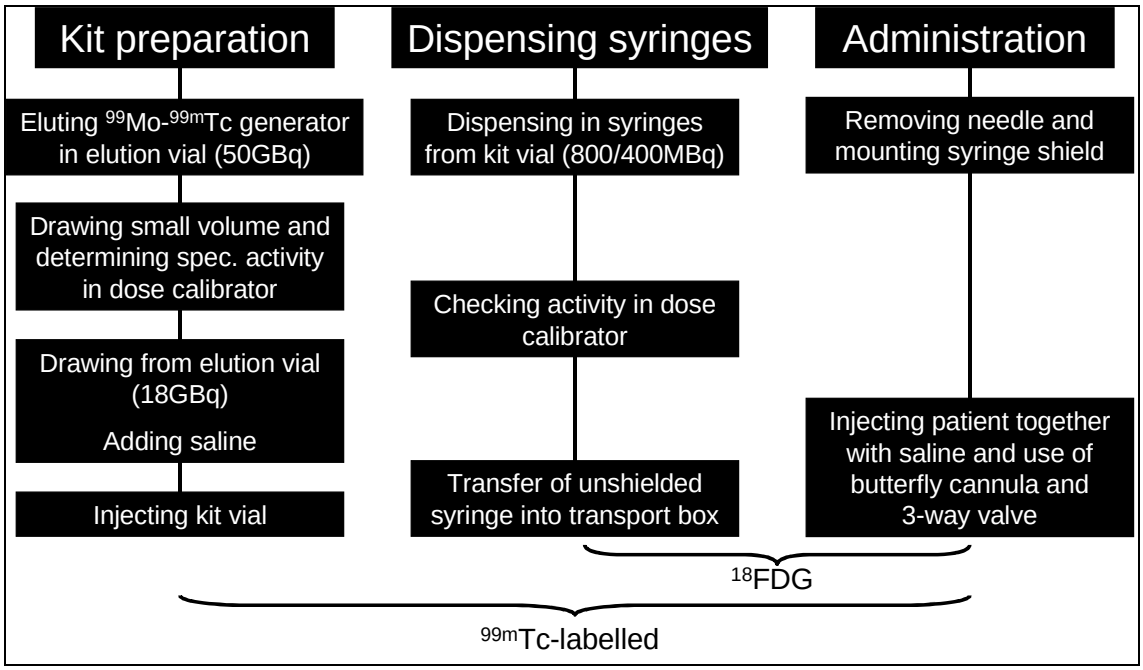


Figure 1: Three basic manipulations of radiopharmaceuticals in nuclear medicine

The internal organisation of these three basic tasks can differ from department to department. Radiopharmacy staff can carry out kit preparation and dispensing, while nursing staff is responsible for administration (AZ -VUB). In other hospitals radiopharmacy staff prepares the kits after which nursing staff dispenses the syringes and administers the activity. In some hospitals, nursing staff members walk through the entire procedure.

Dose reduction during manipulation of radiopharmaceuticals

Many dose reduction tools are commercially available for elution vials, kit vials and syringes. Materials are usually lead, tungsten and high-density lead glass. The attenuation factors range from 4 to 200 depending on the design, material and the radionuclide for which the protective tool is used. These attenuation factors do not result in dose reduction by the same order of magnitude. Quality assurance and radiation protection of patients in a nuclear medicine department requires activity measurements in the dose calibrator, which involves the manipulation of unshielded syringes. Several authors **[6-9]** studied the value of syringe shields during dispensing of ^{99m}Tc-labelled radiopharmaceuticals and concluded that the extremity dose is only reduced by 30% for most types of syringe shields. However according to ref. **[9]** a significant dose reduction factor of 10 could be obtained by using a lead glass shield with 360° visibility of the syringe over its entire length.
Due to the poor effect of most syringe shields, departments should emphasise on performing radiopharmaceutical manipulations in the minimum time and preserving the quality assurance regarding the nuclear medicine patient.
With the increasing number of PET-examinations automated dose dispensers for ^{18}FDG are now commercially available. These automated systems are very expensive (50 000 EUR) and do not give the excepted dose reduction compared to the use of proper syringe shields **[9]**. The

time the staff member needs to remove the filled syringe from the automated dose dispenser is in fact approximately the same when a shielded syringe is filled manually.

Extremity dose results in AZ-VUB

In the nuclear medicine department of AZ-VUB nursing staff members wear wrist dosemeters while radiopharmacy staff members wear a wristdosemeter and a ringdosemeter. Figure 2 shows the dose results of the routine monitoring with wristdosemeters. The collective and individual doses indicate the significant exposure of the skin in the radiopharmacy subdepartment (kit preparation + dispensing). One could add the total administered activity to the same graph and in this way demonstrate a moderate dose reduction in the radiopharmacy obtained by the introduction of new vial containers and new syringe shields.

