EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory For Particle Physics

CERN-TIS-2001-009-RP-PP

Narrow beam dosimetry for high-energy hadrons and electrons

Maurizio Pelliccioni [(1)], Marco Silari [(2)] and Luisa Ulrici [(2)]

[(1)] INFN, Laboratori Nazionali di Frascati, 00044 Frascati, Italy
[(2)] CERN, 1211 Geneva 23, Switzerland

Abstract

Organ doses and effective dose were calculated with the latest version of the Monte Carlo transport code FLUKA in the case of an anthropomorphic mathematical model exposed to monoenergetic narrow beams of protons, pions and electrons in the energy range 10˚— 400 GeV. The target organs considered were right eye, thyroid, thymus, lung and breast. Simple scaling laws to the calculated values are given. The present data and formula should prove useful for dosimetric estimations in case of accidental exposures to high-energy beams.

Submitted for publication in Radiation Protection Dosimetry

CERN, 1211 Geneva 23, Switzerland
30 May 2001

1. Introduction

Data for protection against ionising radiation from external sources are usually expressed in terms of conversion coefficients from measurable quantities (such as particle fluence or air kerma) to protection quantities (such as effective dose and organ dose), calculated in various geometrical conditions of irradiation of human body. Typical irradiation conditions are infinite plane-parallel beam or isotropic beam impinging on an anthropomorphic mathematical model (a phantom). When an assessment of partial exposures of human body is required, which is typical of an accidental irradiation, the broad-beam data are inadequate. In particular, their application to narrow beam exposures leads to (possibly large) errors in the estimates of the body quantities, the degree of which depends on the irradiation geometry and on type and energy of incident radiation.

Although unlikely, such an accidental situation may occur at particle accelerator facilities. Exposures to gas bremsstrahlung and to synchrotron radiation beams as well as to primary and secondary particle beams are typical circumstances in which data for narrow beam dosimetry are needed. Data have recently been made available for gas bremsstrahlung [1,2] as well as photon, electron and proton beams up to 10˚GeV [3], but estimates for higher energy particles are missing. These data are important for high-energy research laboratories such as CERN, where mixed beams with energy up to 400˚GeV are available.

The CERN Super Proton Synchrotron (SPS) accelerates protons to 400 GeV, which are then simultaneously extracted from two regions in the machine and directed to several targets. These targets produce secondary and tertiary beams serving a number of experiments and test areas installed in four experimental halls. Various combinations of secondary beams are available; the beams may have positive or negative momentum and be composed of a mixture of particles, namely protons, positive and negative pions, kaons, electrons and muons. The maximum secondary beam intensity is of the order of 10^8 particles per SPS pulse, i.e. every 14.4˚s, but in practice most of the experiments run with lower intensities (typically in the range 10^6 to 10^7 particles per pulse). The beam composition depends on its energy. A positive secondary beam typically consists of about 80% positive pions and 20% protons at 40˚GeV, 2/3 positive pions and 1/3 protons at 100 GeV, 2/3 protons and 1/3 positive pions at 200˚GeV and protons at 400˚GeV, with a small kaon component (a few per cent). Useful electron beams are typically limited to a maximum energy of 200 GeV, as above this energy the beam intensity drops drastically to below 10^4 particles/pulse, but higher energies are nevertheless possible. Muons are not really focussed into narrow beams. Due to the maximum allowable beam intensities, the beam lines and the experimental areas are fenced off by grids and shielding blocks, but are not top shielded. Access is interlocked to beam operation and is controlled by a one key —one person procedure, but it is left on self-service to the users. Thus while exposure to the primary proton beam circulating in the SPS cannot occur, an accidental scenario involving personnel exposure to a secondary beam cannot *a˚priori* be excluded. Data for narrow beam dosimetry for hadrons and electrons with energy up to several hundreds of GeV may therefore be useful.

The effective dose is not an adequate risk indicator in the case of partial irradiation. It is unable to take into account the incidence of deterministic effects and is not meant for that. Both effective dose and organ dose in the exposed tissue or organ need therefore to be considered. The absorbed dose in the organ accounts for threshold is not approached, the effective dose accounts for the probability of stochastic effects. This paper provides values of effective dose and absorbed doses in various organs due to narrow beams of protons, pions and electrons in the energy range 10 — 400 GeV. Simple scaling laws are derived for application in post-accident dosimetry.

2. Monte Carlo calculations

Calculations were carried out with the latest version of the FLUKA Monte Carlo transport code [(4-7)] (FLUKA2000) [(8)] and a hermaphrodite mathematical model [(9,10)]. A feature relevant to the present work is that the breast is only present on the right half of the phantom. When the breast is the target organ, the underlying lung is simultaneously irradiated. When the lung is selected as target organ, the beam is directed to the left half of the phantom.

Since the protection quantities were proven to be slightly dependent on the beam size of a narrow beam [(11,12)], calculations were performed with a pencil beam with no physical dimensions. A monoenergetic pencil beam of electrons, protons, positive or negative pions impinged in the centre of a given organ or tissue (target organ) of the phantom. Five representative organs were chosen as a target, namely right eye, thyroid, thymus, breast and lung. These organs were selected on the basis of their specific radiosensitivity as well as of the probability of irradiation in the event of an accidental exposure. The radiosensitivity is taken into account by the tissue weighting factor w_T, a factor by which the equivalent dose to a tissue or organ is multiplied in order to account for the relative stochastic detriment resulting from the exposure of different tissues and organs. Here it was assumed that the w_T-values recommended by ICRP 60 [(13)] are applicable in the case of narrow beam exposure. Thyroid is an organ having a specific tissue weighting factor ($w_T = 0.05$), whilst the eye is an example of organ with no specific weighting factor. Breast and lung have specific weighting factor ($w_T = 0.05$ and $w_T = 0.12$, respectively) and represent the case of two organs simultaneously irradiated as target organs by penetrating radiation. Thymus is part of the remainder. These five target organs should provide a fairly comprehensive picture of possible irradiation conditions and the results used for a radiological estimation in case of a real accidental exposure where a different organ may be involved. Both the dose to the target organs, D_T, and the effective dose, E, were calculated.

The probability of stochastic effects also depends on the type and energy of the incident radiation. This is taken into account by weighting the absorbed dose by a factor w_R (radiation weighting factor) related to the quality of the radiation. For protons it is $w_R = 5$, for electrons $w_R = 1$ [(13)], for positive and negative pions $w_R = 2$ [(14)]. We have assumed 5 for protons since this is the value recommended by ICRP, but at very high energies a value of 1 or 2 would be more appropriate [(14)].

Simulations were performed for beam energies of 10, 20, 50, 100, 200 and 400 GeV. The energy per primary particle deposited in the 68 regions of the phantom, representing the various organs and tissues of the human body, was scored. The organ doses were estimated as arithmetic mean of the doses received by the single constituent regions. The effective dose was calculated according to the definition given in ICRP Publication 60 [(13)], as modified in ICRP Publication 69 [(15)]. The statistical uncertainties were estimated by making calculations in several batches and by computing the standard deviation of the mean. The total number of histories was large enough to keep the standard deviation below a few per mil for D_T and below a few per cent for E.

3. Results and discussion

The organ doses and the effective dose for the various target organs and incident particles are given in Tables 1—4 and plotted as a function of energy in Figures 1—8. Tables 1—4 list, for the various incident energies and target organs: effective dose, dose to the target organ, ratio of target organ dose to effective dose, weighted target dose (w_TÆw_RÆD_T) and fractional contribution to effective dose of organs different from the target organ. Figures 1—8 also show the fits to the calculated values according to the empirical law:

$$D_T = A_D + B_D \log K \qquad \text{(Gy per primary particle)}$$

and (1)

$$E = A_E + B_E \log K \qquad \text{(Sv per primary particle)}$$

where K is numerically equal to the energy of the primary particle (proton, pion or electron) in GeV. The parameters of the fits for the various target organs are given in Tables 5—8. It should be underlined that expressions (1) have no physical meaning and are only meant as a computational help.

Several considerations can be made by looking at the above tables and graphs. First of all, the results for positive and negative pions are very similar. This is not surprising, since the difference in the interaction of pions of opposite sign with matter is in the capture of negative pions at the end of their range. This phenomenon is not relevant in the present case as the beam energy is high enough that the particles are not stopped in the body. For electrons, the second terms in equations (1) can in a first approximation be neglected, as is seen from Table 4 and Figures 4 and 8.

When either the thymus or the eye is the target, the most irradiated organ is a remainder, respectively the thymus itself or the brain. In these two cases the effective dose E was calculated by attributing $w_T = 0.025$ to that specific remainder and $w_T = 0.025$ to the average dose in the rest of the remainder (according to footnote 3 in table 2 of ref. [13]). The application of this rule (which under broad-beam irradiation can be disregarded) has certain consequences on the results. If one would neglect such a rule and calculate E as for a broad-beam irradiation, one would underestimate the effective dose by a constant factor of about 1.6 for protons and pions of both signs of all energies irradiating the eye, by a factor ranging from 2.7 at 10 GeV to 2.1 at 400 GeV for protons irradiating the thymus, and by a factor from 2.7 at 10 GeV to 2.2 at 400 GeV for pions of both signs irradiating the thymus.

