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AMBIENT DOSE EQUIVALENT CONVERSION FACTORS FOR HIGH ENERGY NEUTRONS BASED ON THE NEW ICRP RECOMMENDATIONS

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Abstract

Sannikov A.V., Savitskaya E.N. Ambient Dose Equivalent Conversion Factors for High Energy Neutrons Based on the New ICRP Recommendations: IHEP Preprint 95-98. – Protvino, 1995. – p. 25, figs. 14, tables 1, refs.: 34.

The calculations of the ambient dose equivalent conversion factors for neutron energies from 20 MeV to 5 GeV have been performed using the Monte Carlo high energy transport code HADRON based on the cascade-exciton model of nuclear interactions. The kerma-approximation extended to high energy region was applied in the calculations of absorbed dose and dose equivalent. The obtained results are compared with the previous data for the infinite slab 30 cm thick as well as with the recent calculations for the ICRU sphere. The influence of the phantom shape and dimension was found to be not very important for high energy radiations. The discrepancies in dose equivalent data are mainly explained by incorrect quality factors of secondary charged particles used in earlier calculations and by large statistical errors in many cases. Another important conclusion is that the ambient dose equivalent $H^*(10)$ satisfies the requirement of conservativity for high energy radiations and needs no changes.

Аннотация

Санников А.В., Савицкая Е.Н. Факторы конверсии амбиентной эквивалентной дозы высокоэнергетических нейтронов на основе новых рекомендаций МКРЗ: Препринт ИФВЭ 95-98. – Протвино, 1995. – 25 с., 14 рис., 1 табл., библиогр.: 34.

Методом Монте-Карло рассчитаны значения факторов конерсии амбиентной эквивалентной дозы нейтронов с энергиями от 20 МэВ до 5 ГэВ по программе переноса высокоэнергетических адронов HADRON, описывающей неупругие ядерные взаимодействия в рамках каскадно-экситонной модели. Для расчетов поглощенной и эквивалентной доз применено керма-приближение, расширенное на высокоэнергетическую область. Полученные результаты сравниваются с имеющимися данными для бесконечного слоя толщиной 30 см, а также с недавними расчетами для сферы МКРЕ. Найдено, что для высокоэнергетических излучений влияние формы и размеров фантома на величину амбиентной эквивалентной дозы незначительно. Расхождения в данных по эквивалентной дозе объясняются использованием в предшествующих расчетах некорректных коэффициентов качества вторичных заряженных частиц и значительными статистическими погрешностями в большинстве случаев. Другим важным заключением является то, что эквивалентная доза $H^*(10)$ удовлетворяет требованию консервативности для высокоэнергетических излучений и не нуждается в изенениях.

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1. Introduction

The ICRP recommends in Publication 60 [1] to prolong the use in radiation measurements the ICRU operational dosimetric quantities with a redefinition of the quality factor, Q. This newly recommended $Q(L)$-dependence is shown in Fig. 1 in comparison with the old one defined in ICRP-21 [2]. In neutron dosimetry, the main operational quantity for area monitoring is the ambient dose equivalent, $H^*(10)$ [3]. Calculations of the corresponding conversion factors for the new $Q(L)$-dependence have been performed recently by several groups for neutron energies below 20 MeV [4-6] and by Nabelssi and Hertel [7] in the neutron energy range from 30 to 180 MeV. The data for higher energies are absent at present for the ICRP-60 $Q(L)$-relationship.

The present paper is devoted to the calculation of the ambient dose equivalent conversion factors for neutron energies from 20 MeV to 5 GeV performed in the geometry of a normal irradiation of an infinite tissue-equivalent slab 30 cm thick. In spite of this phantom differs from that recommended by the ICRU 30-cm diameter tissue-equivalent sphere, such a choice seems to be appropriate at high energies. It has been shown earlier [8,9] that the dose equivalent conversion factors for fast neutrons are a little sensitive to the phantom shape in case of directional exposure. At higher energies, differences are not expected to be larger since the high anisotropy of secondary radiation reduces the effect of different shapes near the phantom surface. It should be noted as well that the ICRU sphere is not considered by many specialists as a successful substitution of a human body in case of high energy radiations. On the other hand, calculations in the one-dimensional geometry of an infinite slab require much less computing time and enable one to calculate dose equivalents with higher accuracy.

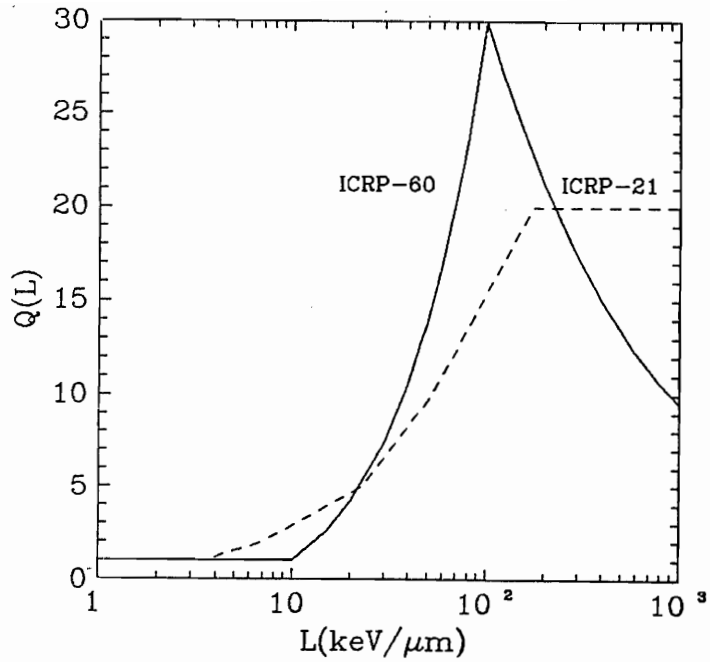

Fig. 1. Quality factor $Q(L)$ as a function of the unrestricted linear energy transfer of charged particles in water L, defined by ICRP-60 [1] and ICRP-21 [2].

2. Method

2.1. Computer codes and transport calculations

The calculations were performed by the Monte Carlo high energy transport code HADRON [9,10,11] based on the cascade-exciton model of nuclear interactions. In inelastic interactions of hadrons with nuclei, $n, p, \pi^0, \pi^\pm$ particles are generated in the program at the cascade stage of interaction and $n, p, d, t, {}^3He, \alpha$ and residual nuclei at the de-excitation stage, which includes a preequilibrium stage as well as an equilibrium one. When simulating hadron interactions with hydrogen nuclei, the experimental differential cross sections from the intranuclear cascade code are used. An elastic scattering of hadrons by nuclei other than hydrogen is calculated by the Ranft formula [12]. The total elastic and inelastic cross sections of hadron collisions with nuclei above 10 MeV were taken from the recent evaluation of Barashenkov [13].

The ICRP-21 based ambient dose equivalent conversion factors for high energy neutrons calculated by the HADRON code in 1989 were reported in [14]. Over the last years, special attention has been paid to more correct calculation of charged particle spectra from nucleon collisions with light nuclei and of the corresponding kerma factors [11]. A new version of this code will be described in the paper [15] devoted to the extensive comparison with the available benchmark experimental data on secondary particle spectra and double differential cross sections. The modified parametrization and improved kinematics at the de-excitation stage resulted in a better description of α-particle spectra especially important for light nuclei. For example, a good agreement with experiment [16] was

obtained for such a complicated reaction as $^{12}C(n,n'3\alpha)$ in the neutron energy range of 10-20 MeV. Another improvement was made in the high energy region where the decrease of nucleon density in nuclei during the cascade stage, important for hadron collisions with light nuclei above 1 GeV, has been taken into account.

Low energy neutrons were transported by the Monte Carlo neutron-photon transport code FANEUT [9,17,18] specially developed for calculation of neutron transport in tissue-equivalent media. The FANEUT cross section treatment is continuous in energy with linear interpolation in a double logarithmic scale between specific energies. The neutron cross-sectional data for tissue nuclei were taken from evaluation [19] based on the ENDF/B-IV and ENDL libraries. Anisotropy of neutron elastic scattering by C, N and O nuclei is taken into account in the P_5-approximation, correlation between the scattering angle and neutron energy loss is calculated with exact kinematical formulae. The double differential scattering cross sections in the thermal energy range (E_n <1 eV) were calculated by the free gas model using the experimental data on total cross section of neutron scattering by hydrogen nuclei in water.

The geometry considered throughout this paper is that of a broad beam of monoenergetic neutrons normally incident on a semi-infinite slab of tissue 30 cm thick. The composition of tissue was taken from the ICRU recommendations [3]. The tissue slab was divided in calculations into 31 layers separated at the depths of 0.8, 1.2, 2, 3 cm etc. up to 30 cm in which the absorbed dose and the dose equivalent were estimated. The doses in the second layer between 0.8 and 1.2 cm were related to the corresponding ambient doses. In our calculations, secondary neutrons, protons and charged pions were transported through the phantom. Kinetic energy of charged particles heavier than a proton such as $d, t, {}^3He, \alpha$ and recoil nuclei having short enough ranges was assumed as deposited locally.

