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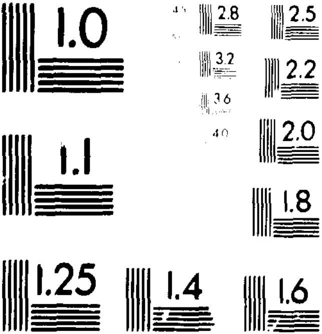

JAN 1995

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Dipartimento Ambiente

MONTE CARLO TECHNIQUE APPLICATIONS IN THE FIELD OF RADIATION DOSIMETRY AT THE ENEA RADIATION PROTECTION INSTITUTE: A REVIEW

G.F. GUALDRINI, L. CASALINI, B. MORELLI
Centro Ricerche "Ezio Clementel", Bologna

Paper presented at the *Fourth Conference on Radiation Protection and Dosimetry*
(Orlando, Florida October 23-27, 1994)

RT/AMB/94/34

ENTE PER LE NUOVE TECNOLOGIE,
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Summary

The present report summarizes the activities concerned with numerical dosimetry as carried out at the ENEA-AMB-IRP (Radiation Protection Institute) on photon dosimetric quantities.

The first part is concerned with MCNP Monte Carlo calculations of field parameters and operational quantities for the ICRU sphere with reference photon beams for the design of personal dosemeters.

The second part is related with studies on the ADAM anthropomorphic phantom using the SABRINA and MCNP codes.

The results of other Monte Carlo studies carried out on electron conversion factors for various tissue equivalent slab phantoms are about to be published in other ENEA reports.

The report has been produced in the framework of the EURADOS WG4 (Numerical Dosimetry) activities within a collaboration between the ENEA Environmental Department and ENEA Energy Department.

Riassunto

Il presente rapporto presenta in breve le attività nel campo della dosimetria numerica svolte presso ENEA AMB-IRP (Istituto per la Radioprotezione) sulle quantità dosimetriche per fotoni. .

La prima parte riguarda calcoli Monte Carlo MCNP di parametri di campo e quantità operazionali per la sfera ICRU con fasci di riferimento fotonici per la progettazione di dosimetri personali.

La seconda parte riguarda studi sul fantoccio antropomorfo ADAMO svolti mediante i codici MCNP e SABRINA.

I risultati di altri studi volti alla determinazione di fattori di conversione per elettroni su vari fantocci a slab di materiali tessuto equivalenti sono in via di pubblicazione in un altro rapporti ENEA.

Il presente rapporto è stato prodotto nell'ambito delle attività EURADOS WG4 (Dosimetria Numerica) nel quadro di una collaborazione fra i Dipartimenti AMB ed ERG dell'ENEA.

1-INTRODUCTION

At the ENEA (Ente Nazionale per le Nuove Tecnologie, l'Energia e l'Ambiente) Institute of Bologna (Italy) since many years various activities have been carried out in the field of experimental dosimetry and radiation protection.

As far as the external radiation monitoring is concerned, these activities dealt with the design development and type test of photon personal dosemeters as well as routine reading and control of dosemeters, calibration activities etc.

As far as the internal dosimetry activities are concerned a whole body counter has been built and used since many years both for research activities and for routine assessment of internal doses.

The WBC has been extensively used in the recent years, especially after the Chernobyl accident, to assess doses from intake of radioactive nuclides for Italian workers employed in Russia as well as normal population mainly leaving in the north-eastern Italian areas.

In the recent years, the necessity of improving the general dose assessment capabilities and to provide accurate field parameters and operational quantities, according to the new international recommendations, outlined the importance of coupling experimental work with Monte Carlo radiation transport modelling.

In this framework the code employed in the calculations was the general purpose Monte Carlo code MCNP (Monte Carlo for Neutrons and Photons) /1/ developed at the Los Alamos Scientific Laboratory (USA). This code, that makes use of a point-wise cross section library for photons with data derived from Hubbell et al. /2/ is provided with a very powerful geometry package, allowing complex geometries to be described and with a large variety of variance reduction techniques (Cell Splitting and Russian Roulette being the most important). The code is one of the most widely used instrument in the OECD countries and outside for neutron, photon and electron transport calculations. Since many years the code has been used at ENEA in the field of reactor physics and shielding design, deep penetration problem solution as well as dose assessment of radioactive material transport packages. Some improvements were also included, like the capability to treat electrons based on multiple scattering algorithms according to the Moliére theory /3/ /4/ (that was included before the release of MCNP-4 in order to treat coupled photon-electron transport problems) and the splitting parameter optimization routines in space and energy based on the DSA method /5/.

The present paper summarizes some studies carried out with Monte Carlo in the framework of the ENEA contribution to the activities of the EURADOS Working Group 4 (Numerical Dosimetry): they are concerned with computations of field parameters and operational quantities for the ICRU sphere with reference photon beams and modelling and calculations for photon internal and external dose assessment with the ADAM anthropomorphic phantom.

2-MONTE CARLO CALCULATIONS OF FIELD PARAMETERS AND OPERATIONAL QUANTITIES FOR THE ICRU SPHERE WITH REFERENCE PHOTON BEAMS FOR THE DESIGN AND CALIBRATION OF PERSONAL DOSEMETERS

The publication in 1985 and 1988 by the International Commission on Radiation Units and Measurements of Reports 39 /6/ and 43 /7/ stimulated attention being given to the appropriate procedure for the calibration of personal dosemeters.

According to these documents the calibration must be performed by placing dosemeters on an appropriate phantom exposed to X and gamma reference radiations as recommended by ISO (International Organization for Standardization) or, in particular cases, BIPM (Bureau International des Poids et Mesures) reference X-ray radiations originally employed for primary calibration.

The Italian regulations in the field of calibration of personal dosemeters do not at the moment comply with the mentioned recommendations (calibrations of photon personal dosemeters being performed in terms of photon exposure): a Task Group has been however set up by the Government to formulate a new National Regulation in the spirit of the CEC directives.

In this framework numerical studies for the characterization of radiation fields produced by the reference radiations as well as calibrations on tissue equivalent phantoms have been started since some years at the ENEA Secondary Standard Dosimetry Laboratory in Bologna, as a feasibility study.

Following the previously mentioned recommendations, the ICRU sphere was taken as a suitable phantom for calibration purposes, whilst in the last years, ICRU has proposed a slab PMMA 30 cm X 30 cm X 15 cm phantom /8/ and very recently ISO proposed a 30 cm X 30 cm X 15 cm water phantom with a front face consisting of a 2.5 mm thick PMMA plate and the other phantom sides consisting of 10 mm thick PMMA plates /9/. This new proposals were formulated when the work herewith summarized was already in progress.