It should be mentioned that the present results for 10 GeV protons and electrons irradiating thyroid and breast cannot be directly compared with the analogous data (the upper energy limit) of ref. [3], as here the beam was shot at the centre of the target organ, unlike in ref. [3] where the beam was off-centre. Similarly, data in the last column of Tables 1 and 4 cannot be directly compared with values in Tables 2 and 3 of ref. [3], as in the present paper the weighted target dose (w_TÆw_RÆD_T) also includes the w_R-factor, which was not the case in ref. [3].

Figures 1—4 show that organ doses generally decrease significantly with increasing organ mass, with irradiation of the eye giving the highest values. Since thymus and thyroid have approximately the same mass, the difference in their absorbed doses can only be imputed to either the organ geometry (the thyroid is represented as a sphere, the thymus as an ellipsoid) or their position in the body. The beam traverses the thymus along its minor axis, which is smaller than the diameter of the thyroid.

Table 1. Dosimetric quantities per primary proton as a function of incident energy for a monoenergetic pencil beam impinging at the centre of various target organs of the human body.

Proton energy (GeV)	Target organ	Effective dose E (Sv per proton)	Organ dose D_T (Gy per proton)	Ratio organ dose to effective dose (Gy/Sv)	Weighted target dose w_TÆw_RÆD_T	Fraction of E due to non-target organs
10	Eye	$1.42\ 10^{-12}$	$3.47\ 10^{-10}$	$2.45\ 10^{2}$	-	1
20		$1.59\ 10^{-12}$	$3.55\ 10^{-10}$	$2.24\ 10^{2}$	-	1
50		$1.88\ 10^{-12}$	$3.63\ 10^{-10}$	$1.94\ 10^{2}$	-	1
100		$2.15\ 10^{-12}$	$3.73\ 10^{-10}$	$1.73\ 10^{2}$	-	1
200		$2.47\ 10^{-12}$	$3.78\ 10^{-10}$	$1.53\ 10^{2}$	-	1
400		$2.83\ 10^{-12}$	$3.85\ 10^{-10}$	$1.36\ 10^{2}$	-	1
10	Breast	$4.66\ 10^{-12}$	$9.15\ 10^{-12}$	1.96	$2.29\ 10^{-12}$	$5.09\ 10^{-1}$
20		$5.12\ 10^{-12}$	$9.46\ 10^{-12}$	1.85	$2.36\ 10^{-12}$	$5.38\ 10^{-1}$
50		$5.81\ 10^{-12}$	$9.95\ 10^{-12}$	1.71	$2.49\ 10^{-12}$	$5.72\ 10^{-1}$
100		$6.36\ 10^{-12}$	$1.03\ 10^{-11}$	1.62	$2.57\ 10^{-12}$	$5.96\ 10^{-1}$
200		$7.15\ 10^{-12}$	$1.07\ 10^{-11}$	1.50	$2.68\ 10^{-12}$	$6.26\ 10^{-1}$
400		$7.88\ 10^{-12}$	$1.11\ 10^{-11}$	1.41	$2.77\ 10^{-12}$	$6.48\ 10^{-1}$
10	Thyroid	$1.87\ 10^{-11}$	$7.10\ 10^{-11}$	3.79	$1.78\ 10^{-11}$	$5.15\ 10^{-2}$
20		$1.96\ 10^{-11}$	$7.40\ 10^{-11}$	3.77	$1.85\ 10^{-11}$	$5.68\ 10^{-2}$
50		$2.08\ 10^{-11}$	$7.77\ 10^{-11}$	3.74	$1.94\ 10^{-11}$	$6.55\ 10^{-2}$
100		$2.19\ 10^{-11}$	$8.12\ 10^{-11}$	3.71	$2.03\ 10^{-11}$	$7.19\ 10^{-2}$
200		$2.33\ 10^{-11}$	$8.59\ 10^{-11}$	3.68	$2.15\ 10^{-11}$	$7.96\ 10^{-2}$
400		$2.48\ 10^{-11}$	$9.05\ 10^{-11}$	3.64	$2.26\ 10^{-11}$	$8.88\ 10^{-2}$
10	Thymus	$7.38\ 10^{-12}$	$4.62\ 10^{-11}$	6.26	$5.78\ 10^{-12}$	$2.17\ 10^{-1}$
20		$8.01\ 10^{-12}$	$4.88\ 10^{-11}$	6.09	$6.10\ 10^{-12}$	$2.39\ 10^{-1}$
50		$8.86\ 10^{-12}$	$5.18\ 10^{-11}$	5.85	$6.48\ 10^{-12}$	$2.69\ 10^{-1}$
100		$9.61\ 10^{-12}$	$5.45\ 10^{-11}$	5.67	$6.81\ 10^{-12}$	$2.92\ 10^{-1}$
200		$1.03\ 10^{-11}$	$5.63\ 10^{-11}$	5.48	$7.04\ 10^{-12}$	$3.16\ 10^{-1}$
400		$1.13\ 10^{-11}$	$5.97\ 10^{-11}$	5.26	$7.46\ 10^{-12}$	$3.43\ 10^{-1}$
10	Lung	$2.22\ 10^{-12}$	$3.39\ 10^{-12}$	1.53	$2.04\ 10^{-12}$	$8.40\ 10^{-2}$
20		$2.51\ 10^{-12}$	$3.82\ 10^{-12}$	1.52	$2.29\ 10^{-12}$	$8.51\ 10^{-2}$
50		$2.90\ 10^{-12}$	$4.43\ 10^{-12}$	1.53	$2.66\ 10^{-12}$	$8.14\ 10^{-2}$
100		$3.23\ 10^{-12}$	$4.97\ 10^{-12}$	1.54	$2.98\ 10^{-12}$	$7.74\ 10^{-2}$
200		$3.62\ 10^{-12}$	$5.59\ 10^{-12}$	1.54	$3.35\ 10^{-12}$	$7.38\ 10^{-2}$
400		$4.09\ 10^{-12}$	$6.35\ 10^{-12}$	1.55	$3.81\ 10^{-12}$	$6.94\ 10^{-2}$

Table 2. Dosimetric quantities per primary <u>*positive*</u> *pion as a function of incident energy for a monoenergetic pencil beam impinging at the centre of various target organs of the human body.*