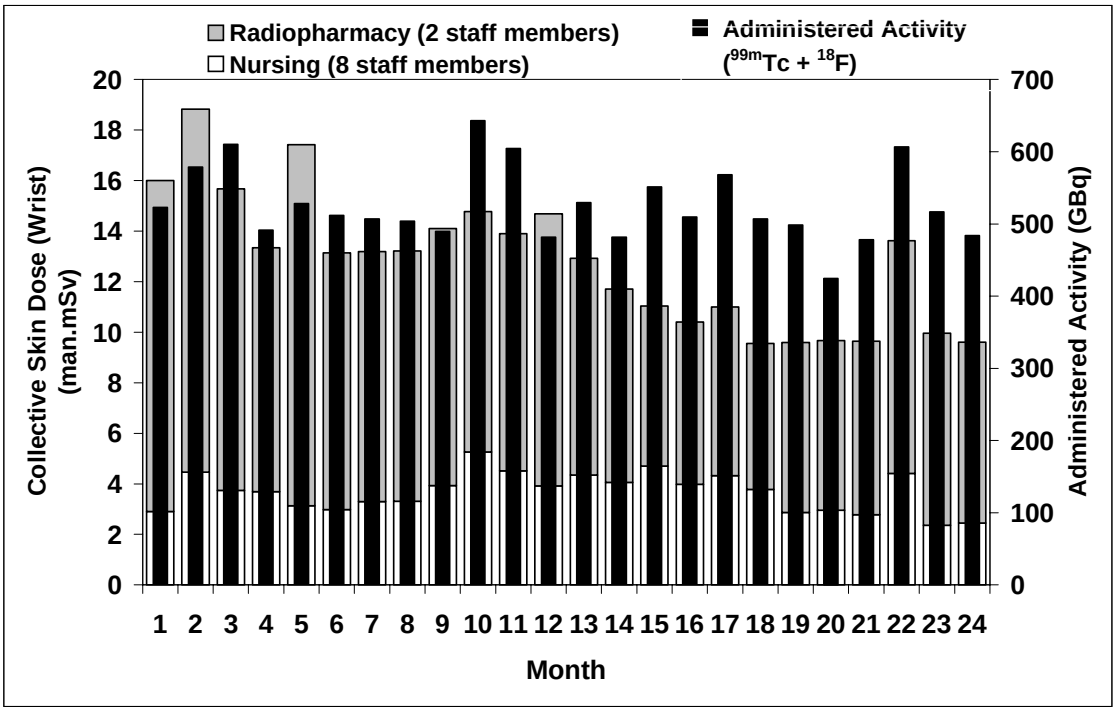


Figure 2: Skin dose (wrist) in the nuclear medicine department AZ-VUB (2001-2002)

The substantial wristdoses asked for the introduction of ringdosemeters for the radiopharmacy staff members. These ringdosemeters are worn at the base of middle finger and confirm also the moderate dose reduction when the results are compared with the administered activity (fig. 3).

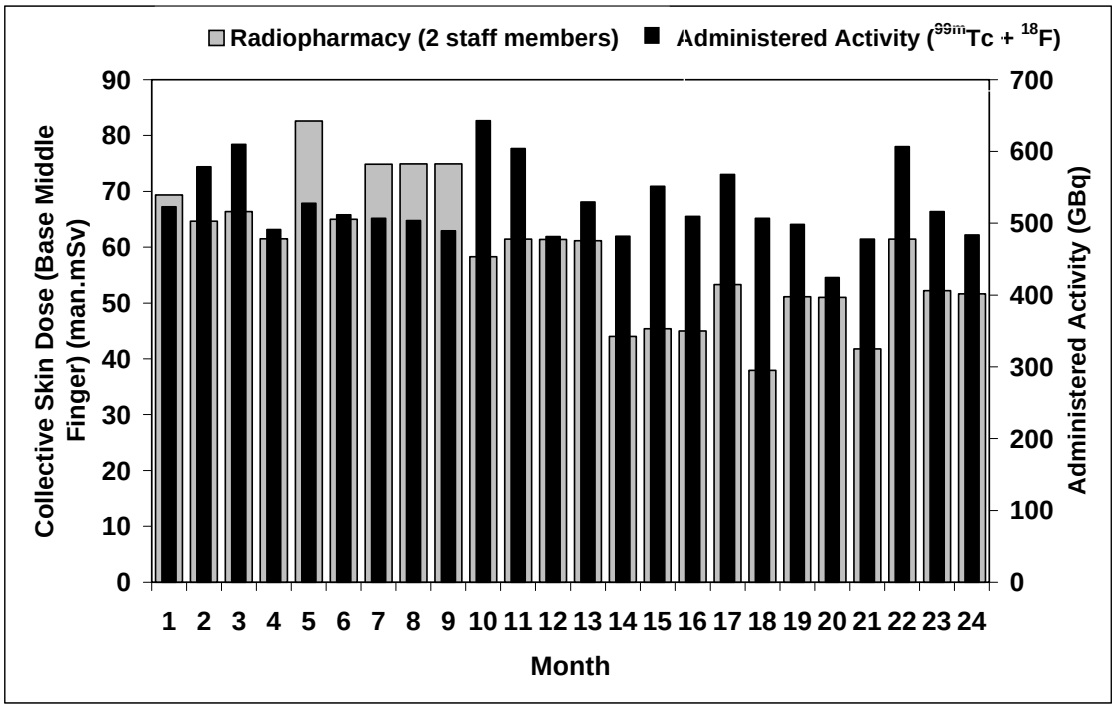


Figure 3: Skin dose (base middle finger) in the radiopharmacy AZ -VUB (2001-2002)

The considerably high collective and individual skin dose still demands further optimisation. Moreover, the location of the ringdosemeter is probably not the highest dose location, meaning this routine monitoring underestimates the actual skin dose of the extremities.

Specific skin dose

In the search for further optimisation, it is important to know during which specific radiopharmaceutical manipulation the highest doses are received. Besides routine monitoring, tens of measurements were carried out at the base of the middle finger in order to determine the specific skin dose for a certain administered activity (Table 2).