Transport of neutral pions was neglected due to a high probability of their decay near the point of origin. Low LET particles such as photons, electrons, positrons and muons were not transported either. Their total contribution to the ambient dose equivalent does not exceed a few percent but requires that such processes as photon escape from excited nuclei, electron-photon cascades initiated by neutral pion decays and muon production from charged pion decays (which are not included at present into the HADRON code) should be taken into account. This component was taken therefore from Alsmiller's data [20] which had been described in detail and seem to be reliable.

The total ambient dose equivalent was calculated as a sum of the following components:

a) heavy particles(A >1);

b) protons;

c) charged pions;

d) low energy neutrons;

e) photons, electrons, muons.

Heavy particles produced by neutrons, protons and pions in nuclear interactions with C, N and O nuclei give the main contribution to the ambient dose equivalent due to their high quality factors. We have paid therefore special attention to the calculational procedure for this component to reduce the computing time and statistical errors.

2.2. Kerma-approximation for high energy particles

Two main equations are used now in dose equivalent calculations

$$H(\vec{r}) = \int Q(L) D_L(\vec{r}, L) dL \tag{1}$$

and

$$H(\vec{r}) = \int \Phi_E(\vec{r}, E) \bar{Q}(E) k(E) dE. \tag{2}$$

The first relation is the basic one and is applicable to all radiation types. The second one describes the kerma-approximation and is employed to low energy neutrons and photons only. Its advantage is due to a separation of two different calculational procedures to obtain:

a) kerma factors and kerma weighted quality factors taking into account the processes of producing and slowing down secondary charged particles;

b) fluence energy distribution of neutrons(photons) at the point of interest using transport calculations.

In our previous paper [11], a generalization of the kerma concept was proposed to extend it to all the ionizing radiations. In the frames of this concept, the kerma factor of ionizing particles, k, is considered as a sum of the electromagnetic, k_e, and nuclear, k_n, components

$$k = k_e + k_n, \tag{3}$$

where the component k_e is equal to

$$k_e = \begin{cases} E(\mu_{tr}/\rho) & \text{(photons)} \\ L/\rho & \text{(charged particles)} \\ 0 & \text{(neutrons)} \end{cases} \tag{4}$$

Nuclear component of the total kerma factor, k_n, is equal to zero for low energy photons and leptons (e, μ) but for hadrons (n, p, π) it plays an essential role.

It can be seen that this approach enables us to link and consider in the same manner two fundamental dosimetric quantities: the linear energy transfer for charged particles and the kerma factor for uncharged ones. The *cema*, a new quantity proposed recently by Kellerer et al. [21] is similar to the partial kerma K_e for charged particles but we do not see a necessity to introduce an additional quantity. In our consideration, we have an opportunuty to apply the kerma-approximation to all particles including high energy hadrons. This is important, first of all, for secondary heavy particles and we introduce for them one more quantity – the partial kerma factor k_h defined as

$$k_n = k_h + k_l, \tag{5}$$

where k_h and k_l describe the heavy and light ($A \leq 1$) charged particle components of the nuclear kerma factor k_n.

Let us consider some arbitrary volume V in which dose equivalent must be determined. To obtain the fluence energy distribution Φ_E for neutrons, the so-called track length estimation is widely used in the Monte Carlo method

$$\Delta\Phi = \Phi_E dE = l/V, \tag{6}$$

where $\Delta\Phi$ is the contribution to neutron fluence from one particle having a track length l in a volume V. The corresponding contribution to dose equivalent is equal in the kerma-approximation (2) to

$$\Delta H = \frac{l}{V}\bar{Q}(E)k(E). \tag{7}$$

For low energy neutrons, the usual kerma factor and quality factor must be used in this equation. The neutron kerma factor $k_n(E)$ and quality factor $\bar{Q}_n(E)$ (ICRP-60 $Q(L)$) were taken from [6]. In the case of ICRP-21 $Q(L)$-dependence, the neutron quality factors [4] were used. For high energy neutrons, the partial kerma factor k_h and the corresponding quality factor $\bar{Q}_h$ were applied in the calculations.

In case of charged hadrons whose energy decreases continuously on the track length l due to ionization losses, relationship (2) is written as

$$\Delta H = \int_{E_2}^{E_1} \Phi_E(E)\bar{Q}(E)k(E)dE, \tag{8}$$

where E_1 and E_2 are the initial and final energies of a charged particle in a considered volume. Separating the electromagnetic k_e and heavy particle k_h components of the total kerma factor $k(E)$ and using the well-known relation for charged particles in a continuous slowing down approximation $\Phi_E(E) = (V \cdot L(E))^{-1}$ that may be easily derived from equation (6), we obtain

$$\Delta H = \Delta H_e + \Delta H_h = \frac{1}{\rho V}\int_{E_2}^{E_1} Q(L(E))dE + \frac{1}{V}\int_{E_2}^{E_1} \frac{\bar{Q}_h(E)k_h(E)}{L(E)}dE. \tag{9}$$

Now we can write the basic equations for the dose equivalent calculation for all particles transported through the phantom

$$\Delta H = \begin{cases} \frac{l}{V}\bar{Q}_n(E)k_n(E) & \text{(low energy neutrons)} \\ \frac{l}{V}\bar{Q}_h(E)k_h(E) & \text{(high energy neutrons)} \\ \frac{\bar{Q}_e(E_1)E_1 - \bar{Q}_e(E_2)E_2}{\rho V} + \frac{\bar{Q}_h^{tot}(E_1)E_h^{tot}(E_1) - \bar{Q}_h^{tot}(E_2)E_h^{tot}(E_2)}{\rho V} & (p, \pi^{\pm}), \end{cases} \tag{10}$$

where $\bar{Q}_e(E)$ and $\bar{Q}_h^{tot}(E)$ define the electromagnetic and heavy particle quality factors for charged hadrons averaged over their ranges and E_h^{tot} is the total average kinetic energy of heavy particles produced by a charged hadron on its range. The corresponding expressions for these quantities will be described below. Absorbed doses for different particles are determined by equations (10) as well with changing all the quality factors by unity.

2.3. Quality factors and partial kerma factors

The preliminary calculations were performed in three steps. At the first one, the quality factors for all secondary charged particles from pions to ^{16}O-nuclei averaged over their ranges were calculated as a function of kinetic energy

$$\bar{Q}_e(E_i) = \frac{1}{E_i}\int_0^{E_i} Q(L_i(E))dE. \tag{11}$$

The new ICRU recommendations [22] on stopping power of protons and α-particles in liquid water were used. In other cases the semiempirical formulae of Andersen and Ziegler [23] with taking into account effective charges of heavy particles were applied below 100 MeV/nucleon and the well-known Bethe formula with density effect correction above this energy. The calculated energy dependences $\bar{Q}_e(E)$ for five different charged particles are shown in Fig.2 for two $Q(L)$-relationships recommended by the ICRP [1,2]. It can be seen that the new quality factors overestimate in most cases the old ones. Exceptions are recoil nuclei (A >4) with L >200 keV/μm and high energy particles having L <30 keV/μm.

The partial kerma factor $k_h(E)$ may be written as

$$k_h(E) = \sum_j N_j \sum_i \int_0^{E_i^{max}(E)} \frac{d\sigma_{ij}}{dE_i}(E, E_i)E_i dE_i, \tag{12}$$

where N_j is the number of nuclei of isotope j per gram of tissue and $d\sigma_{ij}/dE_i$ is the differential cross section of production of heavy particle of i-th type in nuclear interaction with j-th nucleus. The corresponding quality factor is defined by

$$\bar{Q}_h(E) = \sum_j N_j \sum_i \int_0^{E_i^{max}(E)} \frac{d\sigma_{ij}}{dE_i}(E, E_i)\bar{Q}_e(E_i)E_i dE_i / k_h(E), \tag{13}$$

where the quality factors $\bar{Q}_e(E_i)$ are determined by equation (11). The results of calculations performed by the HADRON code for neutrons, protons and charged pions are presented in Figs.3 and 4. One more quantity shown in Fig.3 is an average total kinetic energy of heavy particles per one nuclear interaction produced by hadrons in nuclear collisions with tissue nuclei heavier than hydrogen, $\bar{E}_h$. This quantity given for illustration includes both heavy particles from inelastic interactions and C, N, O recoils from elastic scattering of hadrons by these nuclei. All the quantities presented in Figs.3 and 4 have been calculated with a statistical uncertainty of 2%. One interesting feature of these results is a small difference between the neutron and proton data, especially for the average energy $\bar{E}_h$. This is a consequence of the charge independence of nuclear forces at high energies. The same conclusion can be made for the positive and negative pion data. The differences at low energies are explained by the influence of Coulomb forces. They are noticed especially in the kerma factors which are more dependent on the total cross sections than the average quantities $\bar{E}_h$ and $\bar{Q}_h$.