Pion energy (GeV)	Target organ	Effective dose E (Sv per pion)	Organ dose D_T (Gy per pion)	Ratio organ dose to effective dose (Gy/Sv)	Weighted target dose w_TÆw_RÆD_T	Fraction of E due to non-target organs
10	Eye	$5.22\ 10^{-13}$	$3.41\ 10^{-10}$	$6.53\ 10^{2}$	-	1
20		$5.66\ 10^{-13}$	$3.42\ 10^{-10}$	$6.04\ 10^{2}$	-	1
50		$6.33\ 10^{-13}$	$3.44\ 10^{-10}$	$5.44\ 10^{2}$	-	1
100		$7.04\ 10^{-13}$	$3.49\ 10^{-10}$	$4.95\ 10^{2}$	-	1
200		$7.91\ 10^{-13}$	$3.54\ 10^{-10}$	$4.48\ 10^{2}$	-	1
400		$8.86\ 10^{-13}$	$3.60\ 10^{-10}$	$4.06\ 10^{2}$	-	1
10	Breast	$1.78\ 10^{-12}$	$8.71\ 10^{-12}$	4.88	$8.71\ 10^{-13}$	$5.12\ 10^{-1}$
20		$1.88\ 10^{-12}$	$8.81\ 10^{-12}$	4.70	$8.81\ 10^{-13}$	$5.30\ 10^{-1}$
50		$2.04\ 10^{-12}$	$8.98\ 10^{-12}$	4.39	$8.98\ 10^{-13}$	$5.61\ 10^{-1}$
100		$2.19\ 10^{-12}$	$9.27\ 10^{-12}$	4.24	$9.27\ 10^{-13}$	$5.76\ 10^{-1}$
200		$2.38\ 10^{-12}$	$9.41\ 10^{-12}$	3.95	$9.41\ 10^{-13}$	$6.05\ 10^{-1}$
400		$2.62\ 10^{-12}$	$9.85\ 10^{-12}$	3.75	$9.85\ 10^{-13}$	$6.25\ 10^{-1}$
10	Thyroid	$7.24\ 10^{-12}$	$6.87\ 10^{-11}$	9.49	$6.87\ 10^{-12}$	$5.11\ 10^{-2}$
20		$7.40\ 10^{-12}$	$6.99\ 10^{-11}$	9.45	$6.99\ 10^{-12}$	$5.54\ 10^{-2}$
50		$7.72\ 10^{-12}$	$7.24\ 10^{-11}$	9.38	$7.24\ 10^{-12}$	$6.18\ 10^{-2}$
100		$7.99\ 10^{-12}$	$7.46\ 10^{-11}$	9.33	$7.46\ 10^{-12}$	$6.72\ 10^{-2}$
200		$8.32\ 10^{-12}$	$7.70\ 10^{-11}$	9.26	$7.70\ 10^{-12}$	$7.36\ 10^{-2}$
400		$8.67\ 10^{-12}$	$7.97\ 10^{-11}$	9.19	$7.97\ 10^{-12}$	$8.06\ 10^{-2}$
10	Thymus	$2.87\ 10^{-12}$	$4.53\ 10^{-11}$	15.8	$2.27\ 10^{-12}$	$2.10\ 10^{-1}$
20		$2.95\ 10^{-12}$	$4.57\ 10^{-11}$	15.5	$2.28\ 10^{-12}$	$2.26\ 10^{-1}$
50		$3.17\ 10^{-12}$	$4.77\ 10^{-11}$	15.0	$2.38\ 10^{-12}$	$2.49\ 10^{-1}$
100		$3.35\ 10^{-12}$	$4.91\ 10^{-11}$	14.7	$2.45\ 10^{-12}$	$2.67\ 10^{-1}$
200		$3.57\ 10^{-12}$	$5.11\ 10^{-11}$	14.3	$2.55\ 10^{-12}$	$2.85\ 10^{-1}$
400		$3.78\ 10^{-12}$	$5.23\ 10^{-11}$	13.8	$2.62\ 10^{-12}$	$3.08\ 10^{-1}$
10	Lung	$8.57\ 10^{-13}$	$3.30\ 10^{-12}$	3.85	$7.93\ 10^{-13}$	$7.50\ 10^{-2}$
20		$9.08\ 10^{-13}$	$3.51\ 10^{-12}$	3.87	$8.43\ 10^{-13}$	$7.22\ 10^{-2}$
50		$9.99\ 10^{-13}$	$3.89\ 10^{-12}$	3.90	$9.34\ 10^{-13}$	$6.49\ 10^{-2}$
100		$1.09\ 10^{-12}$	$4.26\ 10^{-12}$	3.90	$1.02\ 10^{-12}$	$6.38\ 10^{-2}$
200		$1.19\ 10^{-12}$	$4.65\ 10^{-12}$	3.92	$1.12\ 10^{-12}$	$5.87\ 10^{-2}$
400		$1.31\ 10^{-12}$	$5.14\ 10^{-12}$	3.92	$1.23\ 10^{-12}$	$5.92\ 10^{-2}$

Table 3. Dosimetric quantities per primary *<u>negative</u>* *pion as a function of incident energy for a monoenergetic pencil beam impinging at the centre of various target organs of the human body.*

Pion energy (GeV)	Target organ	Effective dose E (Sv per pion)	Organ dose D_T (Gy per pion)	Ratio organ dose to effective dose (Gy/Sv)	Weighted target dose w_TÆw_RÆD_T	Fraction of E due to non-target organs
10	Eye	$5.18\ 10^{-13}$	$3.40\ 10^{-10}$	$6.57\ 10^{2}$	-	1
20		$5.67\ 10^{-13}$	$3.43\ 10^{-10}$	$6.05\ 10^{2}$	-	1
50		$6.35\ 10^{-13}$	$3.45\ 10^{-10}$	$5.43\ 10^{2}$	-	1
100		$7.07\ 10^{-13}$	$3.48\ 10^{-10}$	$4.92\ 10^{2}$	-	1
200		$7.86\ 10^{-13}$	$3.53\ 10^{-10}$	$4.50\ 10^{2}$	-	1
400		$8.91\ 10^{-13}$	$3.61\ 10^{-10}$	$4.05\ 10^{2}$	-	1
10	Breast	$1.77\ 10^{-12}$	$8.67\ 10^{-12}$	4.90	$8.67\ 10^{-13}$	$5.10\ 10^{-1}$
20		$1.88\ 10^{-12}$	$8.81\ 10^{-12}$	4.69	$8.81\ 10^{-13}$	$5.31\ 10^{-1}$
50		$2.02\ 10^{-12}$	$8.91\ 10^{-12}$	4.42	$8.91\ 10^{-13}$	$5.58\ 10^{-1}$
100		$2.17\ 10^{-12}$	$9.14\ 10^{-12}$	4.20	$9.14\ 10^{-13}$	$5.80\ 10^{-1}$
200		$2.38\ 10^{-12}$	$9.45\ 10^{-12}$	3.96	$9.45\ 10^{-13}$	$6.04\ 10^{-1}$
400		$2.61\ 10^{-12}$	$9.82\ 10^{-12}$	3.77	$9.82\ 10^{-13}$	$6.23\ 10^{-1}$
10	Thyroid	$7.23\ 10^{-12}$	$6.86\ 10^{-11}$	9.49	$6.86\ 10^{-12}$	$5.10\ 10^{-2}$
20		$7.46\ 10^{-12}$	$7.05\ 10^{-11}$	9.45	$7.05\ 10^{-12}$	$5.51\ 10^{-2}$
50		$7.71\ 10^{-12}$	$7.23\ 10^{-11}$	9.38	$7.23\ 10^{-12}$	$6.24\ 10^{-2}$
100		$7.97\ 10^{-12}$	$7.43\ 10^{-11}$	9.33	$7.43\ 10^{-12}$	$6.74\ 10^{-2}$
200		$8.25\ 10^{-12}$	$7.63\ 10^{-11}$	9.26	$7.63\ 10^{-12}$	$7.43\ 10^{-2}$
400		$8.66\ 10^{-12}$	$7.96\ 10^{-11}$	9.19	$7.96\ 10^{-12}$	$8.12\ 10^{-2}$
10	Thymus	$2.83\ 10^{-12}$	$4.49\ 10^{-11}$	15.8	$2.24\ 10^{-12}$	$2.08\ 10^{-1}$
20		$2.95\ 10^{-12}$	$4.57\ 10^{-11}$	15.5	$2.29\ 10^{-12}$	$2.25\ 10^{-1}$
50		$3.18\ 10^{-12}$	$4.78\ 10^{-11}$	15.1	$2.39\ 10^{-12}$	$2.47\ 10^{-1}$
100		$3.34\ 10^{-12}$	$4.90\ 10^{-11}$	14.7	$2.45\ 10^{-12}$	$2.66\ 10^{-1}$
200		$3.57\ 10^{-12}$	$5.10\ 10^{-11}$	14.3	$2.55\ 10^{-12}$	$2.86\ 10^{-1}$
400		$3.82\ 10^{-12}$	$5.28\ 10^{-11}$	13.8	$2.64\ 10^{-12}$	$3.09\ 10^{-1}$
10	Lung	$8.45\ 10^{-13}$	$3.27\ 10^{-12}$	3.87	$7.85\ 10^{-13}$	$7.11\ 10^{-2}$
20		$9.09\ 10^{-13}$	$3.52\ 10^{-12}$	3.88	$8.46\ 10^{-13}$	$6.95\ 10^{-2}$
50		$9.96\ 10^{-13}$	$3.88\ 10^{-12}$	3.90	$9.32\ 10^{-13}$	$6.37\ 10^{-2}$
100		$1.09\ 10^{-12}$	$4.26\ 10^{-12}$	3.91	$1.02\ 10^{-12}$	$6.18\ 10^{-2}$
200		$1.19\ 10^{-12}$	$4.67\ 10^{-12}$	3.92	$1.12\ 10^{-12}$	$5.95\ 10^{-2}$
400		$1.32\ 10^{-12}$	$5.18\ 10^{-12}$	3.92	$1.24\ 10^{-12}$	$5.81\ 10^{-2}$

Table 4. Dosimetric quantities per primary electron as a function of incident energy for a monoenergetic pencil beam impinging at the centre of various target organs of the human body.