Manipulation	Specific Skin Dose Base Middle Finger: Mean Value ±SD (mSv/patient activity)	Administered Activity (GBq/month)	Total (mSv/month)	Contribution (%)
^{99m}Tc labelled: 800MBq				
Kit preparation	0.036 ± 0.013	600	27	34
Dispensing syringes	0.029 ± 0.007		22	28
Administration	0.018 ± 0.006		14	18
Subtotal ^{99m}Tc	**0.083**		**63**	**80**
^{18}FDG: 400MBq				
Dispensing syringes	0.065 ± 0.016	50	8	10
Administration	0.061 ± 0.012		8	10
Subtotal ^{18}FDG	**0.126**		**16**	**20**
TOTAL			**79**	**100**

Table 2: Specific skin dose during different manipulations of radiopharmaceuticals

It is usefull to express this specific skin dose for the typical administered activities used during many diagnostic examinations in nuclear medicine i.e. 800MBq for ^{99m}Tc-labelled radiopharmaceuticals and 400MBq for ^{18}FDG **[10]**. The administration of 800MBq ^{99m}Tc requires however a kit preparation of 1200MBq since this manipulation is usually carried out in the morning and factors like physical decay and backup have to be considered.
We can easily recalculate this specific skin dose per 1GBq and multiply this value with the total administered activity as shown in column 3. The result of this product (column 4) gives an estimation of the total skin dose received at the base of the middle finger during different manipulations. The sum of the results for the radiopharmacy staff members (57mSv: preparation + dispensing) can be compared to the value of the routine monitoring, illustrated in figure 3.
Table 2 shows that kit preparation of ^{99m}Tc-labelled radiopharmaceuticals gives the highest contribution to the skin dose at the base of middle finger followed by dispensing of the same radiopharmaceutical. It is clear that radiation protection measures are most effective during these manipulations. The use of proper syringe shields as, suggested in ref **[9],** could give an improvement. Secondly, we should examine the calibration of the dose (activity) calibrator for measurement of syringes with mounted shields. This would avoid the removal of these shields during the necessary activity measurements.
The use of an automated dose dispenser for ^{18}FDG is not suitable for dose reduction when the present workload is assumed. Reducing the dose with 50% during dispensing of ^{18}FDG-syringes would be optimistic and should result in an overall dose reduction of only 5%. The use of such a PET dose dispenser is therefore not ALARA, considering an investment of more then 50 000 EUR.

Highest Dose Location

Prior to the implementation of ALARA, one needs to respect the dose limits. Routine dose monitoring with wristdosemeters and/or ringdosemeters is quite convenient during manipulations. Staff members can wear these dosemeters on the left hand, on the right hand or on both hands. However, these locations do not present the highest dose locations. In collaboration with SCK•CEN, a project is started were the skin doses are simultaneously measured at 18 locations on each hand. This project is in its initial phase and the first results will not be discussed in this paper. This study will enable to define the location were the highest dose is received, allowing to compare the order of magnitude of skin doses, received at the highest dose location, with the skin doses, received at the locations used during routine monitoring.
Former studies **[5, 6**, **11**, **12]** indicate the fingertip of the index finger as the highest dose location. Some of these studies also calculated the ratio between doses at the fingertip and doses at the base of middle finger during dispensing of ^{99m}Tc-labelled radiopharmaceuticals. References **[6]** and **[12]** found ratios ranging from 4 to 5 between the doses at these two locations. Dhanse et al **[11]** state that trained staff members show ratios of only 2 when proper syringe shields are used.
Our project will however cover all three manipulations, illustrated in figure 1. When can expect that the order of magnitude will depend on the nature the radiopharmaceutical and the accompanying manipulation.

Conclusion

Extremity dosemeters should not hamper nuclear medicine staff members in order to perform the radiopharmaceutical manipulations in the minimum time. Ringdosemeters can be worn at the base of the middle finger and are convenient during work. The results of the specific skin dose at this location indicate the manipulations were radiation protection measures are necessary. Routine monitoring at the base of middle finger should however be corrected for the highest dose location. This correction will confirm the need of radiation protection measures since the present skin doses will exceed the dose limits when they are multiplied with a ratio> 2. The use of proper syringe shields and the possibility of activity measurement without removing the shield, can be elements in the search of dose reduction opportunities.

Epilogue

At present there is no method, which could be used in order to gain information on biological effects accumulated by daily low radiation doses. The capillary network at the nail groove is however a very sensitive indicator of alterations provoked by ionising radiation. B. Perdereau et al. **[13]** state that with subcutaneous capillaroscopy of the nailfold regions, it would be possible to record radiation-induced modifications through the observation of the microvascular network. The authors examined 19 hospital staff members working in fields such as nuclear medicine, brachytherapy and interventional radiology in the second half of their career and observed alterations which are strictly located at the exposed fingers. Multiparametric analysis made it possible to eliminate artefacts, which can be age-linked or associated with other classic pathologies. The most frequent modifications recorded are morphologic transformations and/or oedema. A significant increase in the number of alterations is observed with increased duration of exposure. On the whole, 6 of 19 subjects appear to be normal or subnormal, 9 subjects show alterations confirmed in infraclinical stage and 4 subjects clearly indicate radiation injuries.
This method was applied to a rather small population of 19 subjects and no routine dose monitoring of the fingers was carried out during their professional career. However, the further development of this method would be justified if it can be applied on a larger scale and when it could be part of a multidisciplinary study on extremity (skin) doses.

References

[1] European Community, *"Council Directive Laying Down Basic Standards for Protection Against Ionising Radiation"*, Directive 96/29/Euratom May 13, 1996, Official Journal EC, L159, 39, June 29, 1996,

[2] KB van 20 juli 2001 tot inwerkingstelling van de wet van 15 april 1994 betreffende de bescherming van de bevolking en van het leefmilieu tegen de uit ioniserende stralingen voortspruitende gevaren en betreffende het Federaal Agentschap voor Nucleaire Controle, B.S. n° 244, 30 augustus 2001

[3] International Commission on Radiological Protection, *"1990 Recommendations of the International Commission on Radiological Protection"*, ICRP Publication 60, Pergamon Press, Oxford, 1990

[4] International Commission on Radiological Protection, *"Report of the Task Group on Reference Man"*, ICRP Publication 23, Pergamon Press, Oxford, 1974

[5] S. Batchelor et al., *"Radiation Dose to the Hands in Nuclear Medicine"*, Nuclear Medicine Communications 12, 439-444, 1991.