The criticism concerning the adoption of the ICRU sphere as a suitable phantom for calibration purposes was motivated by practical reasons: no commercial material can really be considered as a perfect substitute of the ICRU theoretical material, the sphere does not allow contemporary calibration of many dosemeters and, moreover, the non physical effects due to the spherical shape of the phantom (the so-called "ears" effect) are encountered in calculating conversion coefficients especially for higher energies.

Leaving out the quite troublesome discussion on "the most suitable phantom", our numerical evaluations and experimental verifications on reference X-ray beams, with the addition of ^{137}Cs and ^{60}Co sources, concerned principally /10/:

(1) Determination of air kerma backscatter factors and their dependence on the incident angle of the beam in an expanded and aligned field for the ICRU sphere, together with an extensive comparison of the results with those obtained in other European Laboratories /11/.

(2) Monte Carlo calculations of spectral physical parameters, i.e. the backscattered radiation mean energy for the ICRU sphere and its dependence on the beam incident angle.

Moreover a Monte Carlo evaluation of backscattered radiation spectra in front of the ICRU sphere was performed /12/.

(3) Comparison of experimental and calculated backscatter factors (with also their dependence on the beam incident angle) using the RS-1 sphere which is composed of a nearly tissue-equivalent material /13/. The study enabled the code and its associated interaction coefficients library in the range of energies from 30 keV to ^{60}Co to be validated /14/.

Finally a Monte Carlo study of the air kerma to directional dose equivalent conversion factors at the three depths of 7 mg/cm^2, 300 mg/cm^2 and 1000 mg/cm^2 in the ICRU sphere were performed /15/.

All the calculations were carried out in the so-called KERMA approximation, i.e. the secondary electron transport was not taken into accont and the problem mock-up was simplified neglecting the presence of air (to fulfil the definition of aligned field).

2-A *Backscatter factor calculations and measurements*

The air kerma backscatter factors for the ICRU sphere were calculated for the four ISO X-ray refecence series (High Air Kerma Rate Series, Low Air Kerma Rate Series, Wide Spectrum Series and Narrow Spectrum Series) and the BIPM Series at three distances from the phantom surface, i.e: 0 mm, 5 mm and 10 mm. In Figure 1 the energy dependence of the air kerma backscatter factor for the Wide Spectrum Series is presented for a normally incident photon beam.

Figure 2 shows an example of comparison between measured and calculated values for the same ISO Series.

2-B *Energy distribution of backscattered radiation*

The mean energy of backscattered radiation as a function of incident angle was determined. This information, together with the fluence backscatter factor at the same angle, provides information on the average radiation field (in terms of energy) impinging on the detector. Figure 3 supplies the spectrum at 0 degrees incident angle for the same photon beam in front of the ICRU sphere. The convolution of incident and backscattered spectra using the fluence backscatter factor as normalization coefficient determines the mixed spectrum.

Fig.1: Wide Spectrum Series:
Backscatter factors versus equivalent energy at various distances from the ICRU sphere.

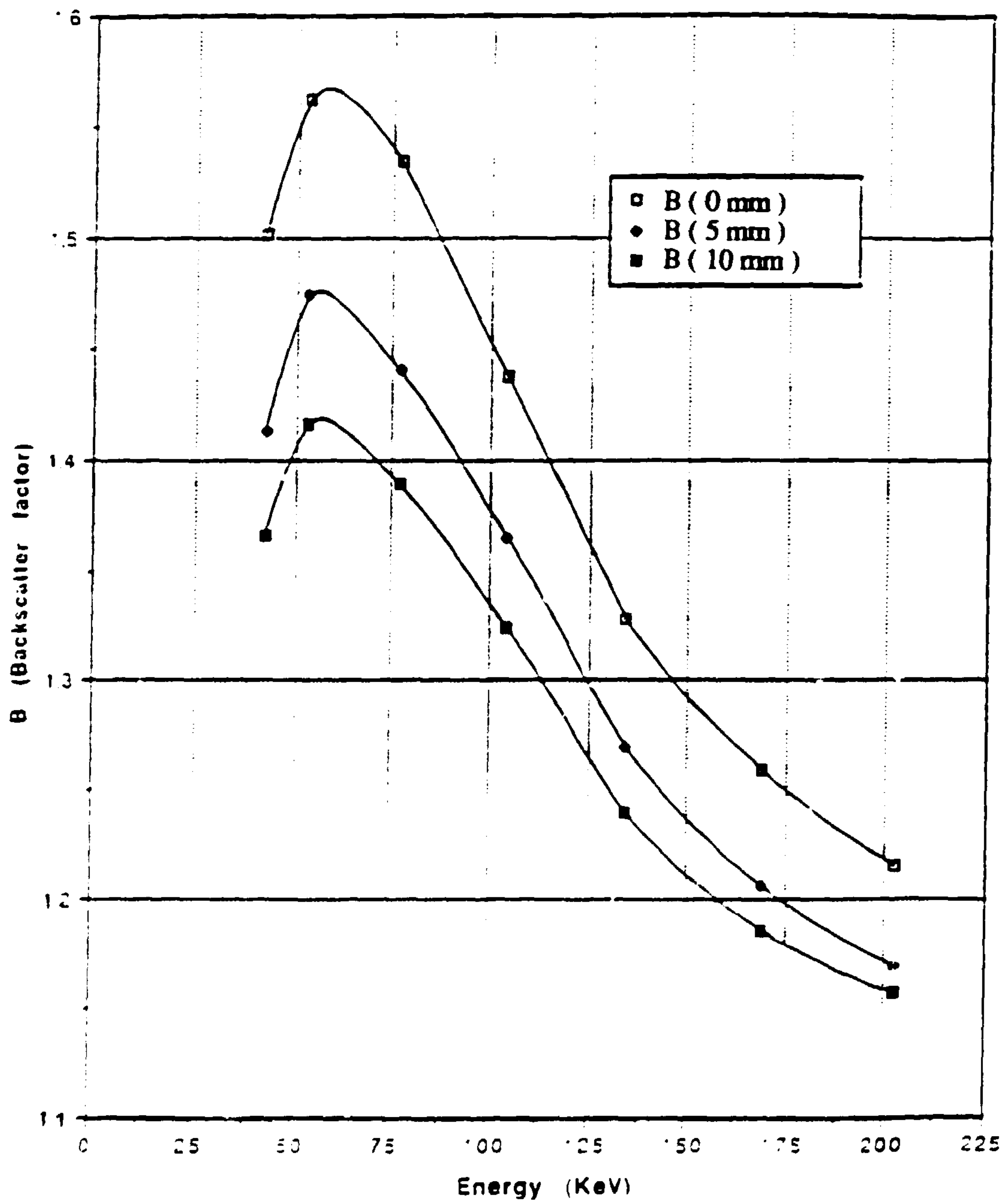


Fig.2: Wide Spectrum Series:
Comparison between experimental and calculated Backscatter factors.