Electron energy (GeV)	Target organ	Effective dose E (Sv per electron)	Organ dose D_T (Gy per electron)	Ratio organ dose to effective dose (Gy/Sv)	Weighted target dose w_TÆw_RÆD_T	Fraction of E due to non-target organs
10	Eye	$2.06\ 10^{-13}$	$2.95\ 10^{-10}$	$1.43\ 10^{3}$	-	1
20		$2.15\ 10^{-13}$	$2.95\ 10^{-10}$	$1.37\ 10^{3}$	-	1
50		$2.27\ 10^{-13}$	$2.95\ 10^{-10}$	$1.30\ 10^{3}$	-	1
100		$2.35\ 10^{-13}$	$2.95\ 10^{-10}$	$1.25\ 10^{3}$	-	1
200		$2.42\ 10^{-13}$	$2.95\ 10^{-10}$	$1.22\ 10^{3}$	-	1
400		$2.45\ 10^{-13}$	$2.95\ 10^{-10}$	$1.20\ 10^{3}$	-	1
10	Breast	$7.19\ 10^{-13}$	$6.67\ 10^{-12}$	9.28	$3.34\ 10^{-13}$	$5.36\ 10^{-1}$
20		$7.38\ 10^{-13}$	$6.69\ 10^{-12}$	9.06	$3.34\ 10^{-13}$	$5.47\ 10^{-1}$
50		$7.61\ 10^{-13}$	$6.70\ 10^{-12}$	8.80	$3.35\ 10^{-13}$	$5.60\ 10^{-1}$
100		$7.77\ 10^{-13}$	$6.70\ 10^{-12}$	8.62	$3.35\ 10^{-13}$	$5.69\ 10^{-1}$
200		$7.87\ 10^{-13}$	$6.70\ 10^{-12}$	8.51	$3.35\ 10^{-13}$	$5.75\ 10^{-1}$
400		$7.94\ 10^{-13}$	$6.70\ 10^{-12}$	8.44	$3.35\ 10^{-13}$	$5.78\ 10^{-1}$
10	Thyroid	$3.01\ 10^{-12}$	$5.67\ 10^{-11}$	18.8	$2.83\ 10^{-12}$	$6.01\ 10^{-2}$
20		$3.03\ 10^{-12}$	$5.67\ 10^{-11}$	18.7	$2.84\ 10^{-12}$	$6.29\ 10^{-2}$
50		$3.05\ 10^{-12}$	$5.69\ 10^{-11}$	18.7	$2.85\ 10^{-12}$	$6.65\ 10^{-2}$
100		$3.06\ 10^{-12}$	$5.70\ 10^{-11}$	18.6	$2.85\ 10^{-12}$	$6.90\ 10^{-2}$
200		$3.07\ 10^{-12}$	$5.70\ 10^{-11}$	18.6	$2.85\ 10^{-12}$	$7.10\ 10^{-2}$
400		$3.07\ 10^{-12}$	$5.70\ 10^{-11}$	18.6	$2.85\ 10^{-12}$	$7.20\ 10^{-2}$
10	Thymus	$1.15\ 10^{-12}$	$3.68\ 10^{-11}$	32.1	$9.21\ 10^{-13}$	$1.97\ 10^{-1}$
20		$1.16\ 10^{-12}$	$3.69\ 10^{-11}$	31.7	$9.23\ 10^{-13}$	$2.07\ 10^{-1}$
50		$1.19\ 10^{-12}$	$3.70\ 10^{-11}$	31.2	$9.26\ 10^{-13}$	$2.19\ 10^{-1}$
100		$1.20\ 10^{-12}$	$3.71\ 10^{-11}$	30.9	$9.28\ 10^{-13}$	$2.27\ 10^{-1}$
200		$1.21\ 10^{-12}$	$3.71\ 10^{-11}$	30.6	$9.27\ 10^{-13}$	$2.35\ 10^{-1}$
400		$1.22\ 10^{-12}$	$3.71\ 10^{-11}$	30.5	$9.28\ 10^{-13}$	$2.38\ 10^{-1}$
10	Lung	$3.30\ 10^{-13}$	$2.74\ 10^{-12}$	8.31	$3.29\ 10^{-13}$	$3.09\ 10^{-3}$
20		$3.39\ 10^{-13}$	$2.81\ 10^{-12}$	8.31	$3.38\ 10^{-13}$	$2.94\ 10^{-3}$
50		$3.50\ 10^{-13}$	$2.91\ 10^{-12}$	8.31	$3.49\ 10^{-13}$	$2.90\ 10^{-3}$
100		$3.57\ 10^{-13}$	$2.97\ 10^{-12}$	8.31	$3.56\ 10^{-13}$	$2.86\ 10^{-3}$
200		$3.62\ 10^{-13}$	$3.00\ 10^{-12}$	8.31	$3.61\ 10^{-13}$	$2.72\ 10^{-3}$
400		$3.64\ 10^{-13}$	$3.02\ 10^{-12}$	8.31	$3.63\ 10^{-13}$	$2.68\ 10^{-3}$

Table 5. Parameters A_D, B_D and A_E, B_E in equations (1) for 10°—°400GeV protons. A_D and B_D are in gray per primary particle, A_E and B_E are in sievert per primary particle.

ORGAN	A_D	B_D	A_E	B_E
Right eye	$3.24\ 10^{-10}$	$2.38\ 10^{-11}$	$4.63\ 10^{-13}$	$8.77\ 10^{-13}$
Thyroid	$5.82\ 10^{-11}$	$1.20\ 10^{-11}$	$1.47\ 10^{-11}$	$3.76\ 10^{-12}$
Thymus	$3.80\ 10^{-11}$	$8.19\ 10^{-12}$	$4.88\ 10^{-12}$	$2.40\ 10^{-12}$
Breast	$7.89\ 10^{-12}$	$1.22\ 10^{-12}$	$2.52\ 10^{-12}$	$2.00\ 10^{-12}$
Lung	$1.45\ 10^{-12}$	$1.82\ 10^{-12}$	$1.01\ 10^{-12}$	$1.15\ 10^{-12}$

Table 6. Parameters A_D, B_D and A_E, B_E in equations (1) for 10°—°400GeV positive pions. A_D and B_D are in gray per primary particle, A_E and B_E are in sievert per primary particle.

ORGAN	A_D	B_D	A_E	B_E
Right eye	$3.27\ 10^{-10}$	$1.19\ 10^{-11}$	$2.74\ 10^{-13}$	$2.56\ 10^{-13}$
Thyroid	$6.11\ 10^{-11}$	$6.92\ 10^{-12}$	$6.26\ 10^{-12}$	$8.97\ 10^{-13}$
Thymus	$4.01\ 10^{-11}$	$4.64\ 10^{-12}$	$2.23\ 10^{-12}$	$5.81\ 10^{-13}$
Breast	$7.93\ 10^{-12}$	$6.84\ 10^{-13}$	$1.21\ 10^{-12}$	$5.14\ 10^{-13}$
Lung	$2.05\ 10^{-12}$	$1.14\ 10^{-12}$	$5.47\ 10^{-13}$	$2.82\ 10^{-13}$

Table 7. Parameters A_D, B_D and A_E, B_E in equations (1) for 10°—°400GeV negative pions. A_D and B_D are in gray per primary particle, A_E and B_E are in sievert per primary particle.

ORGAN	A_D	B_D	A_E	B_E
Right eye	$3.26\ 10^{-10}$	$1.21\ 10^{-11}$	$2.69\ 10^{-13}$	$2.28\ 10^{-13}$
Thyroid	$6.17\ 10^{-11}$	$6.54\ 10^{-12}$	$6.32\ 10^{-12}$	$8.60\ 10^{-13}$
Thymus	$3.95\ 10^{-11}$	$4.99\ 10^{-12}$	$2.17\ 10^{-12}$	$6.14\ 10^{-13}$
Breast	$7.89\ 10^{-12}$	$6.91\ 10^{-13}$	$1.20\ 10^{-12}$	$5.14\ 10^{-13}$
Lung	$1.99\ 10^{-12}$	$1.18\ 10^{-12}$	$5.29\ 10^{-13}$	$2.91\ 10^{-13}$

Table 8. Parameters A_D, B_D and A_E, B_E in equations (1) for 10°—°400GeV electrons. A_D and B_D are in gray per primary particle, A_E and B_E are in sievert per primary particle.

ORGAN	A_D	B_D	A_E	B_E
Right eye	$2.95\ 10^{-10}$	0	$1.82\ 10^{-13}$	$2.52\ 10^{-14}$
Thyroid	$5.65\ 10^{-11}$	$2.25\ 10^{-13}$	$2.98\ 10^{-12}$	$3.83\ 10^{-14}$
Thymus	$3.66\ 10^{-11}$	$1.97\ 10^{-13}$	$1.11\ 10^{-12}$	$4.54\ 10^{-14}$
Breast	$6.66\ 10^{-12}$	$1.62\ 10^{-14}$	$6.76\ 10^{-13}$	$4.78\ 10^{-14}$
Lung	$2.58\ 10^{-12}$	$1.81\ 10^{-13}$	$3.11\ 10^{-13}$	$2.19\ 10^{-14}$

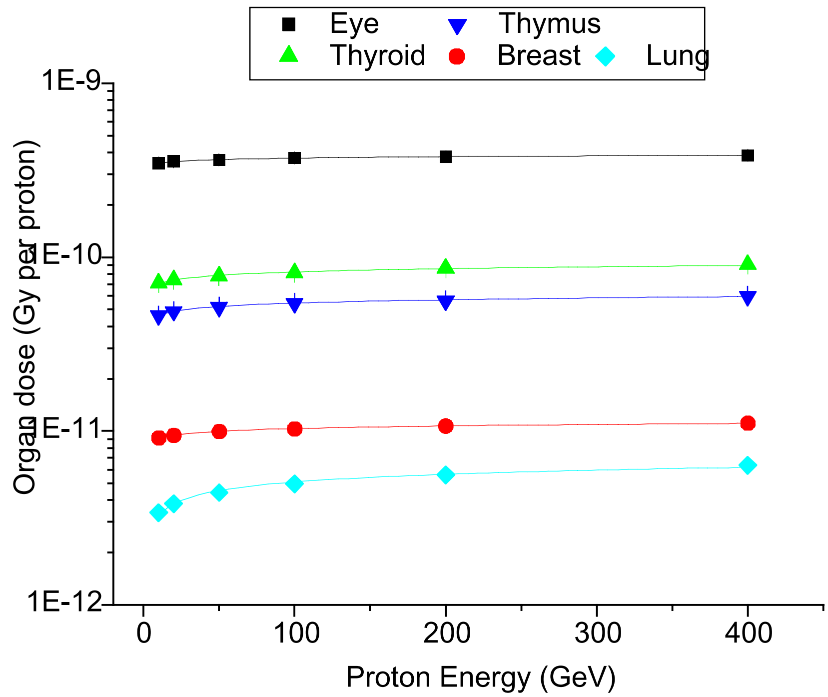

Fig. 1. Dose to various target organs, D_T, for a monoenergetic pencil beam of protons with energy in the range 10 — 400 GeV. A fit according to the law $D_T = A_D + B_D \log K$ is shown. The parameters A_D and B_D are given in Table 5.