[6] L.K. Harding et al., *"The Value of Syringe Shields in a Nuclear Medicine Department"*, Nuclear Medicine Communications 6, 449-454, 1985.

[7] L.K. Harding et al., *"Staff Radiation Doses Associated with Nuclear Medicine Procedures – a Review of Some Recent Measurements"*, Nuclear Medicine Communications 11, 271-277, 1990.

[8] A. Montgomery et al., *"Application of a Gamma Extremity Monitoring System in a Radiopharmaceutical Dispênsary"*, Nuclear Medicine Communications 18, 673-679, 1997.

[9] A. Montgomery et al., *"Reductions in Finger Doses for Radiopharmaceutical Dispensing Afforded by a Syringe Shield and a Automatic Dose Dispenser"*, Nuclear Medicine Communications 20, 189-194, 1999.

[10] Belgian Society of Nuclear Medicine, *"Guidelines for the Reference Administered Activities"*, Published: www.belnuc.be, 2002.

[11] S. Dhanse et al., " A Study of Doses to the Hands During Dispensing of Radiopharmaceuticals" , Nuclear Medicine Communications 21, 511-529, 2000.

[12] E.D. Williams et al., *"Monitoring Radiation Doses to the Hand in Nuclear Medicine: Location of Dosemeters"*, Nuclear Medicine Communications 8, 499-503, 1987.

[13] B. Perdereau et al., *"Contrôle Capillaroscopique Sous-Unguéal des Personnels Radio-Exposés: Résultats Préliminaires et Incidence en Radioprtection"*, Radioprotection 2000, Vol. 35, n°3, 335-366.

Annales de l'Association Belge de Radioprotection Vol. 28,n°1,2003

ESTIMATING OCCUPATIONAL EFFECTIVE DOSE OF LEAD APRON PROTECTED WORKERS IN RADIOLOGY

Buls N, Covens P[*] and Osteaux M

Academisch Ziekenhuis Vrije Universiteit Brussel (az-vub)
Dienst Radiologie en Medische Beeldvorming
[*]Dienst Fysische Controle
Laarbeeklaan 101
B-1090 Brussel

Introduction

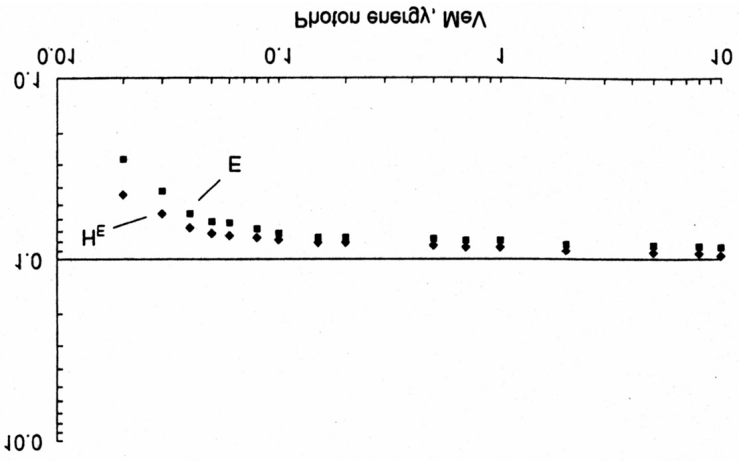
During standard radiodiagnostic examinations, the radiographer protects himself from scatter radiation by standing behind a lead glass shield. However, specific manipulations are often required at a very close distance to the patient. In such occasions the worker protects himself by wearing a lead apron. In general, such radiographic examinations (interventional radiology, digestive radiology, cardiology, CT-fluoroscopy, etc) use a considerable amount of fluoroscopy and it is well known that they present the highest patient and staff doses in radiology.
Since the Royal Decree [1] of 20 July 2001 it is mandatory in Belgium to monitor lead apron workers with two dosimeters when substantial doses could be received. The Royal Decree only specifies that one dosimeter should be worn under the apron, and that the other should be worn above the apron. There is no requirement of the specific location of the over-apron dosimeter, nor is there a guideline for estimating the effective dose (E) from two dosimeter readings.
The monitoring of lead apron workers by two dosimeters was already widely recommended by various authors [5,8,10,12-15] and by several competent bodies such as the NCRP in 1978 [2] and the ICRP in 1982 [3]. It is generally agreed upon that an adequate dose monitoring of lead apron workers requires two dosimeters instead of one. However, there is some scientific debate about the monitoring arrangements and more specifically about the algorithm to be used for the estimation of the effective dose from two dosimeter readings. An adequate estimation of the effective dose is necessary, as it represents the involved radiological risk. Also, regarding regulatory dose limits, the estimated E will have important occupational and patient-related consequences (for example, the restriction of a cardiologist to an x-ray room).
The objective of this paper was to review various proposed methods of estimating effective dose of lead apron workers and to apply them on actual monitoring data of radiology workers.