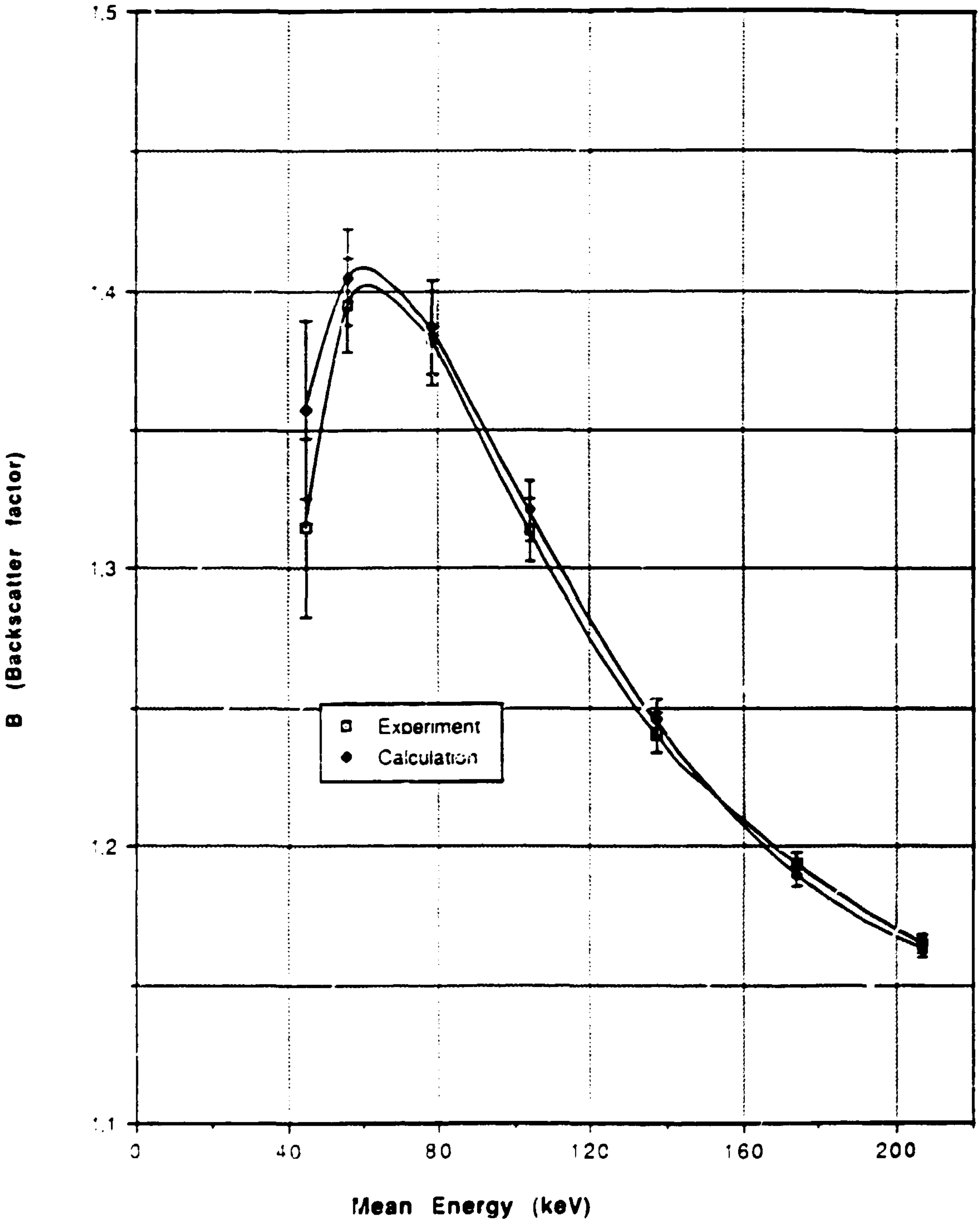
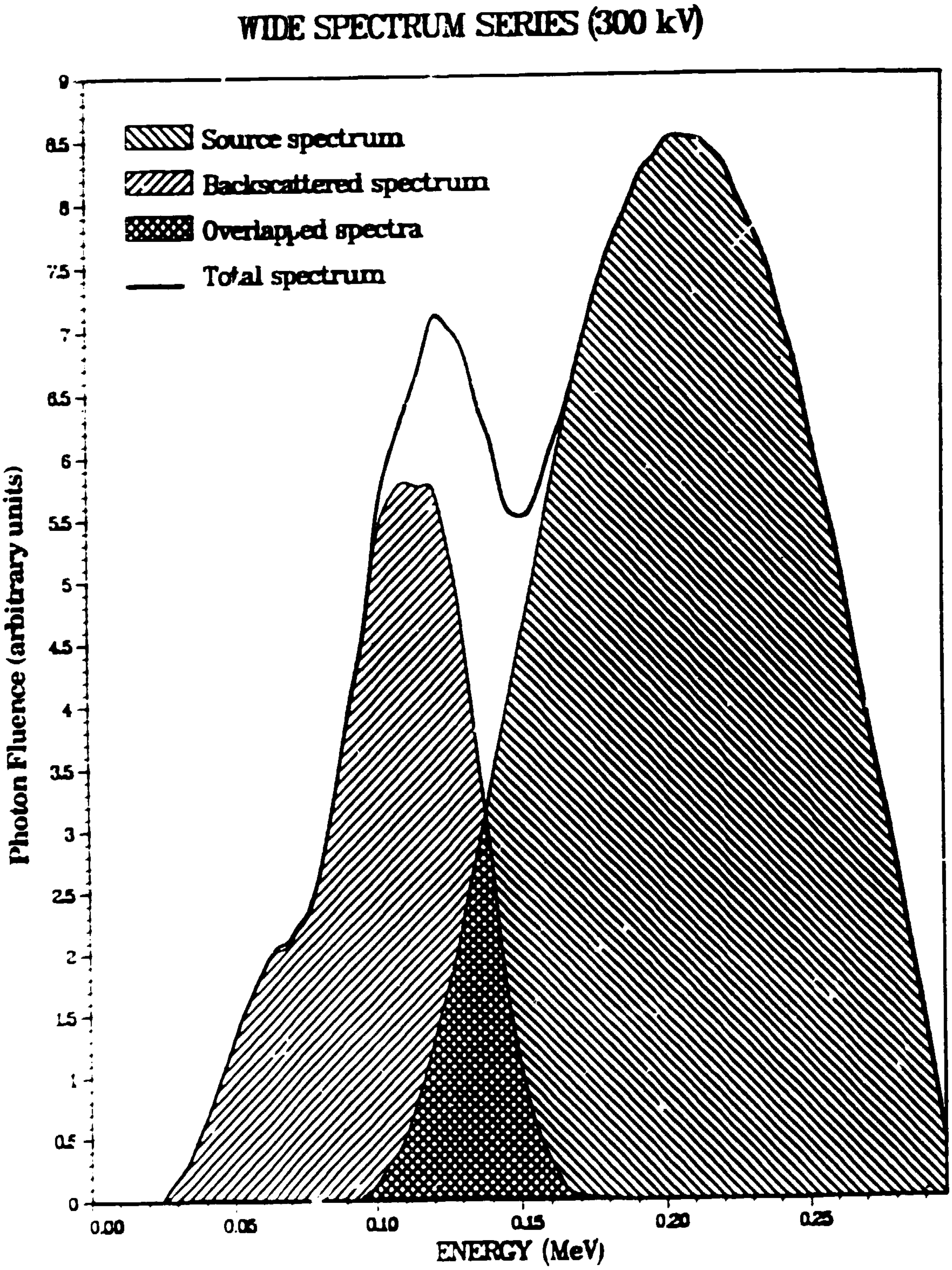