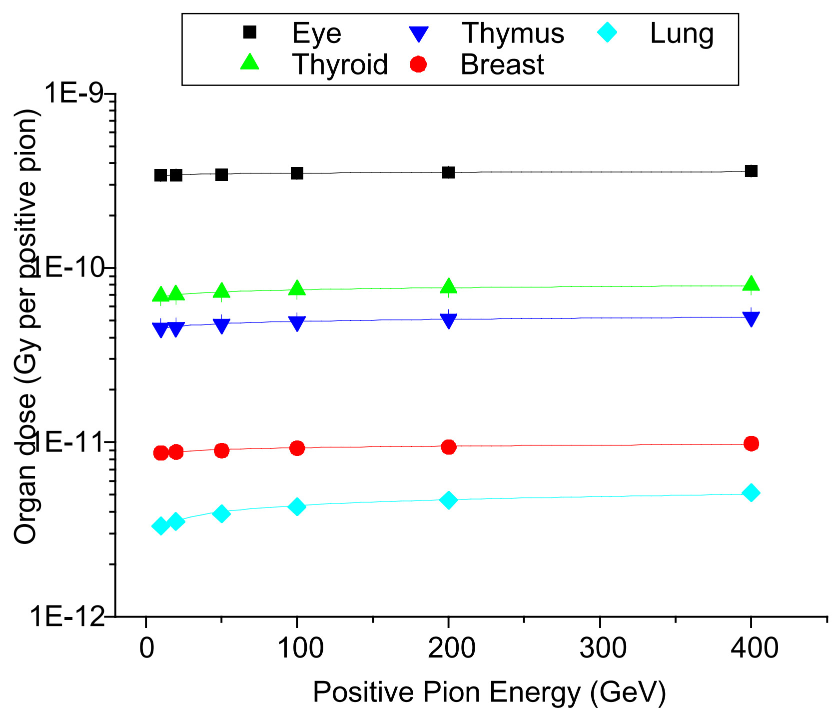

Fig. 2. Dose to various target organs, D_T, for a monoenergetic pencil beam of positive pions with energy in the range 10 — 400 GeV. A fit according to the law $D_T = A_D + B_D \log K$ is shown. The parameters A_D and B_D are given in Table 6.

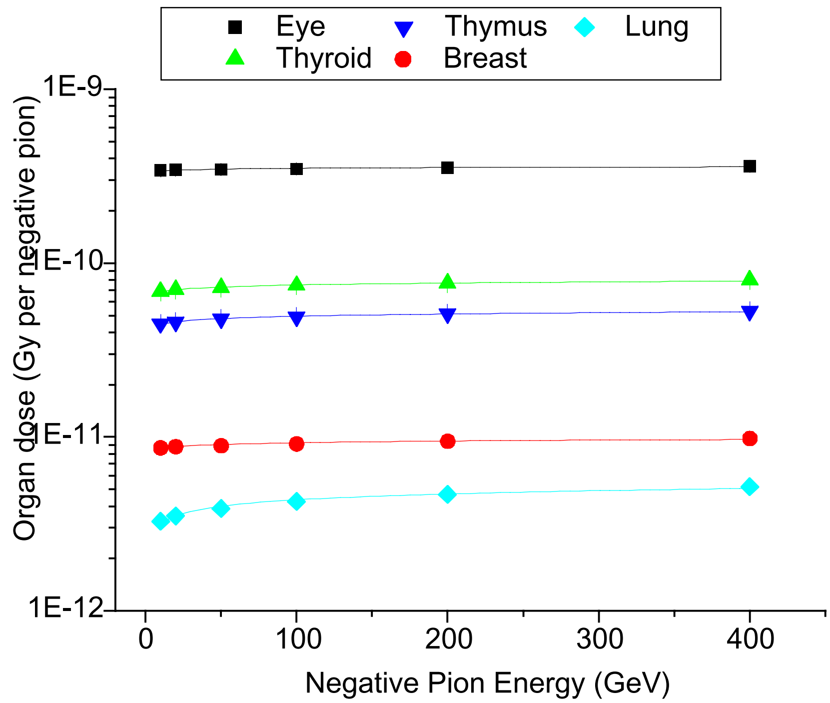

Fig. 3. Dose to various target organs, D_T, for a monoenergetic pencil beam of negative pions with energy in the range 10 — 400 GeV. A fit according to the law $D_T = A_D + B_D \log K$ is shown. The parameters A_D and B_D are given in Table 7.

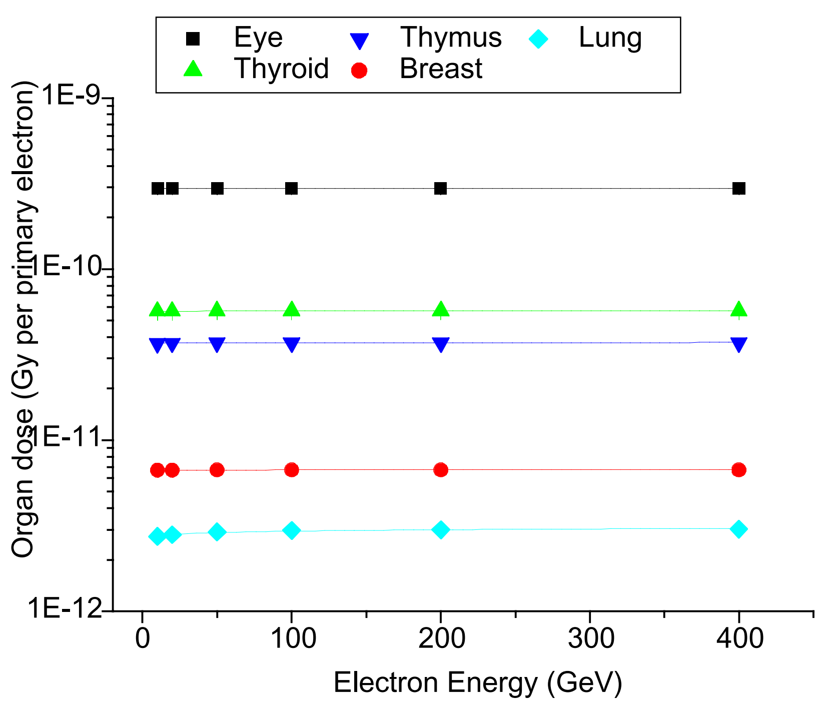

Fig. 4. Dose to various target organs, D_T, for a monoenergetic pencil beam of electrons with energy in the range 10 — 400 GeV. A fit according to the law $D_T = A_D + B_D \log K$ is shown. The parameters A_D and B_D are given in Table 8.