The use of the personal dose equivalent $H_p(10)$ for estimating the effective dose E

As effective dose cannot be directly measured in routine situations, it is generally approximated by the personal dose equivalent $H_p(10)$, which is for strongly

penetrating radiation (x-rays) the dose equivalent in soft tissue at 10 mm below the skin surface [4]. The $H_p(10)$ can be practically measured with a detector which is worn at the surface of the body, covered with an appropriate thickness of tissue-equivalent material. The $H_p(10)$ gives a good estimate of the E under the conditions that the worker is nearly uniformly exposed over the whole body with photon energies above 100 keV, in an anterior-posterior (AP) plane-parallel direction [5]. These conditions are not really valid for a lead apron worker. The irradiation condition of the worker is complex, non-uniform and not plane-parallel. This is attributable to the different exposure geometries of the patient and partial attenuation of the scatter field by several components such as the Bucky and the image intensifier housing. Also, the average photon energy of the scatter radiation is much lower than 100 keV. Fluoroscopic equipment is commonly operated between 60 kVp and 110 kVp, yielding mean photon energies of 36 keV and 52 keV respectively, assuming a 2.5 mm Al filtration and a 17° wolfram target [6]. Most of the workload is found at potentials around 80 kVp [7], yielding a mean photon energy of 43 keV. For energies below 90 keV Compton scattered photons have a similar energy as the primary beam. However, some filtration and hardening occurs in the scattered material so that the mean energy of the scattered radiation tends to be somewhat higher than that of the primary beam [8]. The effect of lower photon energies on the $E/H_p(10)$ ratio is well illustrated in Figure 1 [5]. The figure shows the $E/H_p(10)$ ratio calculated using the Monte Carlo computer code MCNP-4B for a mathematical anthropomorphic phantom in function of the photon energy for a dosimeter worn at the chest level in a plane-parallel broad beam AP geometry. For photon energies below 100 keV, the ratio drops rapidly below one which means that the $H_p(10)$ will overestimate the E considerably.

Figure 1. $E/H_p(10)$ ratio (squares) in function of photon energy for a plane-parallel beam of photons incident on a mathematical anthropomorphic phantom in an AP direction (from [5]).



The multiple dosimeter approach

It is clear that a single dosimeter worn outside of the apron will overestimate the E since it does not take into account the shielded organ doses inside the apron. On the other hand, a single dosimeter worn under the apron will substantially underestimate the E since it does not take into account the dose to the unshielded organs outside the

apron, which are mainly the thyroid and fractions of the oesophagus, red bone marrow, skin and bone. Several authors investigated the relationship between the *E* and a single dosimeter reading [9]. For example, Faulkner and Marshall suggest that the *E* of a worker wearing a 0.5 mm lead equivalent apron, using a 90 kVp primary beam and an under-table tube geometry, can be estimated by dividing the over apron dosimeter reading by 32 [9]. A single dosimeter algorithm requires specific information of the operational conditions since apron attenuation is a function of the x-ray energy, the lead apron thickness and the exposure geometry. As it is difficult to estimate al these parameters for clinical conditions, large errors may result. The readings of two dosimeters, simultaneously worn under and over the apron, will provide information of the apron attenuation and allows to make a more correct estimation of the *E*.

Reviewed algorithms

Table 1 lists several proposed algorithms to estimate the effective dose from over and under dosimeter readings for lead apron workers. When applying these algorithms to annual monitoring data from two radiology workers, a very large variation is observed as shown in the two last columns of the table and also in figure 2.

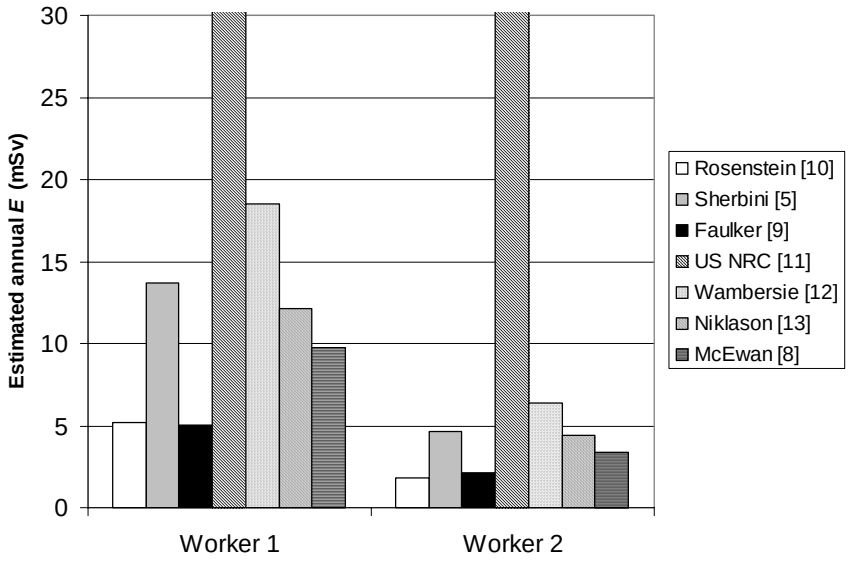
Table 1. Reviewed algorithms applied on annual monitoring data of two radiology workers.

Author		Algorithm	Estimated *E* to worker 1 (mSv)	Estimated *E* to worker 2 (mSv)
Rosenstein	[10]	$E = 0.5 \cdot H_{under} + 0.025 \cdot H_{over}$	5.2	1.8
Sherbini	[5]	$E = 1.0 \cdot H_{under} + 0.07 \cdot H_{over}$	13.7	4.7
Faulkner	[9]	$E = H_{over} / 32$	5.0	2.1
US NRC	[11]	$E = H_{over}$	161	55
Wambersie	[12]	$E = 1.0 \cdot H_{under} + 0.1 \cdot H_{over}$	18.5	6.4
Niklason	[13]	$E = 0.06 \cdot \left(H_{s,over} - H_{under}\right) + H_{under}$	12.1	4.4
McEwan	[8]	$E = 0.71 \cdot H_{under} + 0.05 \cdot H_{over}$	9.8	3.4

$H_{under} = H_p(10)$ measured under the apron; $H_{over} = H_p(10)$ measured over the apron; $H_{s,\,over} = H_p(0.07)$ measured over the apron

Clearly, as there is no consensus, the effective dose depends strongly on which algorithm is applied. This emphasises the need for clear guidelines. For example, worker 1 is almost reaching the 20 mSv annual effective dose limit when applying the Wambersie [12] algorithm. However when using the Faulkner [9] algorithm, the estimated annual effective dose is only 5 mSv, which is still substantial but clearly less problematic than 18.5 mSv. The US NRC [11] algorithm yields the highest *E*, as the $H_p(10)$ should be measured at the point of highest exposure on the body, which is the over-apron reading in the region of the neck.