Fig.3: Wide Spectrum Series:
Photon fluence in presence of the ICRU sphere.



2-C Fluence to directional dose equivalent conversion coefficients

For this kind of operational quantities a certain number of data have been published concerned with both monochromatic energies and X-ray reference photon beams. These data are nevertheless incomplete, being referred mainly to normally incident beams. In our work we tried to supply a rather complete set of H'(d,ω) (both in tabular and graphical form) at the three mentioned depths together with families of depth dose curves for the various radiation incident angles. Figure 4 shows the angular dependence curves for 7 mg/cm^2.

Assuming, as mentioned above, the ICRU sphere as a suitable phantom for individual monitoring, so that the dosemeter design can be performed in terms of H'(d,ω) (that, in this case, corresponds to $H_S(d)$ and $H_p(d)$), the relationship between the dosemeter response and the operational quantity can be expressed by a semi-empirical formula, based on the theoretical expected interactions on the dosemeter when placed on the phantom and irradiated with a known photon beam as well as on the experimental energy response of the bare detector when irradiated free in air with the same photon beam /16/. The same phylosophy can of course be applied when using reference phantoms other than the ICRU sphere.

3-APPLICATIONS OF SABRINA AND MCNP TO DOSE ASSESSMENT STUDIES WITH THE ADAM ANTHROPOMORPHIC PHANTOM

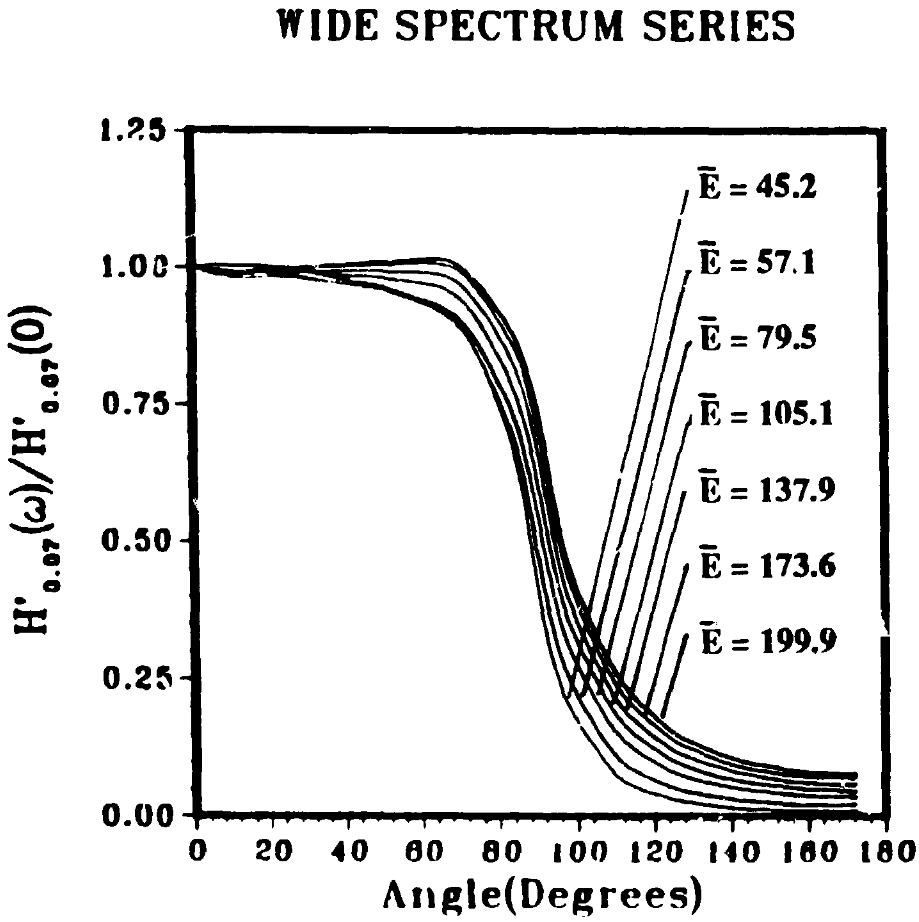
Anthropomorphic phantoms play a very important role for the dose assessment in accidental irradiation conditions as well as in the dose evaluation to the patient during diagnostic and therapy treatments.

A large variety of phantoms has been proposed in the last thirty years, characterized by various degrees of complexity (sex and age-dependent).

A study has been therefore started concerned with the preparation of geometry packages for MCNP describing complex anthropomorphic phantoms. The male phantom was firstly implemented using the ADAM mathematical model /17/, based on the MIRD-5 pamphlet /18/.