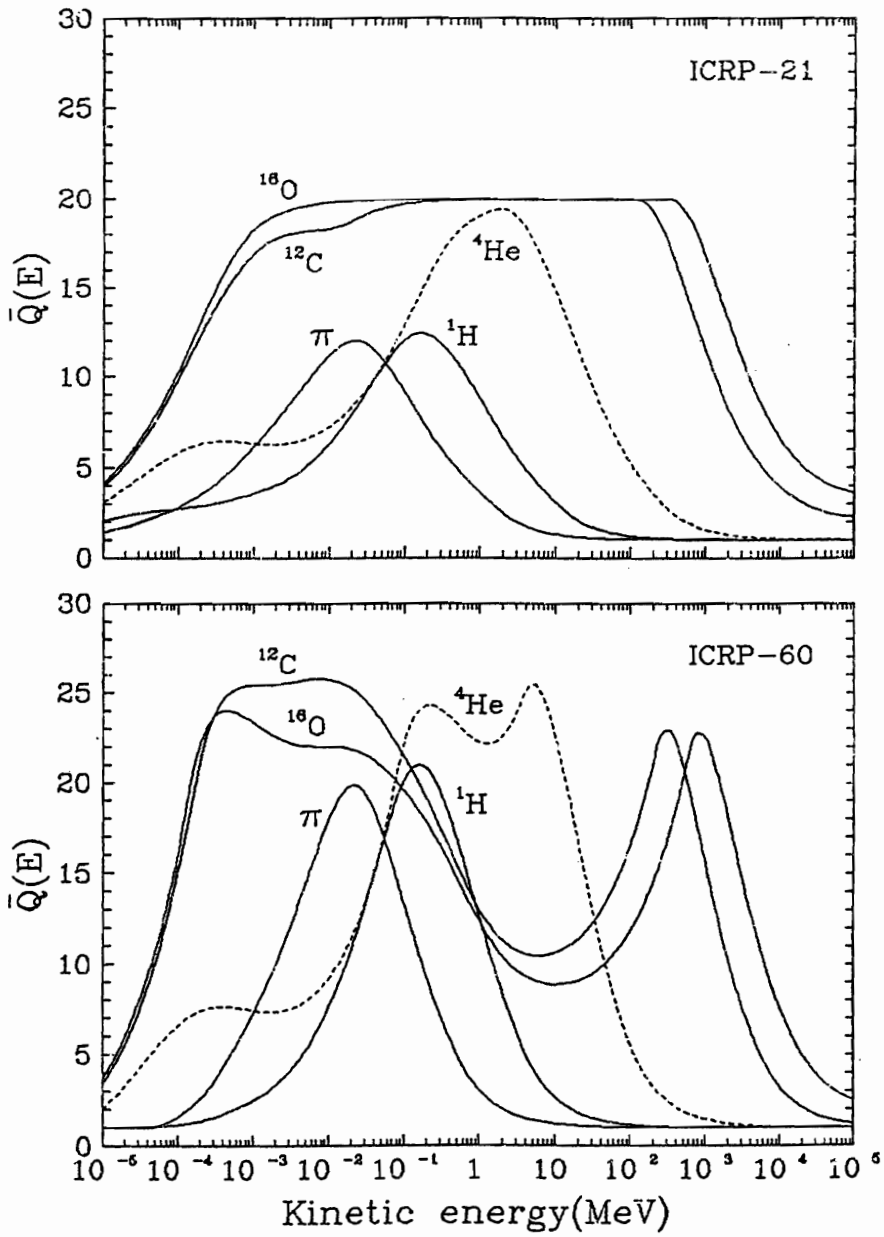

Fig. 2. Quality factors of charged particles averaged over their ranges in the ICRU soft tissue for two $Q(L)$-dependences.

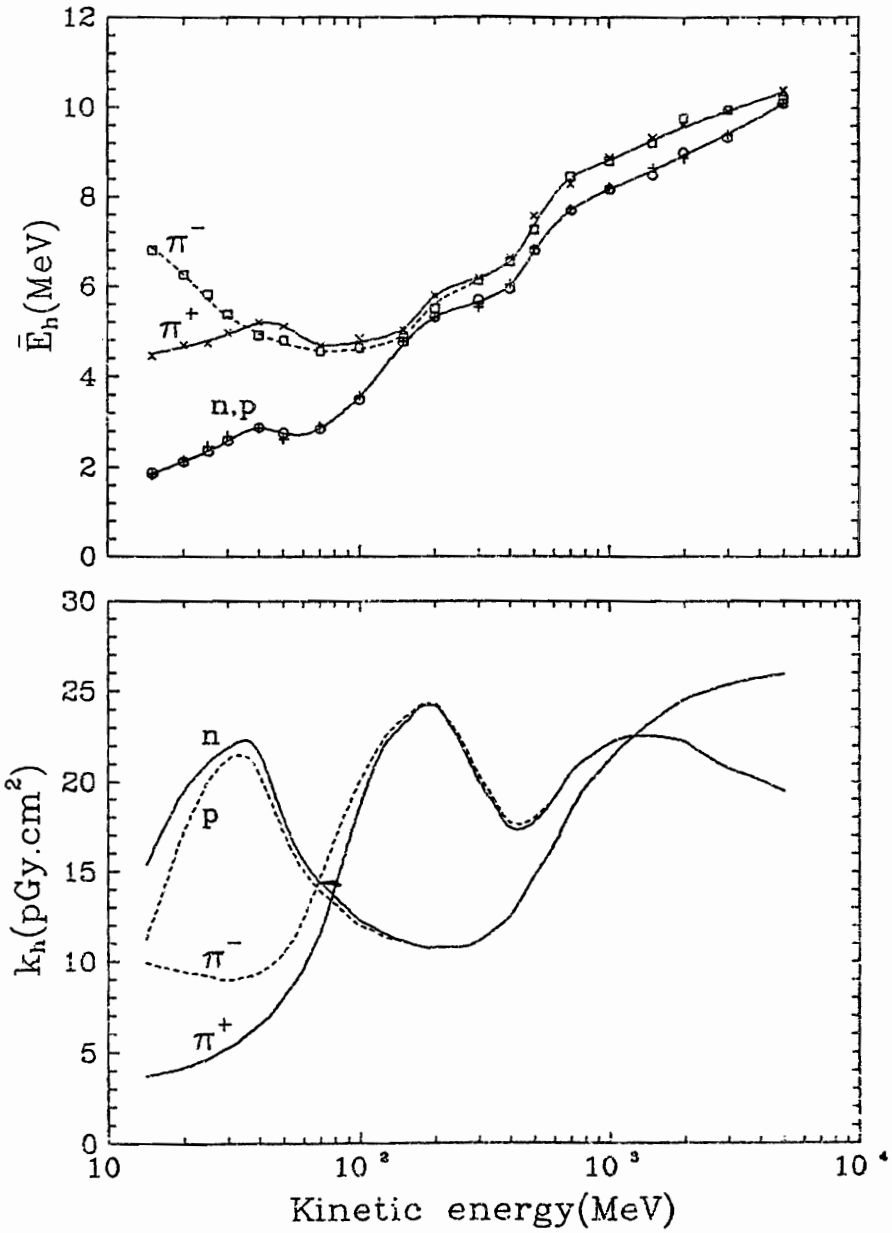

Fig. 3. Average kinetic energy transferred to heavy particles(A>1) in one nuclear collision of hadrons with C, N and O tissue nuclei (top) and partial kerma factor $k_h(E)$ (bottom) as a function of hadron energy.