Figure 2. Estimated annual effective dose (*E*) of two lead apron workers according to several proposed algorithms in literature.



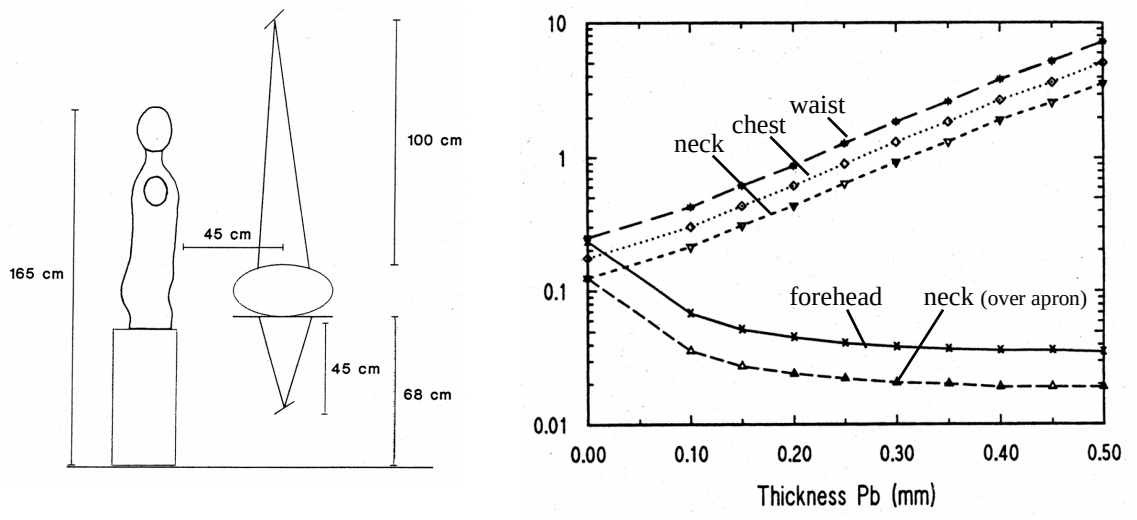
The authors listed in table 1 use mainly three different approaches to retrieve their algorithm. Some authors use experimental data [10], some use a fully computational Monte Carlo simulation [5], others use a more straightforward analytical calculation [8,12,13]. From a radiation protection point of view, it is interesting to note that all authors claim to provide a *conservative* estimation of the effective dose. There is however a difference in the level of pragmatism between the different algorithms. For example, the Wambersie [12] algorithm takes into account a safety factor of two. The next three paragraphs (a-c) briefly discus the different approaches.

a. Based on clinical/experimental data

Rosenstein and Webster [10], algorithm: $E = 0.5 \cdot H_{under} + 0.025 \cdot H_{over}$

This formula is the most applied and recommended algorithm in international literature [15] and is used by national competent bodies such as the NCRP [16,17]. It is based on the experimental data of a Faulkner study, which investigated the effective dose to workers in simulated clinical conditions [9]. The scatter field was produced at various tube potentials (from 70 kVp to 110 kVp), with the x-ray tube in an over-table and under-table position (Fig. 3a). $H_p(10)$ values were measured at different locations on a humanoid (Rando) phantom, under and over an apron. Organ doses were determined by using numerous thermoluminescent dosimeters positioned inside the phantom and the effective dose was computed as described by the ICRP [18] for the different tube potentials and for different lead apron thickness'. Figure 3b is an example of their results and shows the $E/H_p(10)$ ratio for an over-table tube geometry at 70 kVp tube potential condition.

Figure 3 a. Experimental set-up from Faulkner [9]. **b**. *E/Hp(10)* ratio for an over-table tube geometry at 70 kVp. Hp(10) is measured at the level of the waist, chest and neck under the apron and at the level of the forehead and neck above the apron (from Faulkner [9]).



These experiments show that the $E/H_p(10)$ ratio drops below zero when no apron is present (thickness Pb = 0 mm) which again means that the $H_p(10)$ overestimates the *E*, as was also shown by the Sherbini [5] Monte Carlo calculations (Fig.1). When a 0.5 mm lead apron thickness is present, the three under-apron $H_p(10)$ values underestimate the *E*, and the two over-apron $H_p(10)$ values overestimate the *E*. Rosenstein and Webster [10] used this experimental data from Faulkner [9] and iterate weighting values for the under and over apron dosimeter readings until a desired approximation of the effective dose was achieved for a clinical environment. As the algorithm should be used for various clinical conditions, the criteria were

a) to minimise underestimates of *E*, even at the expense of larger overestimates of *E* for some clinical conditions, and
b) to obtain a close estimate of *E* at the combination most frequently encountered in clinical practice.