The ADAM phantom is a simplified description of the standard western European male: the version that has been studied and implemented /19/ for MCNP is represented by 60 cells defined by 170 surfaces (planes, cylinders, cones, spheres, ellipsoids and torii), modelling the various organs, that are composed by four tissue materials: skin tissue (ρ=1.105 g/cm^3), lung tissue (ρ=0.296 g/cm^3), skeleton tissue (ρ=1.486 g/cm^3) that is an homogenized mixture of bone and bone marrow, and finally soft tissue (ρ=0.987 g/cm^3). The ADAM phantom was implemented for MCNP and the geometry could be checked using the SABRINA code, created at the Los Alamos Scientific Laboratory /20/. A series of accurate tests and Monte Carlo preliminary analyses for internal and external dosimetry problems have been performed /21/.

Fig.4: $H'_{0.07}(\omega)/H'_{0.07}(0)$ dependence on the radiation incident direction for Wide Spectrum Series photon beams.



3-A Graphical display and geometry check of ADAM using the SABRINA code

The SABRINA code (LANL) was implemented on a VAX-9000 computer and the graphical studies were performed on a TEKTRONIX 4225 colour terminal connected with a PHASER-II DX colour printer. The code allows three-dimensional geometries to be reproduced (see in figure 5 the external view of the ADAM phantom). It is furthermore designed in order to point out geometry inconsistencies through an "error test", that directly displays on the terminal the geometry areas affected by the error itself. Sectional views and geometry cuts with appropriate bodies, besides the graphical display of the various body organs employing different colours, are also allowed.

In figure 6 a vertical section of the phantom is provided, showing some internal organs.

Furthermore the coupled use of SABRINA and MCNP for radiation transport calculations, i.e. inside the human body, enables the user, through a "collision file", to draw the particle tracks, providing a visual idea about "what the particles are doing and where they are going".

3-B MCNP calculations of organ equivalent doses and effective doses for external photon irradiation

Some external irradiations with mono-energetic expanded and aligned fields were simulated in antero-posterior (A/P) postero-anterior (P/A) as well as lateral (LAT) conditions /22/.

The organ doses have been compared with the results supplied in ICRP Publication 51 /23/: the results for lungs and testes for photon energies ranging from 50 keV to 3 MeV are presented in table 1 for the A/P irradiation.

Tab. 1 : Comparison between the organ equivalent doses per unit fluence as calculated for lungs and testes in antero-posterior (A/P) irradiation condition.

Photon Energy (MeV)	Dose equivalent per unit fluence (Sv cm^2)					
	MCNP ENEA calculation		Data from ref./23/		Ratios of results	
	Lungs(*)	Testes(**)	Lungs(+)	Testes(++)	(*)/(+)	(**)/(++)
0.05	3.46E-13	5.56E-13	3.47E-13	5.69E-13	0.997	0.977
0.06	3.67E-13	5.42E-13	3.63E-13	5.61E-13	1.011	0.966
0.07	3.95E-13	5.58E-13	3.97E-13	5.92E-13	0.995	0.943
0.08	4.24E-13	5.89E-13	4.10E-13	5.86E-13	1.034	1.005
0.1	4.98E-13	6.72E-13	4.84E-13	6.70E-13	1.029	1.003
0.15	7.35E-13	9.80E-13	7.23E-13	9.84E-13	1.017	0.996
0.2	9.99E-13	1.30E-12	9.87E-13	1.31E-12	1.012	0.992
0.3	1.53E-12	1.90E-12	1.52E-12	1.93E-12	1.007	0.985
0.5	2.54E-12	3.04E-12	2.53E-12	3.00E-12	1.004	1.013
1.0	4.65E-12	5.24E-12	4.61E-12	5.18E-12	1.009	1.012
3.0	1.03E-11	1.10E-11	1.02E-11	1.14E-11	1.010	0.965

Fig.5: External view of the ADAM phantom as produced by the SABRINA code.