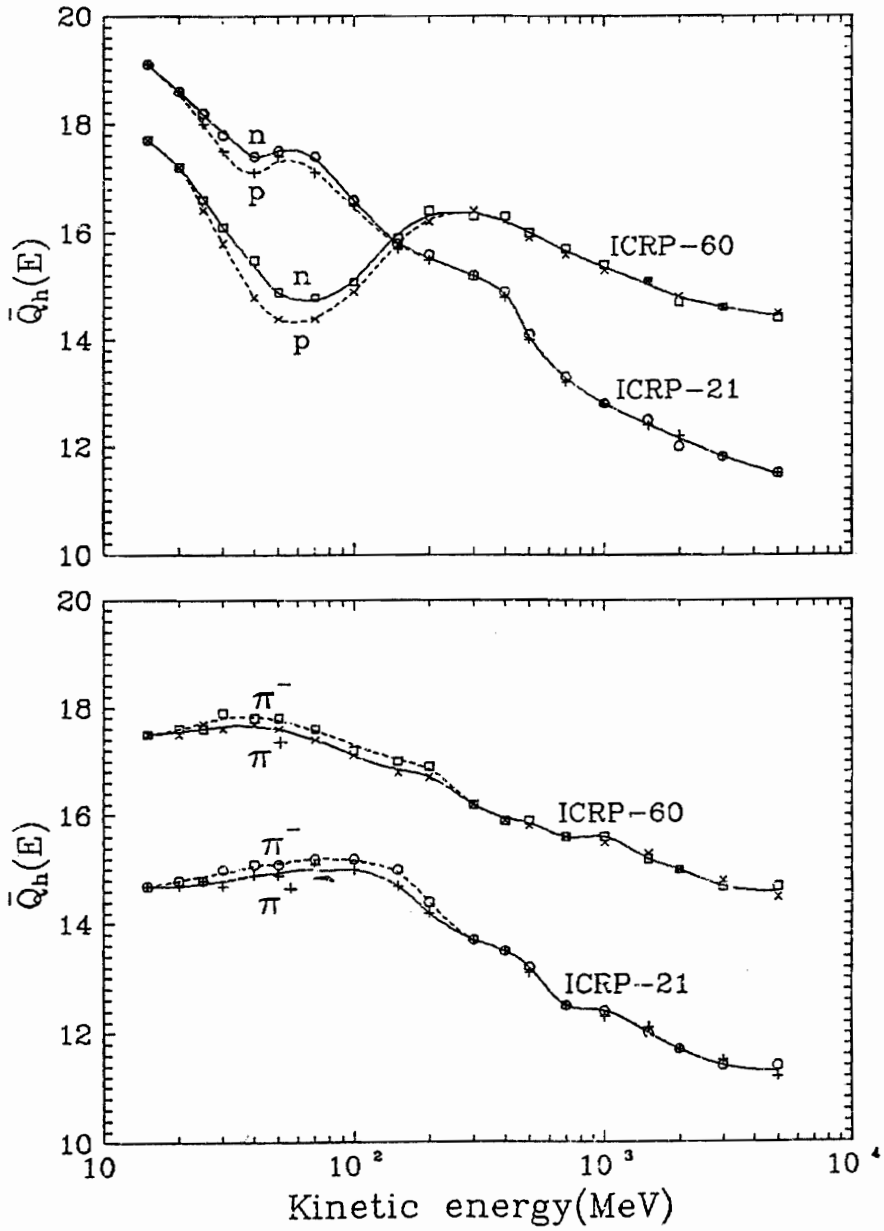

Fig. 4. Average quality factors $\bar{Q}_h$ of heavy particles produced by hadrons in the ICRU soft tissue for two $Q(L)$-dependences.

Another important feature is that the ICRP-60 quality factors $\bar{Q}_h$ for nucleons below 150 MeV are lower than the ICRP-21 ones. The explanation of this effect may be found in the comparison of the quality factors $\bar{Q}_e$ for carbon and oxygen nuclei (Fig.2) which are nearly half as low for the ICRP-60 $Q(L)$-dependence as compared to the ICRP-21 ones in the practically important energy range of 1-20 MeV. These elastically scattered recoils contribute considerably to the integrals in (13) at nucleon energies below 150 MeV where the elastic scattering cross sections are high enough. This is not the case for charged pions which produce recoil nuclei of much lower energies due to their lower masses.

At the last step of preparing the data for dose calculations, the total kinetic energies $E_h^{tot}(E)$ and the corresponding quality factors $\bar{Q}_h^{tot}(E)$ for protons and charged pions were calculated using equations

$$E_h^{tot}(E) = \int_0^E \frac{k_h(E')}{L(E')/\rho} dE' \tag{14}$$

and

$$\bar{Q}_h^{tot}(E) = \int_0^E \frac{\bar{Q}_h(E') k_h(E')}{L(E')/\rho} dE' / E_h^{tot}(E), \tag{15}$$

where all the quantities used were described above. One can see now that in all the expressions (10) previously calculated quantities averaged over the ranges of charged particles one, two or three ($E_h^{tot}(E)$ and $\bar{Q}_h^{tot}(E)$) times are used. This provides a considerable gain in accuracy of calculations.

3. Results and discussion

3.1. Ambient absorbed dose data

The calculated ambient absorbed dose conversion factors are shown in Fig.5 in comparison with the data of previous calculations for neutron energies of 10 MeV - 100 GeV. The differences between the new data and our old results [14] obtained in 1989 are explained by better description of neutron kerma factors at energies of 20-60 MeV and by taking into account the decrease of nucleon density in nuclei during the cascade stage above 1 GeV. Another reason is higher accuracy of the present calculations. Statistical errors of ambient absorbed doses were less than 2% and for ambient dose equivalents they were as a rule lower than 1%.

These errors are much higher for all the previous data especially for dose equivalent ones, with an exception of the results of Golovachik et al. [28] calculated by the method of numerical integration of the cascade transport equations. In contrast to paper [14] where in the comparison were used the doses at a depth of 5 mm taken from reference [29], all the presented here results were derived from original papers and correspond to the depth of 10 mm. Many calculations were performed with the depth bins of 10 mm. In these cases the required ambient dose values were obtained by averaging the data for two first layers. As a result of more accurate approach in this comparison, we have much better agreement of different absorbed dose data.

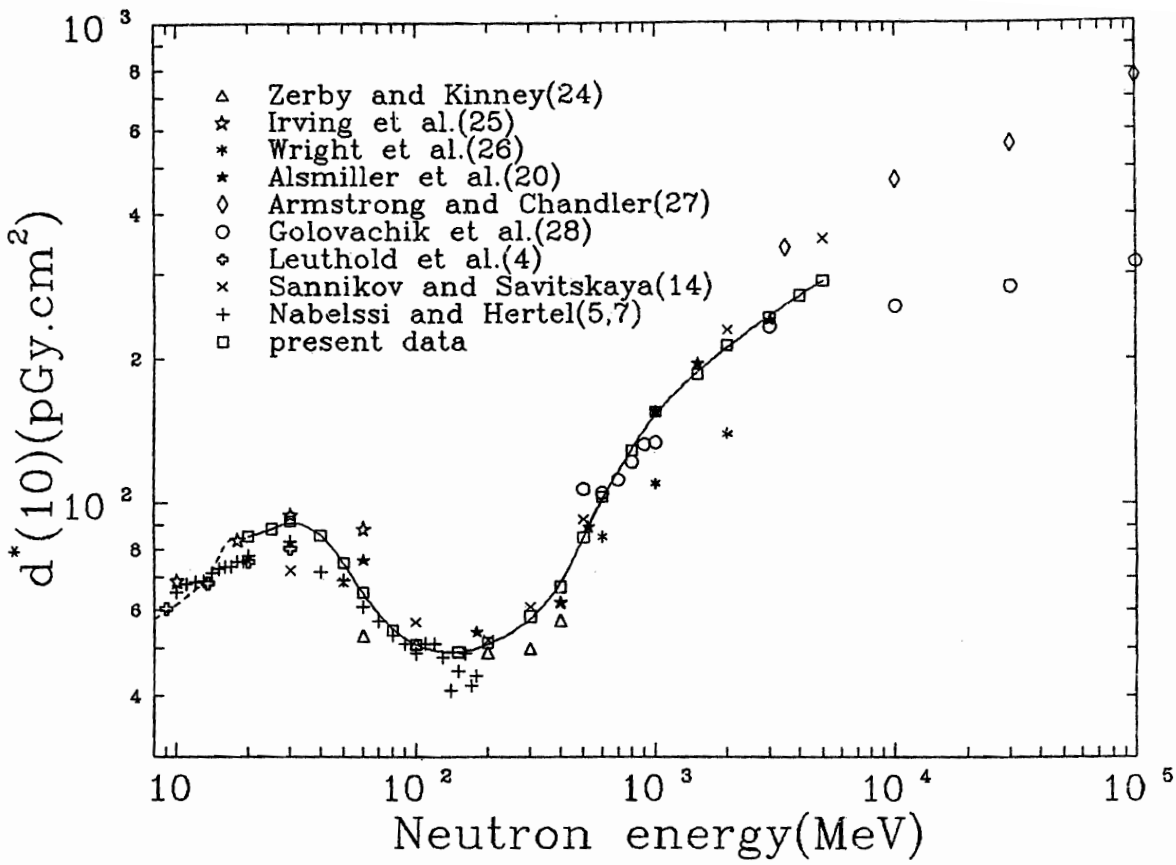

Fig. 5. Comparison of calculated data for neutron ambient absorbed dose. Solid curve shows the smoothed data of present calculafions, dashed curve - ICRP recommendation [30].

Our results agree on an average with earlier calculations. For instance, good enough agreement takes place with the data of Alsmiller et al. [20] in a wide energy range of 60-3000 MeV. The latter ones were obtained using the well-known high energy transport code HETC based on the cascade-evaporation model. These data were acknowledged in ICRP-51 [30] as the most reliable ones below 3 GeV and we may confirm this estimation in part of absorbed doses. Some differences with our data are explained mainly by statistical errors in calculations [20]. All the calculations above 20 MeV were performed in the geometry of an infinite slab, with an exception of recent calculations of Nabelssi and Hertel [7] which were made for the ICRU sphere. These data are consistent with our results at energies of 50-130 MeV and somewhat lower at 30-40 MeV and at 140-180 MeV. The large spread of data noticed in the last case is attributed to statistical errors. At the energy of 20 MeV our ambient absorbed dose is close to the ICRP-51 recommendation [30].