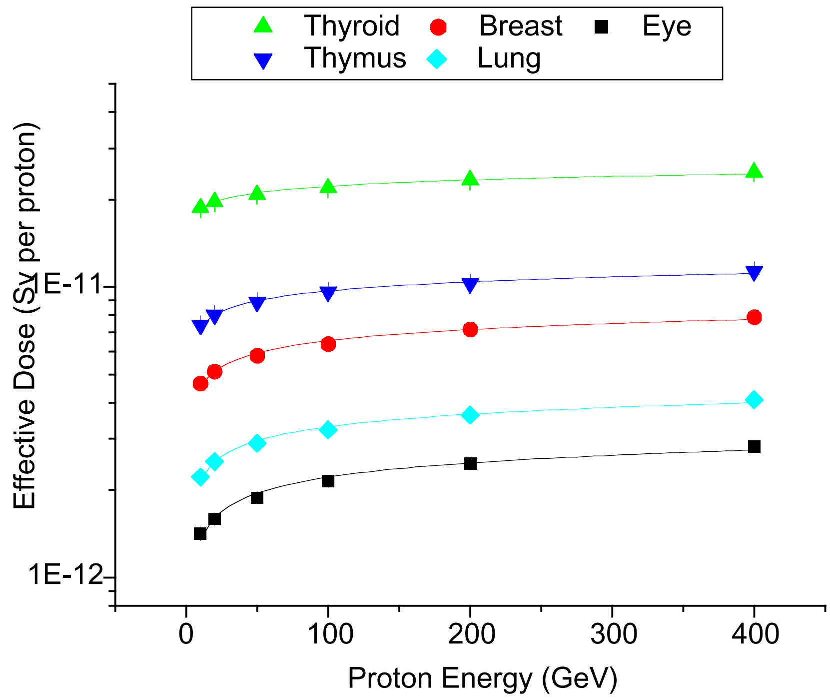

Fig. 5. Effective dose E for various target organs, for a monoenergetic pencil beam of protons with energy in the range 10 — 400GeV. A fit according to the law $E = A_E + B_E \log K$ *is shown. The parameters* A_E *and* B_E *are given in Table 5.*

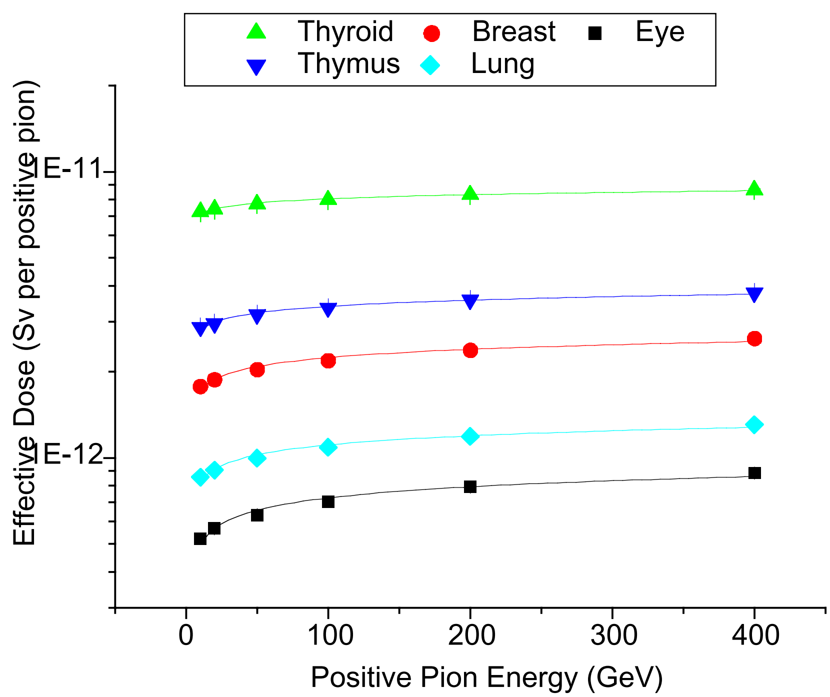

Fig. 6. Effective dose E for various target organs, for a monoenergetic pencil beam of positive pions with energy in the range 10 — 400GeV. A fit according to the law $E = A_E + B_E \log K$ *is shown. The parameters* A_E *and* B_E *are given in Table 6.*

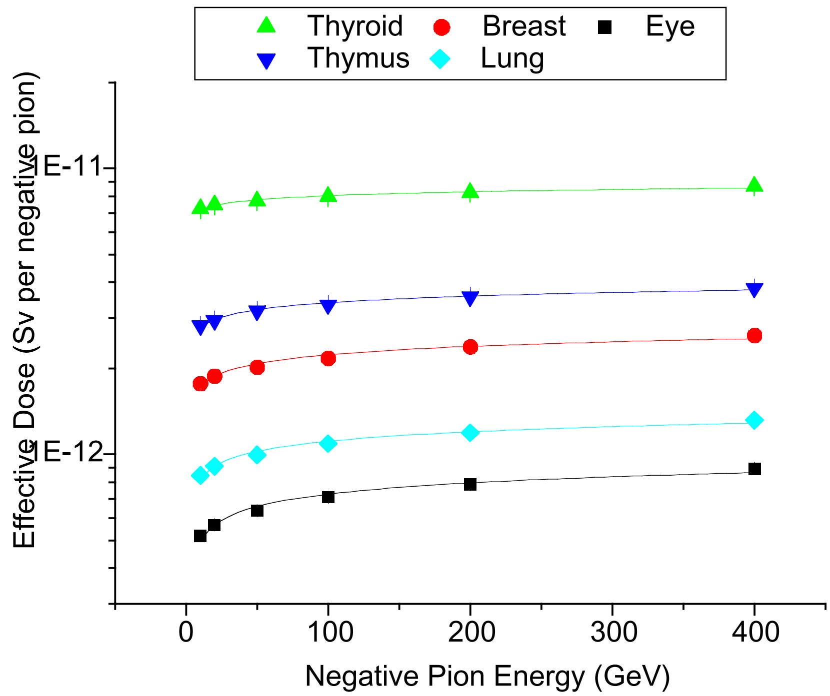

Fig. 7. Effective dose E for various target organs, for a monoenergetic pencil beam of negative pions with energy in the range 10 — 400GeV. A fit according to the law $E = A_E + B_E \log K$ is shown. The parameters A_E and B_E are given in Table 7.

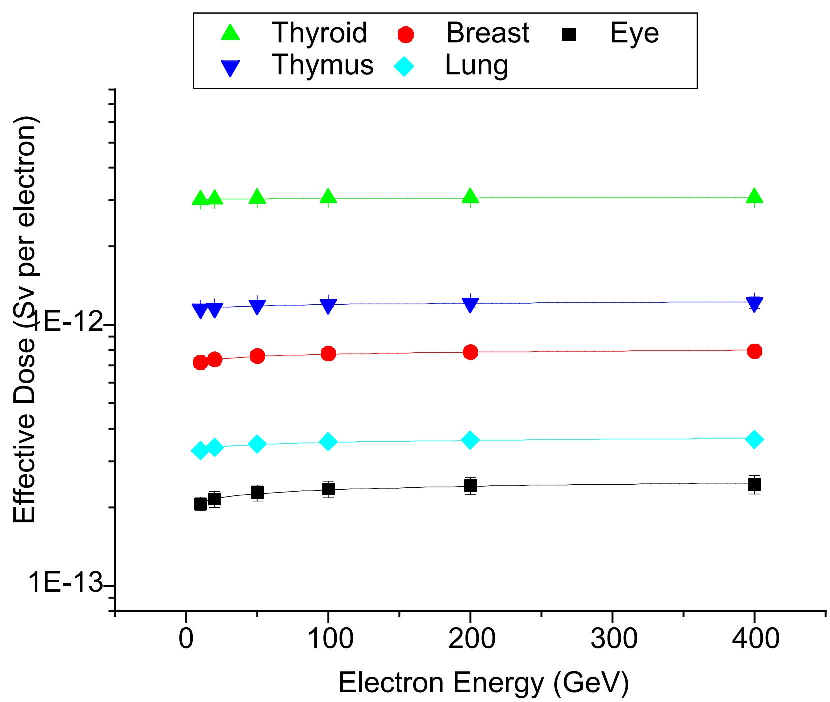

Fig. 8. Effective dose E for various target organs, for a monoenergetic pencil beam of electrons with energy in the range 10 — 400GeV. A fit according to the law $E = A_E + B_E \log K$ is shown. The parameters A_E and B_E are given in Table 8.

The results for lung and breast deserve a specific comment. Table 9 gives the absorbed dose for the male lung (the lung not covered by the breast) and for the female lung (the lung located under the breast), for the various particles and for the five target organs. The ratio of the doses to the two lungs is shown in Figure 9 for protons (for pions the plots are very similar). This ratio is practically 1 when the target organ is either the eye, the thyroid or the thymus: this is perfectly understandable as the absorbed dose is due to scattered radiation and there is no reason that the two lungs are irradiated differently. The situation is much different when either the (male) lung or the breast are target. In this case Figure 9 shows that, when breast is irradiated, the ratio is approximately 100, as the lung underneath in practice is also a target. When (the other) lung is the target, the situation is reversed. For electrons, the behaviour for the various organs is the same, but for breast and (male) lung the ratio is a factor of 10000 rather than 100, because at GeV energies little energy is lost by collision processes.