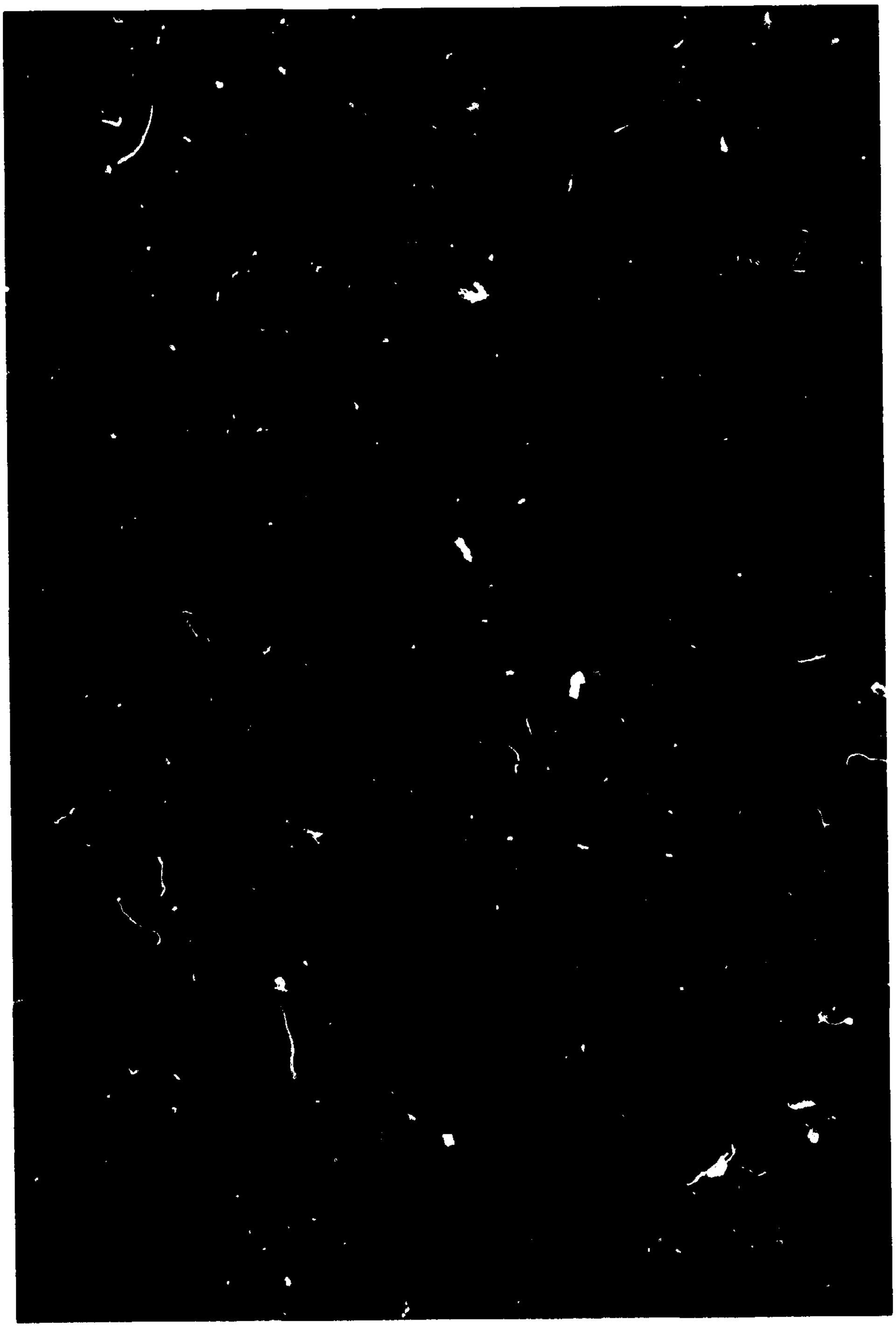
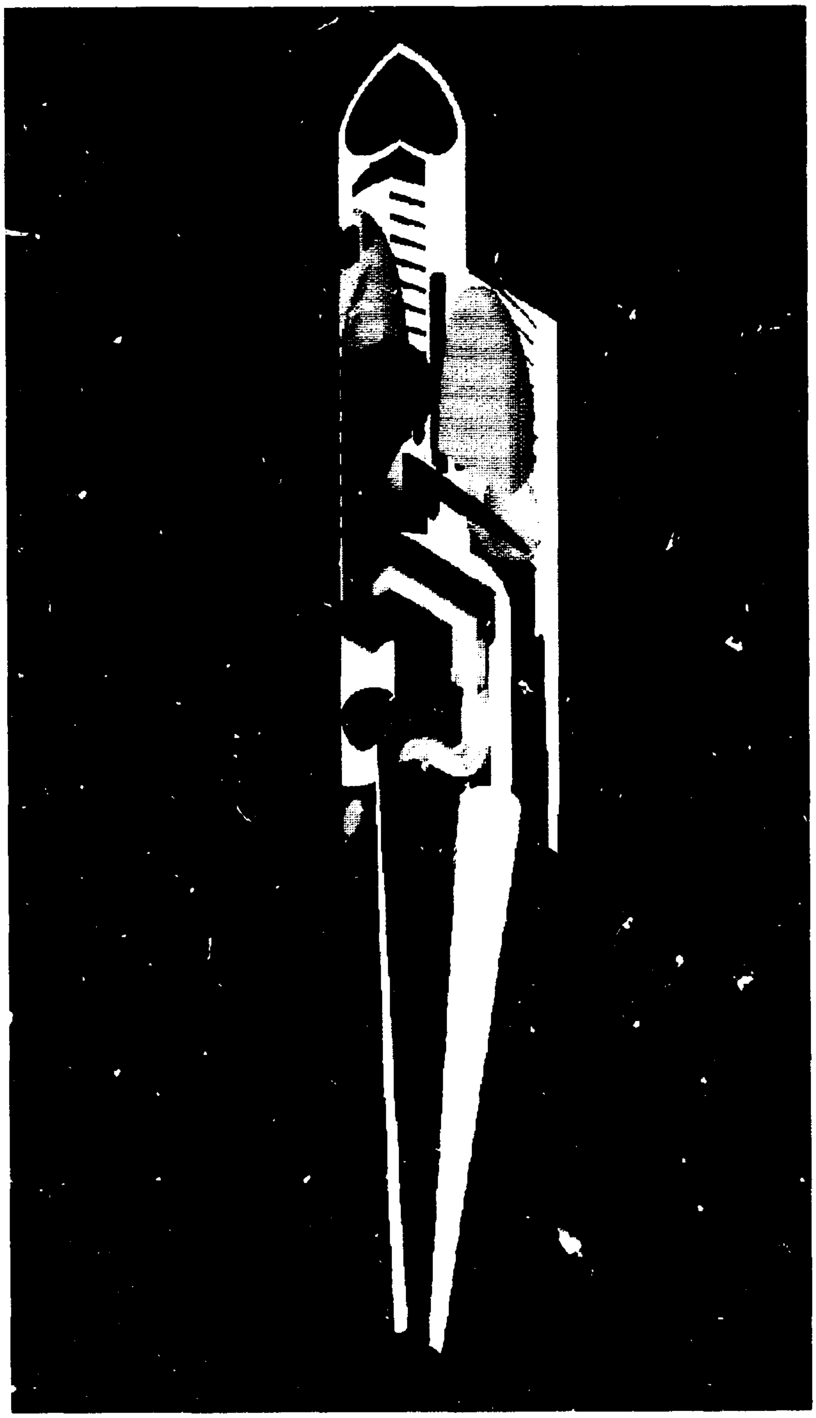


Fig.6: Sectional view of the ADAM phantom with internal organs as produced by the SABRINA code.



The good agreement in the estimated values has to be pointed out: the MCNP result uncertainties lay within 2% (one standard deviation) whilst the ICRP-51 uncertainties are within 5% (one standard deviation). Similar agreements have been obtained for other organs and irradiation conditions. Figure 7 illustrates the A/P irradiation condition together with 1 MeV incident photon tracks (the lungs and testes are pointed out).

3-C MCNP calculations of equivalent dose to the testes from internal irradiation with radioiodine therapy sources

The DOTE (DOse to the TEstes) project has been recently set up in the framework of a collaboration between the ENEA Radiation Protection Institute (IRP) and the University of Pisa. The research, that is at its very preliminary stages, has been motivated by the evidence of chronic or temporary sterility in male patients, with thyroid cancer, treated with a postsurgery ablation dose of radioiodine /24/.

The aim of the project is to evaluate the possible correlation between the equivalent dose to the testes after the radioiodine treatment and the appearance of alterations in the clinical parameters dealing with the spermatogenetic function.

The preliminary stage of the study is concerned with the standardization of a procedure for the evaluation of the equivalent dose to the testes. It will be based on experimental techniques (TLD dosimetry, WBC measurements as well as gamma spectrometry of biological samples) associated with appropriate metabolic kinetics models, together with the application of the MCNP code to the equivalent dose calculation in various situations of the nuclide distribution in the body as provided by the metabolic model itself.

Some preliminary calculations were therefore carried out in simplified conditions of the radionuclide distribution in the standard human body.