3.2. ICRP-21 based ambient dose equivalent and quality factor

The comparison of published data for ambient dose equivalent calculated using the ICRP-21 $Q(L)$-relationship is presented in Fig.6. The corresponding effective quality factors $Q^*(10)$ are shown in Fig.7. The scatter of data is much higher in these cases as compared to absorbed dose results, especially for quality factors. In the high energy region above 400 MeV, our calculations give lower values of ambient dose equivalent and quality factor as compared to other data. This is explained by the overestimated quality factor of 20 attributed to heavy particles in most of previous calculations, independently of hadron energy. It can be seen from Fig.4 that in more thorough consideration these values lie between 11 and 14 at hadron energies above 400 MeV.

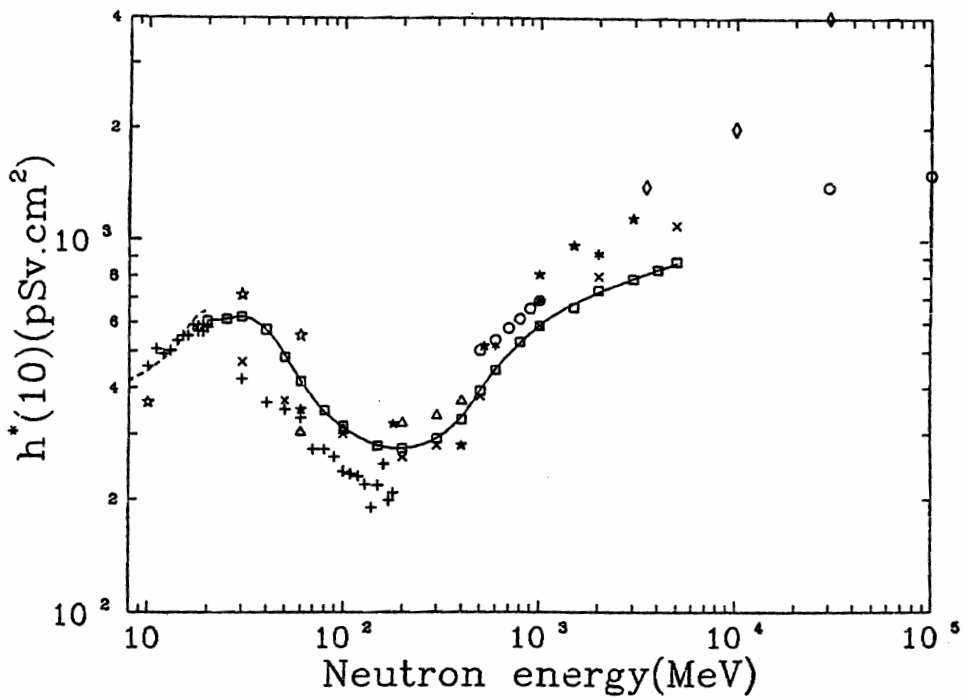

Fig. 6. The same as in Fig.5, for ambient dose equivalent calculated using the ICRP-21 $Q(L)$-relationship.

The situation at lower energies is more complicated. The dose equivalents calculated by Nabelssi and Hertel [7] above 20 MeV are 20-30% lower than our results. These differences are mainly explained by large discrepancies in quality factors (Fig.7). It should be mentioned that the quality factors of Nabelssi and Hertel above 20 MeV [7] are fully inconsistent with their own data for lower energies [5]. The 30% jump of quality factor between 20 and 30 MeV can not be justified by any physical reason. On the contrary, the results of present calculations are consistent with low energy data [4,5,30] both for ambient dose equivalent and quality factor.

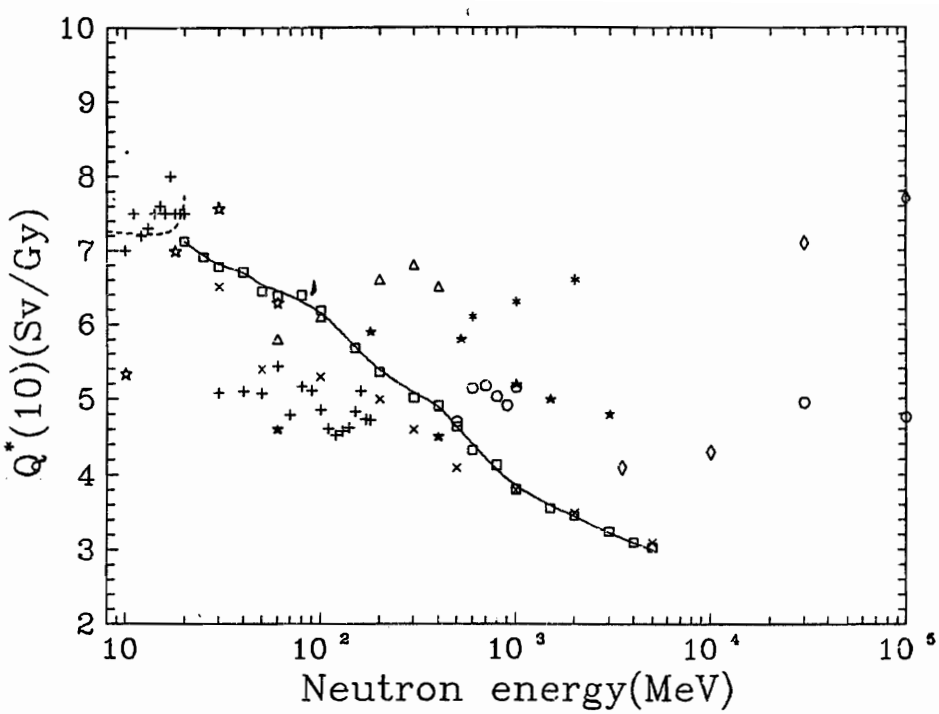

Fig. 7. The same as in Fig.5, for effective quality factor $Q^*(10)$ calculated using the ICRP-21 $Q(L)$-relationship.

3.3. Comparison of depth dose distributions

To understand the discrepancies with the data of Nabelssi and Hertel, let us consider the depth dose distributions along the principal axis of the ICRU sphere given in reference [7] for 180 MeV incident neutrons. These distributions for different components of absorbed dose and dose equivalent are shown in Fig.8 in comparison with the data of present calculations. The absorbed dose components of secondary protons and heavy nuclei are in a good agreement. In the case of low energy neutrons our results overestimate the data [7] by a factor of 2 approximately and for photons this overestimation exceeds a factor of 10. The reasons of these large discrepancies are not clear since the influence of the phantom shape on the doses of neutrons below 20 MeV was found in [9] to be much lower. We do not expect that this changes drastically at higher energies.

Anyway, these differences do not play an important role for dose equivalent. In this case large discrepancies take place for the main components of heavy nuclei and secondary protons. They are fully explained by differences in the corresponding quality factors which are lower in both cases for the Nabelssi and Hertel data. From the analysis of the method used in calculations of the quality factors for secondary charged particles in reference [7], the conclusion can be made that the slowing down of charged particles was not, probably, taken into account. A comparison of the proton quality factors calculated with and without taking into account this effect gives for 1 MeV protons, for instance, the values of 9 and 6, respectively. Another reason important for a heavy nuclei component is that the elasic scattering of neutrons by C, N and O nuclei was included in calculations [7]