The advantage of this approach is that it uses a clinical set-up (Fig. 3a) and therefore takes into account the complex irradiation conditions that are encountered in clinical practice. The approach also takes into account the photon energy dependence which substantially influences the relationship between the $H_p(10)$ and the *E*. A shortcoming to the accuracy of this approach may be that only two exposure geometries are used (over-table tube and under-table tube) and that the worker is standing in only one position (in front of the patient). This latter will however tend to overestimate the *E* as x-ray photons, that are obliquely incident when the worker is standing lateral to the patient, have longer attenuation paths. This results in less absorbed dose to the internal organs.

b. Based on a Monte Carlo simulation

Sherbini and DeCicco [5], algorithm: $E = 1.0 \cdot H_{under} + 0.07 \cdot H_{over}$

These authors used a fully computational approach. The worker was simulated by a mathematical anthropomorphic phantom which was exposed by a point source (x-ray

spectra from 30 to 150 kVp) located at 1 m in front of the phantom. The organ doses, $H_p(10)$ values and the E were assessed by using the Monte Carlo transport code MCNP-4B. The authors evaluated different algorithms and found that a four-dosimeter algorithm gave the best results for all the different kVp settings that are encountered in clinical conditions. They also proposed an adjustment of the weighting coefficients of the Rosenstein [10] formula in order to find a better agreement with their findings. These adjusted coefficients yield a considerable higher effective dose estimation.
As with the previous algorithm, also this approach takes into account the photon energy dependence which partly determines the relationship between the $H_p(10)$ and the E. A shortcoming of the accuracy of this approach may be that it simulates the complex scatter field by a simplified point source in plane-parallel geometry. This tends to overestimate the E as it would subject internal organs to more absorbed dose than in a complex irradiation.

c. Based on a straightforward analytical calculation

McEwan [8], algorithm: $E = 0.71 \cdot H_{under} + 0.05 \cdot H_{over}$

Niklason, Marx and Chan [13], algorithm: $E = 1.0 \cdot H_{under} + 0.06 \cdot \left(H_{s,over} - H_{under}\right)$

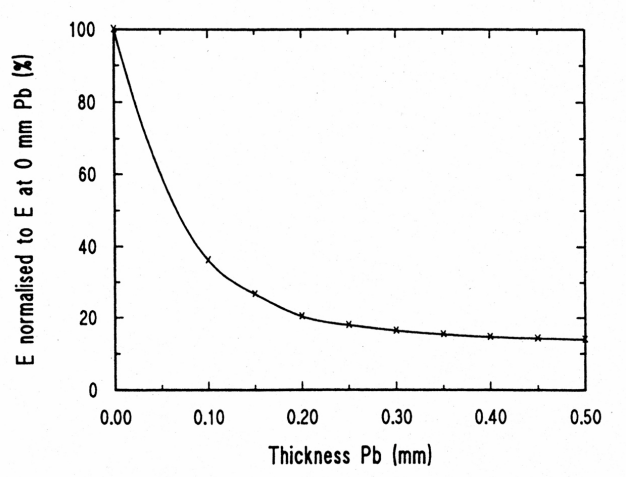
Wambersie and Delhove [12], algorithm: $E = 1.0 \cdot H_{under} + 0.1 \cdot H_{over}$

These three authors use more or less the same approach. The under-apron dosimeter reading $H_p(10)$ is assumed to be the whole body dose. The over-apron dosimeter reading $H_p(10)$ is used to estimate the dose to the fraction of the tissues and organs which are not protected by the apron (head, neck and extremities). Both values are added to retrieve the effective dose. Thus, the weighting factor for the under-apron dosimeter reading is equal to one, except for the McEwan [8] formula which takes into account a correction factor for the energy dependence of the $E/H_p(10)$ ratio and excludes the thyroid dose from the under-apron dosimeter reading. The weighting factor for the over-apron dosimeter reading is determined by the contributing ICRP tissue weighting factors [18] of the tissues and organs not protected by the apron. This contribution is more or less equal to 0.05 (depending on which anatomical model is used) and comes mainly from the thyroid, red bone marrow (RBM) and oesophagus. The Wambersie [12] formula contains a safety factor of two and therefore uses a weighting factor of 0.1. The authorities of the Swiss confederation also use this formula [19].
When removing the safety factor of two from the Wambersie [12] formula, the three formulas yield more or less comparable values of the estimated effective dose. The McEwan [8] formula gives a lower value since it includes the photon energy correction and excludes the thyroid from the under-apron reading.
A shortcoming of the accuracy of these three algorithms may be that they are directly derived from the $H_p(10)$ value and therefore assume a uniform, plan-parallel, high photon energy irradiation, which is not the case in clinical conditions. This will tend to overestimate the effective dose. Also, the doses to all the unshielded tissues are directly derived from the reading of the over-apron dosimeter, which also assumes a uniform scatter field. In a complex scatter field, the kerma at the location of the head can differ considerably from the kerma at the location of the chest.

The influence of apron thickness and complementary shielding

Figure 4 is retrieved from Faulkner [9] and shows the variation of the normalised effective dose in function of lead apron thickness for a specific irradiation condition. The over-apron dosimeter is unaffected by the presence of the apron. As the apron thickness is increased, the under apron dosimeter reading will decrease (depending on the energy and uniformity of the scatter field) and the effective dose will be dominated by the contributions from the doses of the unshielded organs. As a result, the effective dose tends towards a constant value in function of the apron thickness. Efforts to decrease the effective dose will thus be more efficient by shielding the unshielded organs instead of increasing the lead apron thickness even further. Shielding of the thyroid will be the most effective since it is located completely outside the apron and it has a relatively high tissue weighting factor of 0.05 [19]. Consequently, when worn, a thyroid shield should also be taken into account for an adequate estimation of the effective dose. Niklason [13] proposes a weighting factor for the over apron dosimeter reading of 0.02 instead of 0.06 when an apron is complemented by a thyroid shield. This results in a reduction of the estimated effective dose by nearly 50%.

Figure 4. Normalised effective dose in function of lead apron thickness for an over-table x-ray tube 90 kVp exposure geometry (from Faulkner [9]).



Conclusions

As it is mandatory in Belgium, lead apron workers should be monitored by two dosimeters when substantial doses could be received. One dosimeter should be worn under the apron, the other should be worn over the apron. There is no requirement of the specific location of the over-apron dosimeter, nor is there a guideline for estimating the effective dose (E) from two dosimeter readings. When reviewing proposed algorithms for estimating the E from two dosimeter readings, it is clear that no consensus has yet emerged and that there is a ongoing scientific debate. When applying these various proposed algorithms, large differences of the estimated effective dose are observed as shown in table 1 and figure 2.