A first approach was to consider the nuclide as uniformly distributed in the content of the following seven organs: urinary bladder, sigmoid colon, descending colon, small intestine, ascending colon, transverse colon and liver, and to calculate the specific energy deposition (in MeV g^{-1}) in the target organ, represented by the testes. Of course this calculation is not exhaustive for the dose assessment, that should require, besides other irradiation conditions, the study of the self absorption of the testes both from β and gamma emission from the blood vessels.

Several assumptions have been made to model the problem and to obtain acceptable standard deviations on the estimated quantities. As far as the source was concerned the line photon spectrum has been explicitly treated in the Monte Carlo calculation and for variance reduction purposes a series of facilities have been employed: spatial and energy biasing with the addition of the DXTRAN sphere. This method, provided in MCNP, is a way of increasing the particle population in a small region of interest (like testes). A visual idea of the particle increase in the testes area due to the DXTRAN sphere application is shown in figure 8.

Fig.7: ADAM phantom geometry and 1 MeV photon radiation tracks for an A/P irradiation of the human body.

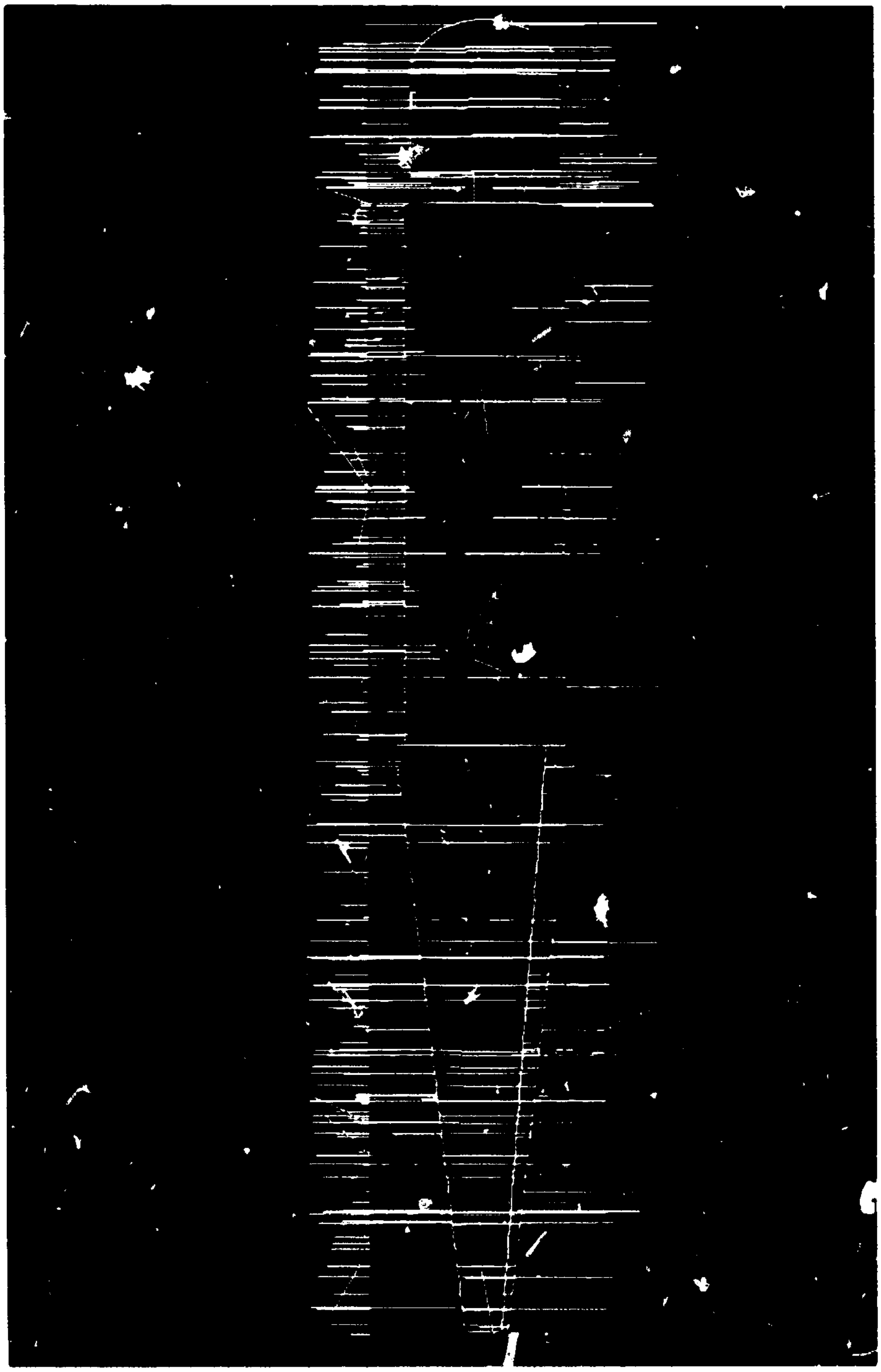
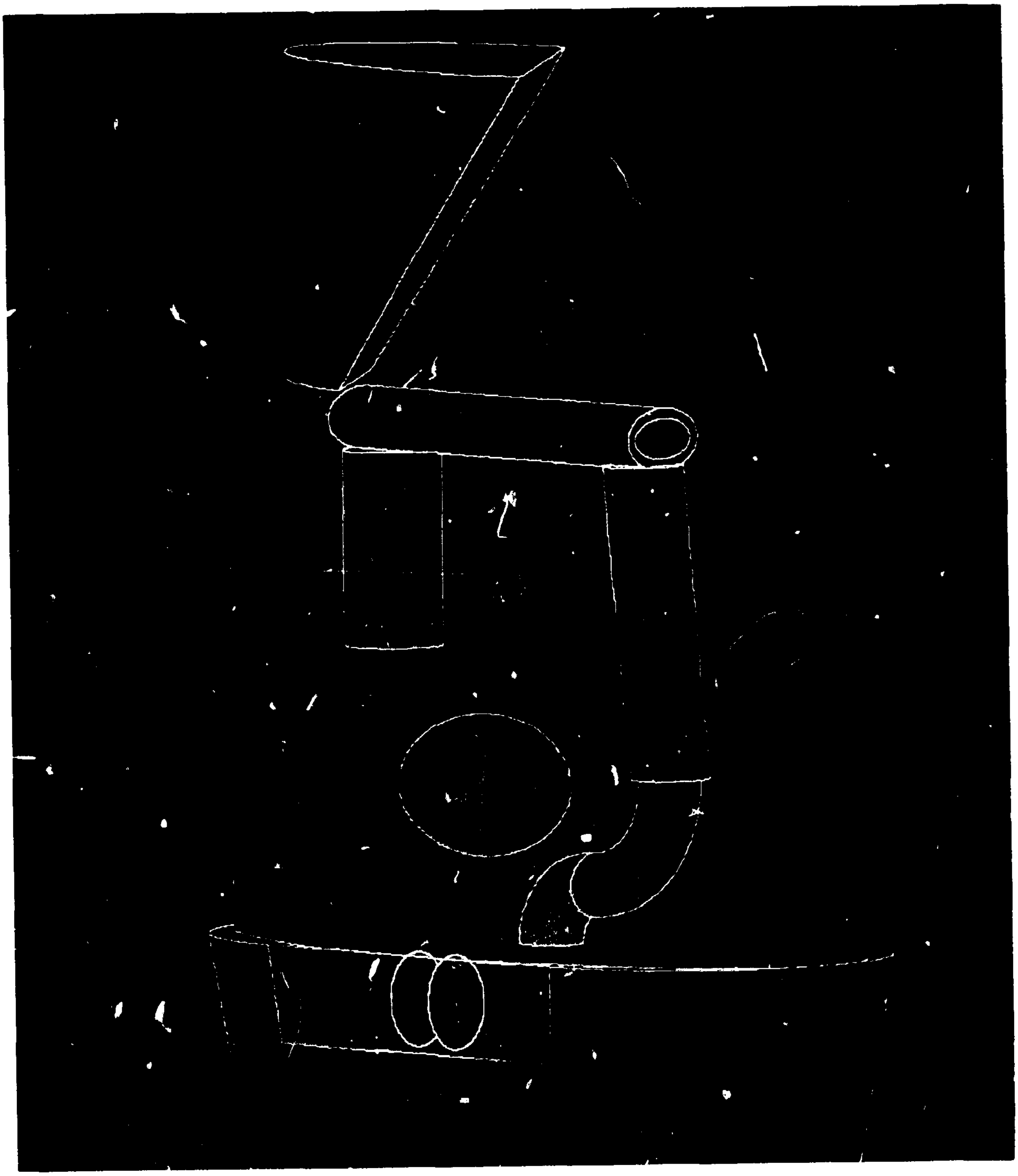