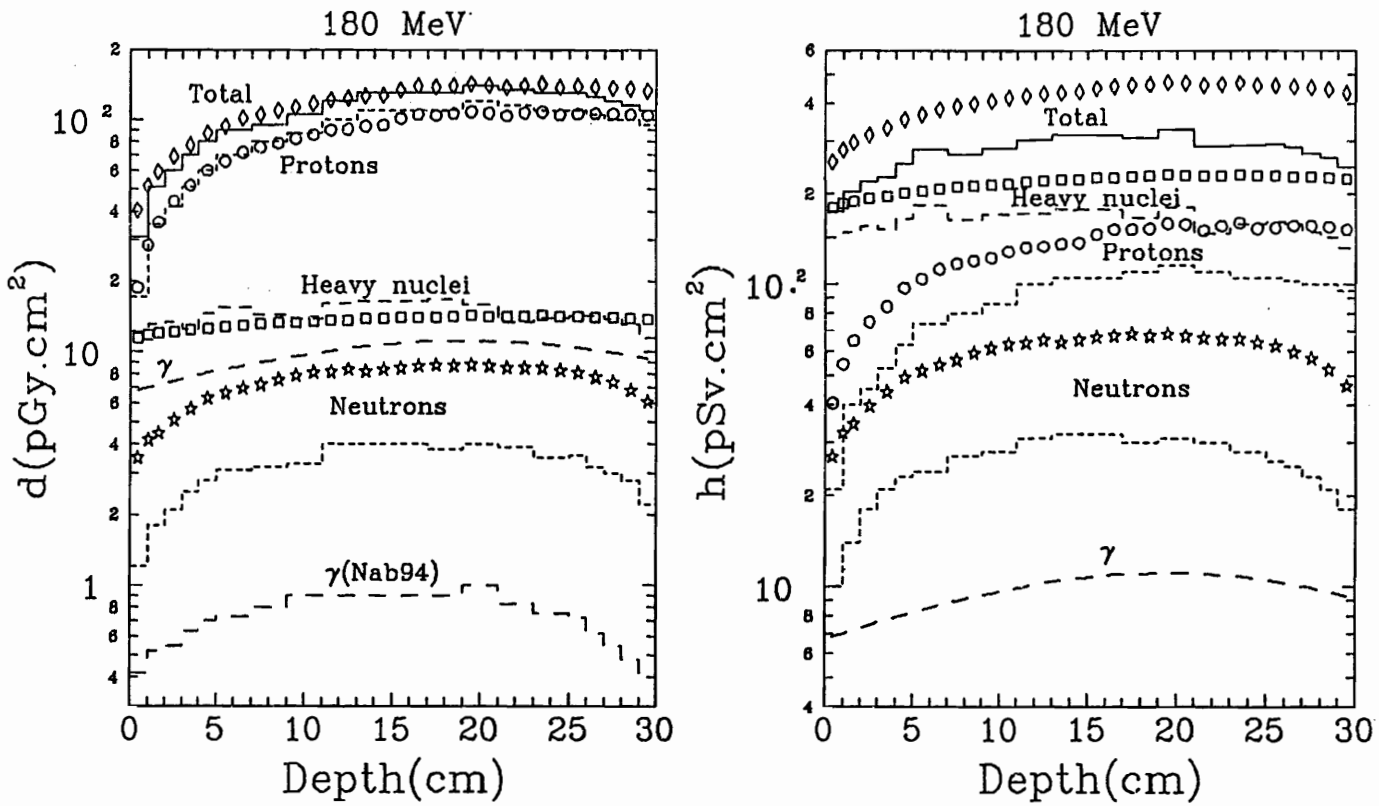

Fig. 8. Comparison of present calculations (points and curves) with the data of Nabelssi and Hertel [7] (histograms) for the depth dose distributions of 180-MeV neutrons.

below 100 MeV only. It can be seen from Fig.2 that elastically scattered recoils have the highest quality factor of 20 for the ICRP-21 $Q(L)$-dependence and have to be considered more carefully.

In a support of our data, Fig.9 presents the depth distributions for different components of dose equivalent calculated by Alsmiller et al. [20] for the same neutron energy. For comparison we deducted our neutron component from the proton component of Alsmiller since they had not been separated in calculations [20]. A good agreement is noticed in both the cases of proton and heavy nuclei components as well as in the total dose equivalents, in the limits of statistical errors [20]. A realistic quality factor for heavy nuclei does not strongly differ at this energy from the constant value of 20 used by Alsmiller et al. The situation is changed considerably at higher energies where the quality factor for heavy nuclei rapidly decreases. This fact is reflected in Fig.10 where the dose equivalent of heavy nuclei calculated in [20] is 50% higher than the present data. All other components are in a good consistency both for absorbed dose and dose equivalent in spite of different computer codes and cross-sectional data being used in calculations.

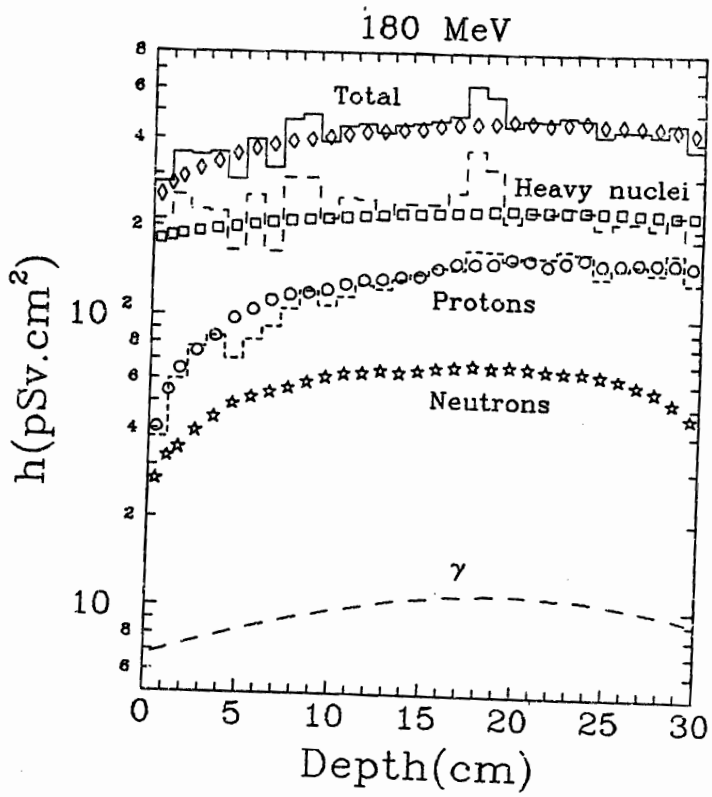

Fig. 9. Comparison of present calculations (points and curves) with the data of Alsmiller et al. [20] (histograms) for the depth dose equivalent distributions of 180-MeV neutrons.

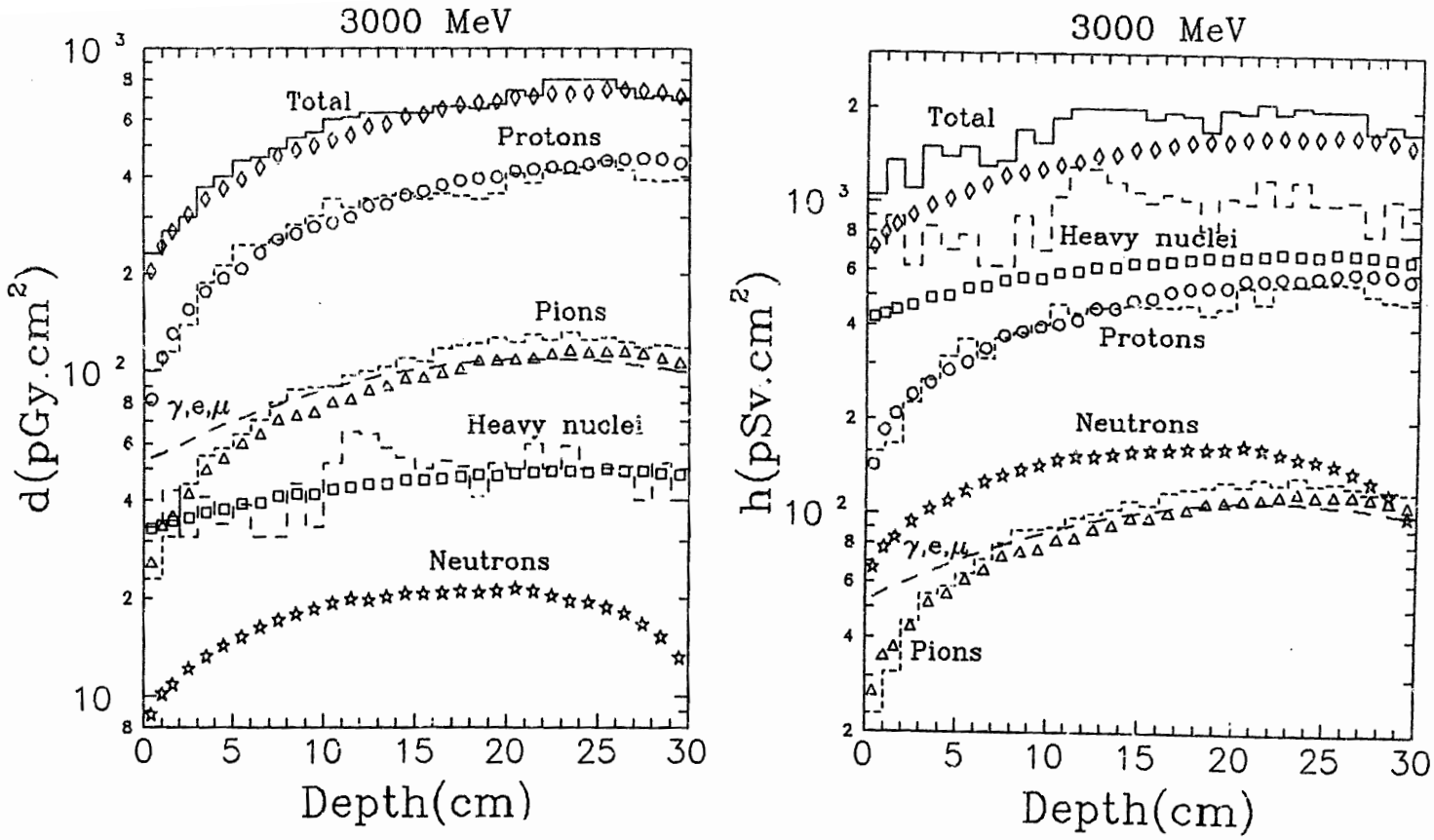

Fig. 10. Comparison of present calculations(points and curves) with the data of Alsmiller et al. [20] (histograms) for the depth dose distributions of 3000-MeV neutrons.