From a radiation protection point of view, it is necessary to choose a conservative approach for estimating the effective dose. However, caution should be taken that the effective dose is not excessively overestimated. Besides the radiological risk, one should also keep the occupational consequences for the worker in mind. A good practise for estimating the *E* for lead apron workers is to obtain a close estimate of the *E* for all the encountered clinical conditions without underestimating the *E* for one specific condition.
It is likely that the approach used by Rosenstein and Webster [10] gives the most accurate estimation of the effective dose since it takes into account both the real clinical conditions of the worker, and the energy dependence of the $E/H_p(10)$ ratio. In general, the uncorrected $H_p(10)$ value is not a good estimate of the *E* for all workers who use medical x-rays (not only lead apron workers) due to the low photon energies (mean 40~ 50 keV) which are encountered in clinical practise. The other reviewed algorithms often use an oversimplified model of the scatter radiation field by simulating it as a point source [5], or by directly using the $H_p(10)$ value [8,12,13] which assumes a uniform, high photon energy, whole body irradiation. This assumption is not valid in clinical practise and tends to overestimate the effective dose. It is unlikely that one could identify the complex irradiation conditions of the worker, which is why scatter fields should be generated by clinical simulations. Consequently, it may be useful to validate the Rosenstein [10] approach for more various exposure geometries encountered in clinical practise, such as lateral-oblique projections or scatter fields generated by CT-Fluoroscopy [20] procedures.
Obviously, there is an urgent need for strict guidelines which a) indicate the exact location of the over apron dosimeter and b) imply an algorithm to derive the effective dose from the two dosimeter readings, also in combination with a complementary thyroid shield.

References

[1] Koninklijk besluit houdende algemeen reglement op de bescherming van de bevolking, van de werknemers en het leefmilieu tegen het gevaar van de ioniserende stralingen. 20 juli 2001 (BS 30.08.2001).

[2] National Council on Radiation Protection and Measurements. Instrumentation and monitoring methods for radiation protection. Bethesda, MD: NCRP; NCRP Report No. 57; 1978.

[3] International Commission on Radiation Protection. General principles of monitoring for radiation protection of workers. Oxford: Pergamon Press; ICRP Publication 35; 1982.

[4] International Commission on Radiation Units and Measurements. Quantities and units in radiation protection dosimetry. Bethesda, MD: ICRU; Report 51; 1993.

[5] Sherbini S, DeCicco J. Estimation of the effective dose when protective aprons are used in medical procedures: a theoretical evaluation of several methods. Health Phys 83(6):861-870; 2002.

[6] Birch R, Marshall M, Ardran GM. Catalogue of the spectral data for diagnostic x-rays. London: The Hospital Physicists Association; Scientific Report Series 30; 1975.

[7] Dixon R, Simpkin D. New concepts for radiation shielding of medical diagnostic x-ray facilities. In: Frey G, Spralws P, eds. The expanding role of medical physics in diagnostic imaging. Madison: Advanced Medical Publishing; 1992: 283-311.

[8] McEwan A. Assessment of occupational exposure in New Z ealand from personal monitoring records. Radiation Protection in Australasia 17(2):60-66; 2000.

[9] Faulkner K, Marshall N. The relationship of effective dose to personnel and monitor reading for simulated fluoroscopic irradiation conditions. Health Phys 64(5):502-508; 1993.

[10] Rosenstein M, Webster W. Effective dose to personnel wearing protective aprons during fluoroscopy and interventional radiology. Health Phys 67(1):88-89; 1994.

[11] United States Nuclear Regulatory Commission. Standards for protection against radiation. Washington DC: United States Government Printing Office; United States Code of Federal Regulations, Title 10: Part 20; 2000.

[12] Wambersie A, Delhove J. Radiation protection in diagnostic radiology, a debated practice: how to wear the individual dosemeters? JBR-BTR 76:382-385; 1993.

[13] Niklason L, Marx M, Chan H. The estimation of occupational effective dose in diagnostic radiology with two dosimeters. Health Phys 67(6):611-615; 1994.

[14] Mol H, De Luyck I, Vandenbranden S, Eggermont G, Van Loon R. Dosimetrie bij het gebruik van een loodschort. Annalen van de Belgische Vereniging voor Stralingsbescherming 23(1):85-99; 1998.

[15] Faulkner K, Vañ o E, Ortiz P, Ruiz R. Practical aspects of radiation protection in interventional radiology. In: The international conference on radiological protection of patients in diagnostic and interventional radiology, nuclear medicine and radiotherapy; 2001 March 26-30; Malaga. Vienna: International Atomic Energy Agency, 2001.

[16] National Council on Radiation Protection and Measurements. Use of personal monitors to estimate effective dose equivalent and effective dose to workers for external exposure to low-LET radiation. Bethesda, MD: NCRP; NCRP Report No. 122; 1995.

[17] National Council on Radiation Protection and Measurements. Radiation protection for procedures performed outside the radiology department. Bethesda, MD: NCRP; NCRP Report No. 133; 2000.

[18] International Commission on Radiation Protection. Recommendations of the International Commission on Radiological Protection. Oxford: Pergamon Press; ICRP Publication 60; 1991.

[19] Confoederatio Helvetica, Die Bundesbehö rden der Schweizerischen Eidgenossenschaft. Strahlenschutzverordnung vom 22 Juni 1994 (StSV). SR No. 814.501; 1994.

[20] Buls N, Pages J, de Mey J, Osteaux M. Evaluation of patient and staff doses during various CT Fluoroscopy guided interventions. Health Phys, *in press*.