Fig.8: Effect of the DXTRAN sphere application to the improvement of the particle population in the testes due to the ^{131}I irradiation. The source is located in the content of the seven organs: urinary bladder, sigmoid colon, descending colon, ascending colon, transverse colon, small intestine and liver.



The calculation was carried out in only one run of several hours computer time on an IBM-3090/XA mainframe corresponding to more than 2.5 10^6 photon histories.

A summary of the computed values is presented in table 2. For each source organ the percentage contribution to the energy deposition in the testes is presented. It has to be pointed out than 50% of the testes absorbed dose is due to the urinary bladder, as on the other hand qualitatively expected, small intestine more than 24%, sigmoid colon about 9%, descending colon and liver about 4-5%, ascending colon 3% and finally transverse colon less than 2%: liver that is 53% of the total source volume contributes to the response for less than 5%, introducing problems of source sampling optimization. Very reasonable standard deviations, ranging from 2% to 7%, were nevertheless obtained taking advantage of the extensive use of variance reduction techniques.

A spectral information is also supplied: for each source organ as well as for each energy bin (from 45.6 keV to 723 keV) the percentage contribution is supplied. These supplementary information can be useful in order to optimize the calculation and to allow necessary comparisons with the MIRD-5 pamphlet.

Table 3, e.g., shows a comparison in terms of specific energy fraction deposited in testes (g^{-1}) for four photon spectrum lines (the ENEA values can be compared by interpolation with those of ref. /18/).

Tab. 3 : Comparison of the deposited energy fractions in 1 g of testes for various photon energies.

Source Organ	Specific energy fraction deposited in testes (g^{-1}) and relative σ (%)							
	MCNP ENEA calculation				data from ref. /18/ (*)			
	0.17 MeV	0.36 MeV	0.50 MeV	0.63 MeV	0.10 MeV	0.20 MeV	0.50 MeV	1.00 MeV
Urinary Bladder Content	1.76E-5 (2.[illegible])	1.70E-5 (2.5)	1.76E-5 (3.5)	1.67E-5 (1.3)	1.88E-5 (7)	1.59E-5 (8)	1.75E-5 (10)	1.57E-5 (12)
LLI Content (Des+Sig Colon)	6.46E-6 (4.2)	6.65E-6 (7.9)	6.60E-6 (3.8)	6.38E-6 (3.1)	6.27E-6 (11)	7.25E-6 (13)	7.14E-6 (16)	4.86E-6 (19)
ULI Content (Asc+Tra Colon)	1.04E-6 (7.1)	1.32E-6 (7.8)	1.61E-6 (9.5)	1.54E-6 (6.4)	9.33E-6 (29)	1.15E-6 (31)	1.78E-6 (28)	1.92E-6 (34)
Small Intestine	1.49E-6 (8.6)	1.55E-6 (7.4)	1.60E-6 (7.7)	1.62E-6 (4.2)	1.10E-6 (23)	1.28E-6 (27)	1.24E-6 (30)	1.79E-6 (35)
Liver	1.01E-7 (14)	1.61E-7 (7.2)	1.92E-7 (7.7)	2.52E-7 (8.0)	1.90E-7 (a)	3.05E-7 (a)	3.92E-7 (a)	8.76E-7 (48)

(*) The values have been obtained using Monte Carlo methods with the exception of those marked with (a) that have been calculated with the "build-up factor method".

The agreement is satisfactory, except for the liver values. For this organ the ENEA results are however to be considered as more reliable. The values reported in ref. /18/ are in fact affected by a high statistical error when calculated with the Monte Carlo method, or rather approximate when determined with the "build-up factor method".

The comprehensive study for the dose assessment will include the treatment of a series of stationary conditions (during the distribution of the n .clide in the body as a function of time) obtained from ^{131}I kinetics model and direct measurements carried out on the patient.

4-FINAL REMARKS AND FUTURE DEVELOPMENTS

In the framework of the ENEA Radiation Protection Institute activities Monte Carlo numerical evaluations are being progressively coupled with experimental work. These techniques are demonstrating their high effectiveness in solving a large variety of problems. For the future further extensions in the use of codes as well as more complex phantoms is planned.

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