3.4. ICRP-60 based ambient dose equivalent and quality factor

The presented above dose equivalents are related to the ICRP-21 $Q(L)$-relationship. Now, after extensive comparisons, let us consider the impact of the ICRP-60 recommendation on the new $Q(L)$-dependence. The ambient dose equivalents and the corresponding quality factors calculated by different groups using the ICRP-60 $Q(L)$-relationship are shown in Figs.11 and 12. Our results for dose equivalent at 20 MeV agree well with the data calculated by the MCNP code [4,5,6]. In the case of quality factor, some underestimation of the present data is observed related to the corresponding difference in absorbed doses (Fig.5). The discrepancies with the data [7] for ambient dose equivalent above 20 MeV are explained mainly by the absorbed dose data too. It can be seen from Fig.12 that the quality factors of Nabelssi and Hertel are close to our results. This fact is somewhat strange taking into account large differences for the ICRP-21 quality factors.

A comparison of the present data for the new and old $Q(L)$-relationships shows that the ICRP-60 based dose equivalents are lower than the ICRP-21 ones below 130 MeV and higher above this energy. As expected, differences are not large and do not exceed 10%. This effect is explained by the energy dependences of quality factor for heavy nuclei $\bar{Q}_h(E)$ given in Fig.4, and by a considerable contribution of this component to the total ambient dose equivalent, as shown in Fig.13. The relative contributions of heavy nuclei and protons are nearly independent of neutron energy and are equal on an average to 60% and 20%. The low energy neutron component rapidly decreases above 20 MeV and reaches the constant value of 10% at high energies. The two other components, of low LET particles and of charged pions, are not of great importance in the energy range considered. Their maximum contributions do not exceed 9% and 5%, respectively.

3.5. Applicability of the ambient dose equivalent $H^*(10)$ for high energy radiations

The smoothed depth distributions of absorbed dose and dose equivalent (ICRP-60 $Q(L)$) for different neutron energies are shown in Fig.14. It may be clearly seen that the maxima of dose equivalent are situated deeper than 10 mm for all neutron energies. Below 100 MeV they lie at the depths less than 15 cm and above this critical energy the maxima move to the depths of 20-25 cm. This is a well-known fact that the ambient dose equivalent $H^*(10)$ is not a conservative quantity for high energy monoenergetic particles. It represents neither maximum dose equivalent nor effective dose equivalent in this case. For that reason, there are various proposals to change the depth of measurement of ambient dose equivalent in high energy region. For instance, Nabelssi and Hertel [7] propose to use the quantity $H^*(120)$ for neutrons above 30 MeV. On the other hand, Ferrari and Pellicioni [31] suggest the depth of 45 mm for photons.

It should be noted that there is another trial to overcome this problem. Thus, the ambient dose equivalent conversion factors $h^*(10)$ for photons calculated for the ICRU sphere in air are recommended for use in ICRU report 47 [32]. As a result, these data for 10 MeV photons are 3 times higher as compared to the calculations in vacuum [33] due to the contribution of photon interactions in the air column in front of the sphere, whose

dimensions (column) were such as to attain full electronic equilibrium. As was stated in [31] such an approach is in contradiction to the own ICRU definition of ambient dose equivalent [3]. Its most important consequence is that ambient dose equivalent becomes nonadditive quantity due to different requirements for electronic equilibrium for different radiations. The statement about nonadditivity is true too in case of changing the depth of ambient dose equivalent measurement.

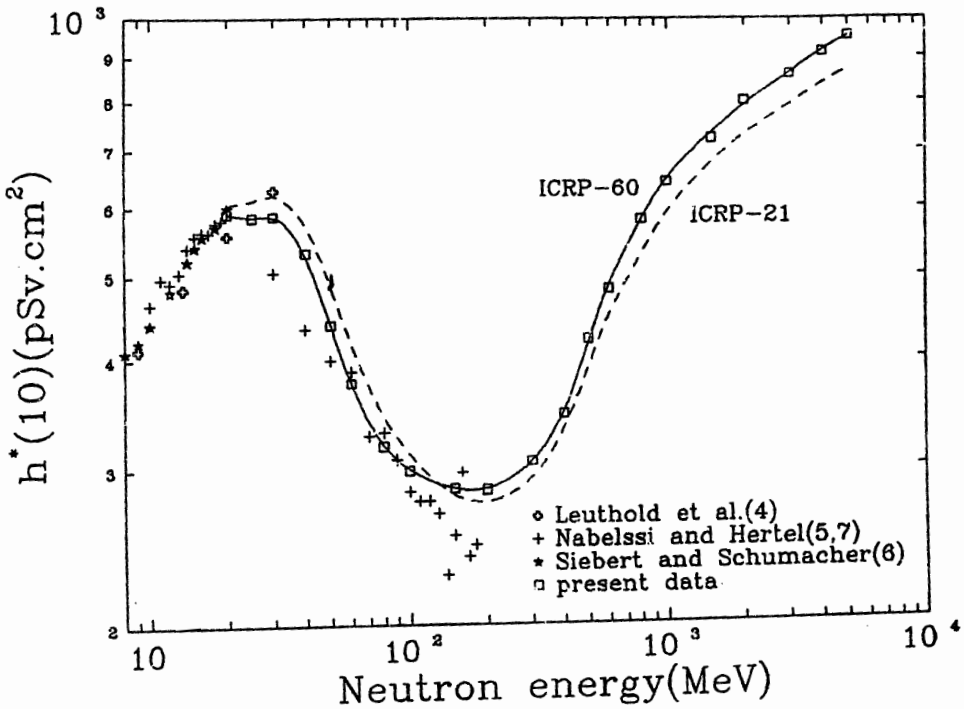

Fig. 11. Comparison of ambient dose equivalent data calculated using the ICRP-60 $Q(L)$-dependence. The present results for the ICRP-21 $Q(L)$-dependence are shown for illustration.

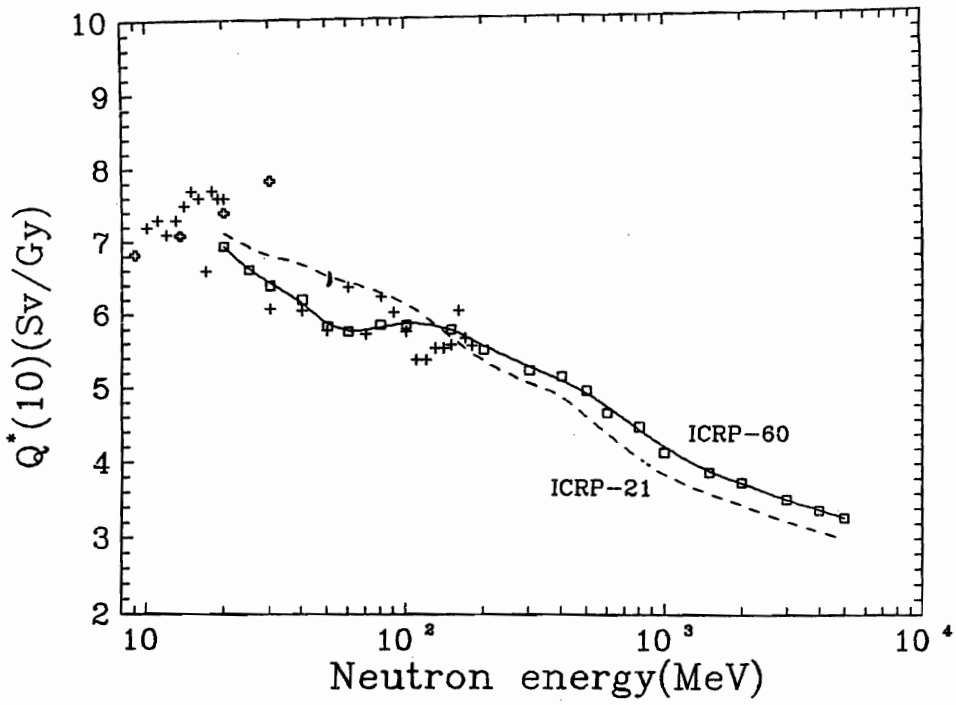

Fig. 12. The same as in Fig.11, for effective quality factor $Q^*(10)$ calculated using the ICRP-60 $Q(L)$-relationship.