From Figures 5 — 8 one sees that the effective dose increases with increasing w_T and with decreasing mass of the target organ. For breast, about half of the effective dose is due to the breast itself and half to the lung, the other target organ. When a pencil beam hits a selected target organ, the rest of the phantom also absorbs a certain dose released by secondary radiation. The effective dose is thus the sum of a main contribution from the target organ and several minor contributions from the other tissues. The fraction of effective dose due to non-target organs is given in the last column of Tables 1 — 4 and shown for protons in Figure 10 (for pions the behaviour is very similar) and for electrons in Figure 11. For lung (which is the male lung not covered by the breast, as explained above) most of the effective dose is due to the target organ. For breast, a large fraction of the non-target dose is due to the underlying lung which in practice is also a target, as stated above: for protons the fraction of effective dose due to non-target organs is thus actually less than 10%. The values for lung and breast in Figure 10 are therefore coherent. For thymus a substantial fraction of E comes from other organs because the target has a comparatively low w_T-value. When eye is the target organ there is no contribution to the effective dose from the target since there is no associated w_T-value. These observations are also valid for electrons, but for lung this fraction is lower, about 3×10^{-3}.

The curves of organ doses (Figures 1 — 4) and of effective dose (Figures 5 — 8) versus energy are almost constant. This is reflected by the fits to the calculated values given by equation (1), which is the superposition of two terms, one constant and one weakly varying with energy. This behaviour can be explained in terms of stopping powers. In fact, proton stopping powers decrease as a function of energy up to 1 GeV and are approximately constant above. In practice a very weak variation can still be observed above 10 GeV, which can explain the bend at the lower energy end of the plots for hadrons. The collision energy loss for electrons is practically constant above a few tens of MeV and this reflects in the very smooth behaviour of the dosimetric quantities with beam energy.

4. Conclusions

The radiological hazard posed by a narrow beam of high-energy hadrons and electrons was assessed by Monte Carlo calculations. Pencil beams of monoenergetic protons, pions and electrons with energy in the range 10 — 400 GeV were made to impinge on an anthropomorphic mathematical model to calculate values of effective dose and absorbed doses in five representative target organs (right eye, breast, thyroid, thymus and lung). Given the present lack of literature data on narrow beam dosimetry

Table 9. Absorbed dose (Gy per primary particle) for the male lung (the lung not covered by the breast) and for the female lung (the lung located under the breast), for the various particles and for the five target organs investigated.

		Protons		Positive pions		Negative pions		Electrons	
Energy	Target	female lung	male lung	female lung	male lung	female lung	male lung	female lung	male lung
10	Eye	$1.73\ 10^{-14}$	$1.45\ 10^{-14}$	$1.28\ 10^{-14}$	$1.06\ 10^{-14}$	$1.26\ 10^{-14}$	$1.05\ 10^{-14}$	$7.96\ 10^{-17}$	$6.34\ 10^{-17}$
20		$1.85\ 10^{-14}$	$1.46\ 10^{-14}$	$1.29\ 10^{-14}$	$1.07\ 10^{-14}$	$1.26\ 10^{-14}$	$1.18\ 10^{-14}$	$7.37\ 10^{-17}$	$6.06\ 10^{-17}$
50		$2.16\ 10^{-14}$	$1.75\ 10^{-14}$	$1.35\ 10^{-14}$	$1.18\ 10^{-14}$	$1.37\ 10^{-14}$	$1.14\ 10^{-14}$	$7.34\ 10^{-17}$	$5.27\ 10^{-17}$
100		$2.33\ 10^{-14}$	$1.86\ 10^{-14}$	$1.50\ 10^{-14}$	$1.26\ 10^{-14}$	$1.46\ 10^{-14}$	$1.31\ 10^{-14}$	$6.87\ 10^{-17}$	$4.87\ 10^{-17}$
200		$2.39\ 10^{-14}$	$2.14\ 10^{-14}$	$1.75\ 10^{-14}$	$1.38\ 10^{-14}$	$1.68\ 10^{-14}$	$1.44\ 10^{-14}$	$6.28\ 10^{-17}$	$3.93\ 10^{-17}$
400		$2.78\ 10^{-14}$	$2.43\ 10^{-14}$	$1.91\ 10^{-14}$	$1.57\ 10^{-14}$	$2.01\ 10^{-14}$	$1.59\ 10^{-14}$	$5.13\ 10^{-17}$	$3.41\ 10^{-17}$
10	Breast	$3.61\ 10^{-12}$	$6.63\ 10^{-14}$	$3.51\ 10^{-12}$	$5.34\ 10^{-14}$	$3.47\ 10^{-12}$	$5.33\ 10^{-14}$	$3.20\ 10^{-12}$	$4.02\ 10^{-16}$
20		$4.20\ 10^{-12}$	$7.62\ 10^{-14}$	$3.86\ 10^{-12}$	$5.41\ 10^{-14}$	$3.87\ 10^{-12}$	$5.50\ 10^{-14}$	$3.35\ 10^{-12}$	$3.99\ 10^{-16}$
50		$5.11\ 10^{-12}$	$8.36\ 10^{-14}$	$4.47\ 10^{-12}$	$5.63\ 10^{-14}$	$4.40\ 10^{-12}$	$5.39\ 10^{-14}$	$3.54\ 10^{-12}$	$3.29\ 10^{-16}$
100		$5.85\ 10^{-12}$	$9.13\ 10^{-14}$	$4.93\ 10^{-12}$	$5.81\ 10^{-14}$	$4.94\ 10^{-12}$	$5.88\ 10^{-14}$	$3.67\ 10^{-12}$	$2.83\ 10^{-16}$
200		$6.89\ 10^{-12}$	$9.91\ 10^{-14}$	$5.64\ 10^{-12}$	$6.83\ 10^{-14}$	$5.64\ 10^{-12}$	$6.59\ 10^{-14}$	$3.76\ 10^{-12}$	$2.55\ 10^{-16}$
400		$7.94\ 10^{-12}$	$1.10\ 10^{-13}$	$6.42\ 10^{-12}$	$7.22\ 10^{-14}$	$6.38\ 10^{-12}$	$7.15\ 10^{-14}$	$3.81\ 10^{-12}$	$2.09\ 10^{-16}$
10	Thyroid	$3.98\ 10^{-14}$	$3.98\ 10^{-14}$	$3.26\ 10^{-14}$	$3.44\ 10^{-14}$	$3.32\ 10^{-14}$	$3.33\ 10^{-14}$	$2.71\ 10^{-16}$	$2.71\ 10^{-16}$
20		$4.48\ 10^{-14}$	$4.68\ 10^{-14}$	$3.52\ 10^{-14}$	$3.43\ 10^{-14}$	$3.47\ 10^{-14}$	$3.43\ 10^{-14}$	$2.61\ 10^{-16}$	$2.58\ 10^{-16}$
50		$5.27\ 10^{-14}$	$5.13\ 10^{-14}$	$3.67\ 10^{-14}$	$3.81\ 10^{-14}$	$3.68\ 10^{-14}$	$3.62\ 10^{-14}$	$1.99\ 10^{-16}$	$2.05\ 10^{-16}$
100		$5.69\ 10^{-14}$	$5.66\ 10^{-14}$	$3.81\ 10^{-14}$	$3.84\ 10^{-14}$	$3.71\ 10^{-14}$	$3.89\ 10^{-14}$	$1.94\ 10^{-16}$	$2.10\ 10^{-16}$
200		$6.57\ 10^{-14}$	$6.13\ 10^{-14}$	$4.11\ 10^{-14}$	$4.12\ 10^{-14}$	$3.85\ 10^{-14}$	$3.90\ 10^{-14}$	$1.82\ 10^{-16}$	$1.93\ 10^{-16}$
400		$6.78\ 10^{-14}$	$6.90\ 10^{-14}$	$4.36\ 10^{-14}$	$4.57\ 10^{-14}$	$4.46\ 10^{-14}$	$4.14\ 10^{-14}$	$1.41\ 10^{-16}$	$1.55\ 10^{-16}$
10	Thymus	$2.15\ 10^{-13}$	$2.10\ 10^{-13}$	$1.79\ 10^{-13}$	$1.83\ 10^{-13}$	$1.77\ 10^{-13}$	$1.75\ 10^{-13}$	$3.16\ 10^{-15}$	$3.30\ 10^{-15}$
20		$2.49\ 10^{-13}$	$2.43\ 10^{-13}$	$1.80\ 10^{-13}$	$1.87\ 10^{-13}$	$1.79\ 10^{-13}$	$1.80\ 10^{-13}$	$3.15\ 10^{-15}$	$2.99\ 10^{-15}$
50		$2.76\ 10^{-13}$	$2.74\ 10^{-13}$	$1.92\ 10^{-13}$	$1.97\ 10^{-13}$	$1.94\ 10^{-13}$	$1.99\ 10^{-13}$	$2.78\ 10^{-15}$	$2.95\ 10^{-15}$
100		$3.05\ 10^{-13}$	$3.07\ 10^{-13}$	$2.10\ 10^{-13}$	$2.08\ 10^{-13}$	$2.07\ 10^{-13}$	$2.06\ 10^{-13}$	$2.67\ 10^{-15}$	$2.81\ 10^{-15}$
200		$3.35\ 10^{-13}$	$3.34\ 10^{-13}$	$2.24\ 10^{-13}$	$2.32\ 10^{-13}$	$2.30\ 10^{-13}$	$2.31\ 10^{-13}$	$2.66\ 10^{-15}$	$2.53\ 10^{-15}$
400		$3.68\ 10^{-13}$	$3.64\ 10^{-13}$	$2.49\ 10^{-13}$	$2.46\ 10^{-13}$	$2.59\ 10^{-13}$	$2.55\ 10^{-13}$	$2.25\ 10^{-15}$	$2.09\ 10^{-15}$
10	Lung	$4.37\ 10^{-14}$	$3.39\ 10^{-12}$	$3.69\ 10^{-14}$	$3.30\ 10^{-12}$	$3.69\ 10^{-14}$	$3.27\ 10^{-12}$	$2.17\ 10^{-16}$	$2.74\ 10^{-12}$
20		$5.04\ 10^{-14}$	$3.82\ 10^{-12}$	$3.67\ 10^{-14}$	$3.51\ 10^{-12}$	$3.52\ 10^{-14}$	$3.52\ 10^{-12}$	$1.87\ 10^{-16}$	$2.81\ 10^{-12}$
50		$5.52\ 10^{-14}$	$4.43\ 10^{-12}$	$3.70\ 10^{-14}$	$3.89\ 10^{-12}$	$3.68\ 10^{-14}$	$3.88\ 10^{-12}$	$1.72\ 10^{-16}$	$2.91\ 10^{-12}$
100		$5.93\ 10^{-14}$	$4.97\ 10^{-12}$	$3.82\ 10^{-14}$	$4.26\ 10^{-12}$	$3.98\ 10^{-14}$	$4.26\ 10^{-12}$	$1.38\ 10^{-16}$	$2.97\ 10^{-12}$
200		$6.33\ 10^{-14}$	$5.59\ 10^{-12}$	$4.09\ 10^{-14}$	$4.65\ 10^{-12}$	$4.12\ 10^{-14}$	$4.67\ 10^{-12}$	$1.27\ 10^{-16}$	$3.00\ 10^{-12}$
400		$6.86\ 10^{-14}$	$6.35\ 10^{-12}$	$4.55\ 10^{-14}$	$5.14\ 10^{-12}$	$4.61\ 10^{-14}$	$5.18\ 10^{-12}$	$9.74\ 10^{-17}$	$3.02\ 10^{-12}$