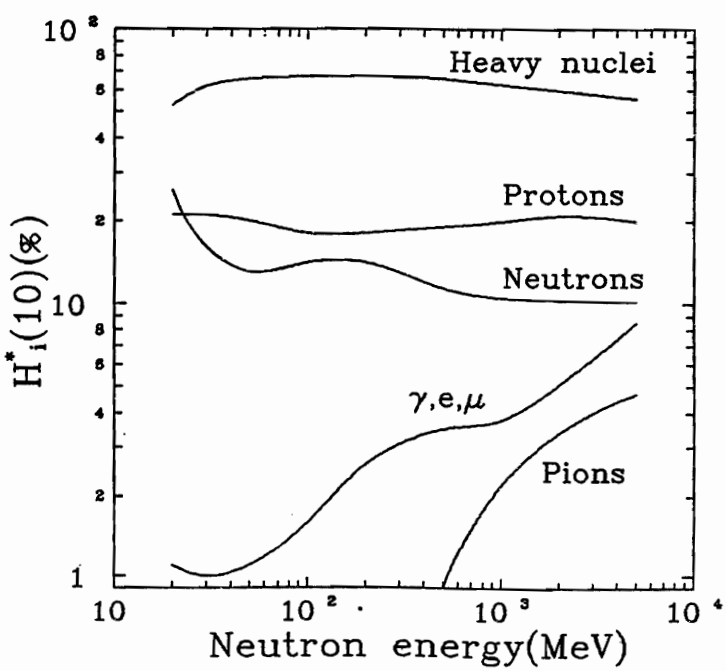

Fig. 13. Contribution of different components to the total ambient dose equivalent calculated using the ICRP-60 $Q(L)$-relationship.

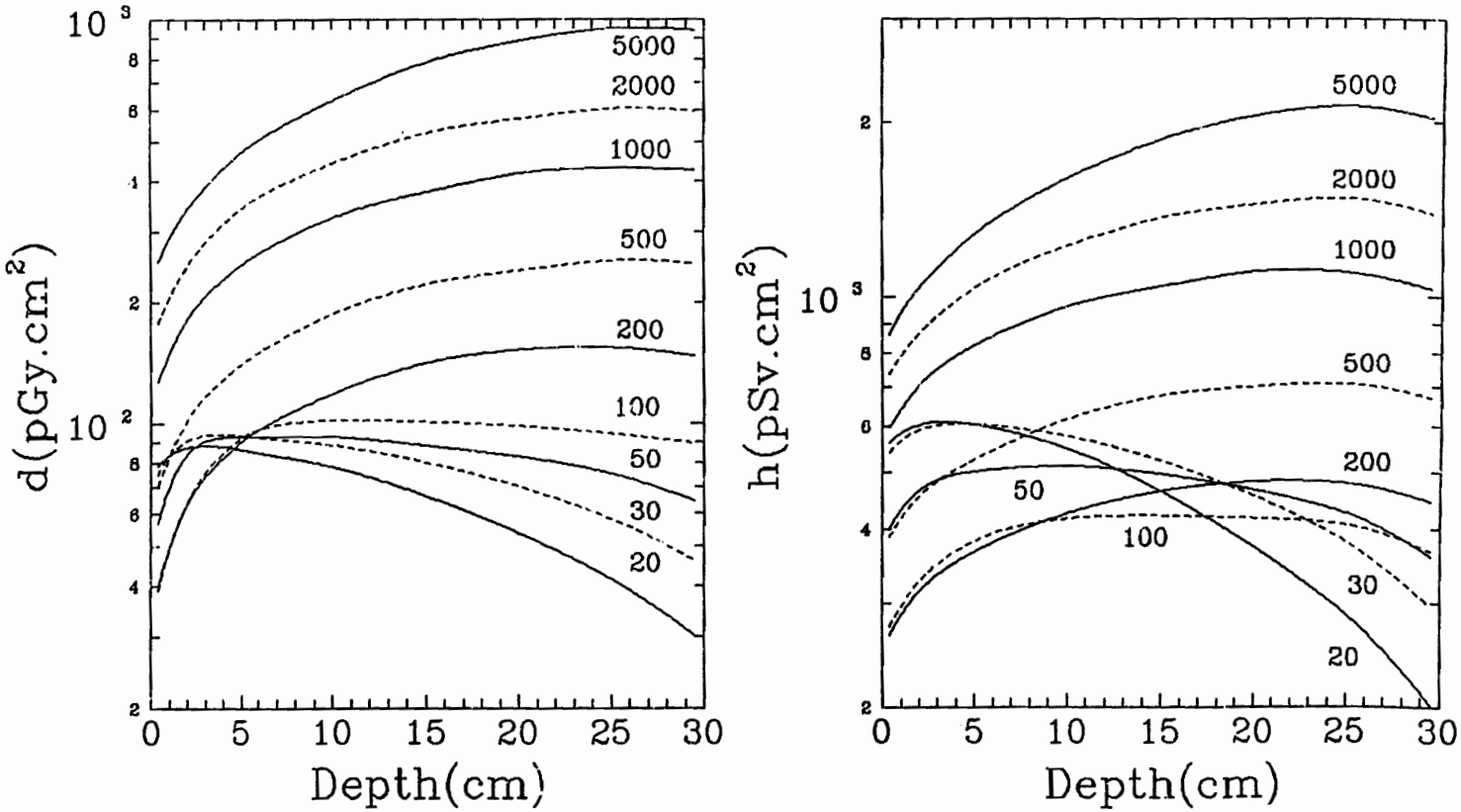

Fig. 14. Depth dose and depth dose equivalent distributions calculated using the ICRP-60 $Q(L)$-dependence for different neutron energies.

In our opinion, the common shortcoming of considered proposals is that they are based on the unrealistic situation of exposure by *monoenergetic* high energy particles that never takes place in practice. The only cases where such conditions exist are specially prepared particle beams with strongly restricted admittance at high energy accelerators. In those very rare cases when exposure of a personal by high energy beams happens, this is a subject of accidental dosimetry. In all the practical situations, exposure of a personal and public takes place in the conditions of equilibrium spectra outside shields where high energy particles are accompanied by a large number of low energy secondaries. No build-up effect exists therefore for equilibrium high energy spectra and the maximum of dose equivalent lies near the phantom surface. This is an obvious statement made earlier in different calculational and experimental works. An additional confirmation may be found in reference [34] devoted to the recent study of build-up effects in high energy radiation fields at CERN. The practical conclusion of this consideration is that there is no necessity to introduce any innovations to the definition of ambient dose equivalent $H^*(10)$ which seem to be successful and long-stable.

4. Conclusions

The new approach based on the extension of the kerma concept to high energy region was applied to calculations of the ambient dose equivalent conversion factors for high energy neutrons. The calculations were performed in the geometry of a normal irradiation of an infinite slab 30 cm thick by monoenergetic neutrons with energies of 20-5000 MeV. In all the calculations of partial kerma factors and quality factors for high energy hadrons as well as in transport calculations, the modified version of high energy transport code HADRON was used. The obtained data for ambient absorbed dose, ambient dose equivalent and effective quality factor for two $Q(L)$-dependences recommended by the ICRP are presented in Table 1 for 21 neutron energies.

The extensive comparison with the data of previous calculations have shown that the phantom shape and dimension do not play an important role for ambient dose equivalent results in high energy region. Discrepancies between different calculations are explained mainly by the approximate methods of estimating the quality factors of secondary charged particles produced by high energy hadrons. Another reason is large statistical errors in most of earlier calculations. The statistical uncertainties of the present data for ambient dose equivalent are less than 1%.

In contrast to the recent data of Nabelssi and Hertel for 30-180 MeV neutrons, the ICRP-60 based quality factors are lower than the ICRP-21 ones below 130 MeV and higher above this energy. As expected, these differences are not large and do not exceed 10%. Analysis of applicability of the ambient dose equivalent $H^*(10)$ for high energy particles enables us to make a conclusion that in all the practical situations of equilibrium high energy spectra outside shields this quantity provides a conservative estimation both for maximum dose equivalent and effective dose equivalent.

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Table 1. Ambient dose and ambient dose equivalent conversion factors for high energy neutrons calculated using the ICRP-21 and ICRP-60 $Q(L)$-relationships

E_n (MeV)	$d^*(10)$ $(pGy \cdot cm^2)$	ICRP-21 $h^*(10)$ $(pSv \cdot cm^2)$	ICRP-21 $Q^*(10)$ (Sv/Gy)	ICRP-60 $h^*(10)$ $(pSv \cdot cm^2)$	ICRP-60 $Q^*(10)$ (Sv/Gy)
20	85.1	606	7.12	591	6.94
25	88.4	613	6.93	586	6.63
30	91.0	620	6.81	586	6.44
40	85.7	573	6.69	528	6.16
50	74.7	488	6.53	440	5.89
60	65.0	419	6.45	377	5.80
80	54.8	345	6.30	320	5.84
100	50.9	313	6.15	300	5.89
150	49.1	280	5.70	285	5.80
200	51.0	275	5.39	285	5.59
300	57.6	293	5.09	306	5.31
400	68.1	334	4.90	349	5.12
500	84.8	393	4.63	420	4.95
600	102	450	4.41	487	4.77
800	130	529	4.07	580	4.46
1000	153	591	3.86	647	4.23
1500	188	677	3.60	733	3.90
2000	211	728	3.45	789	3.74
3000	245	791	3.23	862	3.52
4000	270	837	3.10	915	3.39
5000	290	870	3.00	951	3.28

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