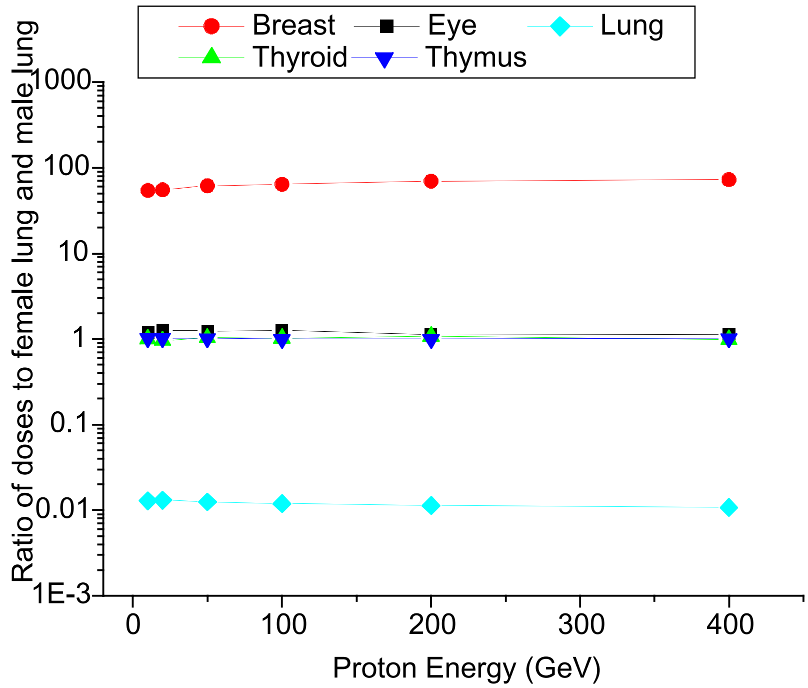

Fig. 9. Ratio of absorbed dose by the female and male lungs (see text) for protons and for the five target organs investigated.

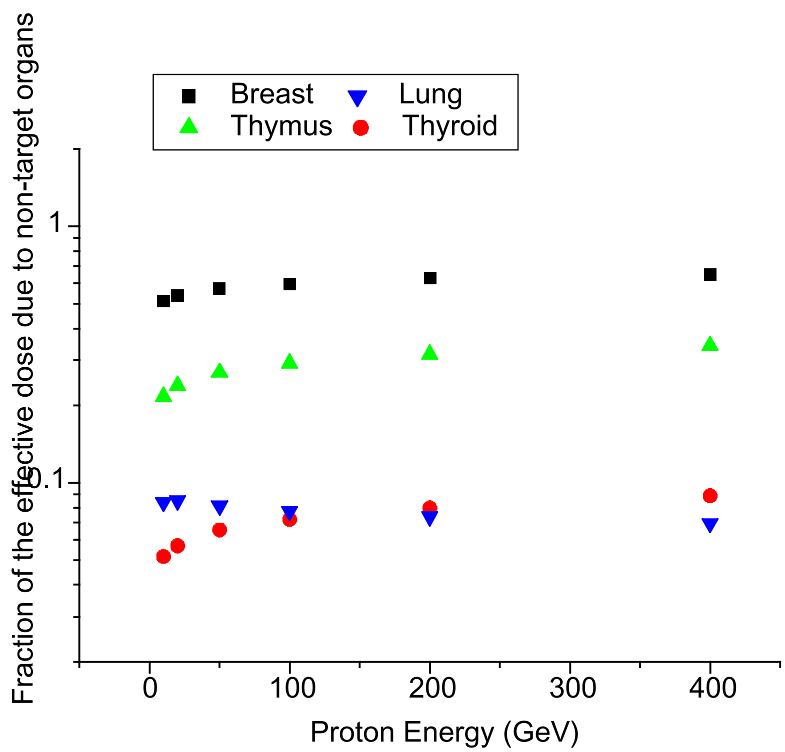

Fig. 10. Fraction of effective dose due to non-target organs for protons, for four of the five target organs investigated (the eye has no associated w_T-value).

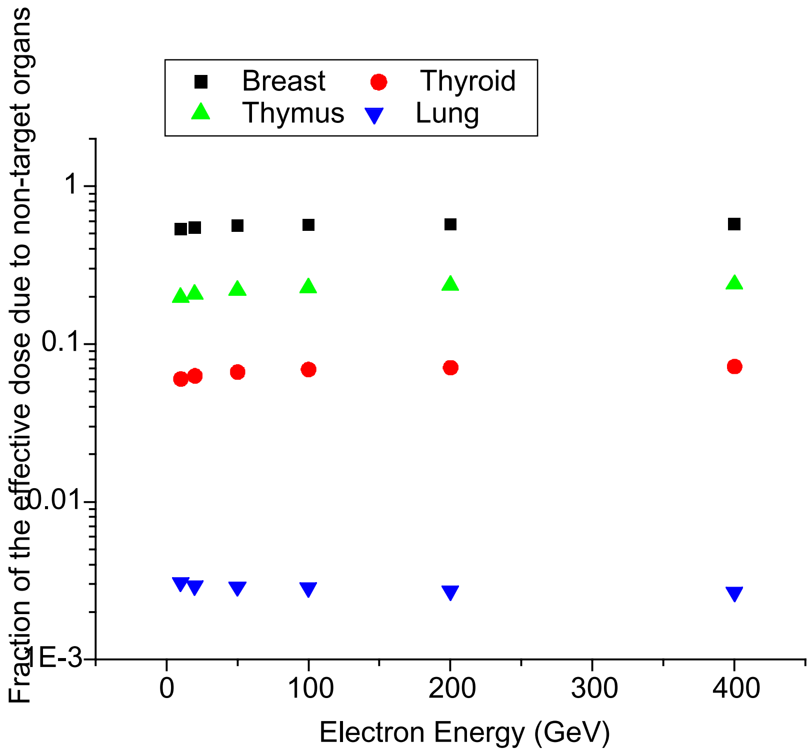

Fig. 11. Fraction of effective dose due to non-target organs for electrons, for four of the five target organs investigated (the eye has no associated w_T-value).

of high-energy particles, the five organs selected for the present study should provide a fairly comprehensive picture of the different irradiation conditions which might be encountered in an accident scenario. For a mixed beam of protons and positive pions, the narrow beam data here presented for the different particles should be properly weighted. The present results, along with the fits to the calculated values, should be of help in post-accident dosimetry in case of an exposure where a different organ may be involved and under different conditions than those here considered. The present information are supplementary to existing data on conversion coefficients from fluence to limiting quantities, calculated for a phantom exposed to broad beams. The strong dependence of effective dose on the target organ is indeed a proof of the usefulness of specific conversion coefficients for use in narrow beam dosimetry.

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