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Vectorial and plane energy fluences - useful concepts in radiation physics

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by

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I. Introduction

In determinations of absorbed dose, knowledge of the directions of motion of the ionizing particles is often uninteresting. As a consequence the use of vectorial physical quantities describing the radiation field is rare in radiation dosimetry literature.

Since WHYTE 1956 popularized the quantity plane intensity, this scalar quantity has more or less been forgotten. In present day terminology "plane intensity" should be called "plane energy flux density" or "plane energy fluence rate". The plane energy fluence rate is a useful quantity in cases with plane irradiation geometries. The plane energy fluence rate is closely related to the vectorial energy fluence rate.

In the following we prefer to work with the time integral of these quantities, i.e. with plane and vectorial energy fluence. Vectorial energy fluence has been used by ROSSI and ROESCH 1962, ROESCH 1968, SPENCER 1971, ALM CARLSSON and others.

II. Definitions of quantities in the radiation field

At spectral measurements or calculations in and around phantoms or radiation shields, one determines kinetic energy (T), direction ($\vec{\Omega}$), and number (N) of ionizing particles (photons, neutrons, ...). Some fundamental quantities in the radiation field will therefore be described differentiated in kinetic energy and direction. Time and other eventual variables are neglected. The quantities defined here are nonstochastic corresponding to expectation values and a continously varying radiation field.

1. Fluence, Φ, is defined (ICRU 1971)

$$\Phi = \frac{dN}{da} \qquad \text{(1)}$$

where N is the number of particles which enter a sphere of cross-sectional area a. In differential terms Φ can be written

$$\Phi = \iint \frac{\partial^2 \Phi(T,\vec{\Omega})}{\partial T \partial \Omega}\, dT d\Omega \qquad \text{(2)}$$

The differential terms are added scalarly.

2. Vectorial fluence, $\vec{\Phi}$, is defined

$$\vec{\Phi} = \iint \frac{\partial^2 \Phi(T,\vec{\Omega})}{\partial T \partial \Omega}\, \vec{\Omega}\, dT d\Omega \qquad \text{(3)}$$

where $\vec{\Omega}$ is a unit vector with the same direction as the particle. The vectorial addition gives both size and direction of the resultant.

$$|\vec{\Phi}| \leq \Phi \qquad \text{(4)}$$

3. Plane fluence, Φ_{pl}, is defined

$$\Phi_{pl} = \iint \frac{\partial^2 \Phi(T,\vec{\Omega})}{\partial T \partial \Omega}\, \vec{A}\cdot\vec{\Omega}\, dT d\Omega \qquad \text{(5)}$$

where $\vec{A}$ is a unit vector perpendicular to a given plane. As $\vec{A}$ is a fix vector it can be taken out from the integral

$$\Phi_{pl} = \vec{A}\cdot\vec{\Phi} \qquad \text{(6)}$$

The scalar quantity plane fluence can adopt positive as well as negative values.

$$|\Phi_{pl}| \leq |\vec{\Phi}| \leq \Phi \qquad \text{...........} \quad (7)$$

The scalar product of the unit vector $\vec{A}$ and the unit vector $\vec{\Omega}_{\vec{\Phi}}$ that gives the resultant direction of $\vec{\Phi}$ is $\cos\theta$, where θ is the angle between the two vectors, fig 1.

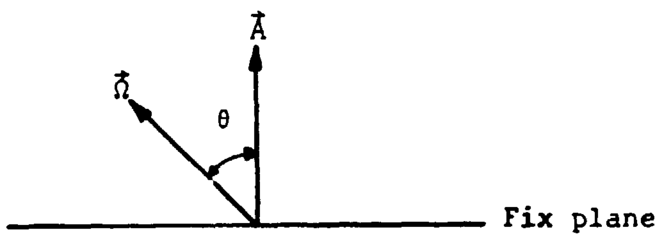

Fig 1: $\vec{\Omega}$ is a unit vector in the direction of a particle or of the vectorial fluence. $\vec{A}$ is a unit vector perpendicular to a fix plane. $\vec{A}\cdot\vec{\Omega} = \cos\theta$, where θ is the angle between the two vectors.

4. Energy fluence, Ψ, is defined (ICRU 1971)

$$\Psi = \frac{dE_{fl}}{da} \qquad \text{...........} \quad (8)$$

where E_{fl} is the sum of the kinetic energies of all the ionizing particles which enter a sphere of cross-sectional area a. In differential terms Ψ can be written

$$\Psi = \iint \frac{\partial^2\Phi(T,\vec{\Omega})}{\partial T \partial \Omega} \, T \, dT d\Omega \qquad \text{...........} \quad (9)$$

5. Vectorial energy fluence, $\vec{\Psi}$, is defined

$$\vec{\Psi} = \iint \frac{\partial^2 \Phi(T,\vec{\Omega})}{\partial T \partial \Omega} \, T \, \vec{\Omega} \, dT d\Omega \qquad \text{.......... (10)}$$

6. Plane energy fluence, Ψ_{pl}, is defined

$$\Psi_{pl} = \iint \frac{\partial^2 \Phi(T,\vec{\Omega})}{\partial T \partial \Omega} \, T \, \vec{\Omega} \cdot \vec{A} \, dT d\Omega \qquad \text{.......... (11)}$$

and

$$\Psi_{pl} = \vec{A} \cdot \vec{\Psi} \qquad \text{.......... (12)}$$

Parallel to eq 7 the following is valid

$$|\Psi_{pl}| \le |\vec{\Psi}| \le \Psi \qquad \text{.......... (13)}$$

III. Energy transport through a plane

Consider a fix plane, the direction of which is defined by a unit vector $\vec{A}$ perpendicular to this plane. An area element dA of the plane is chosen so small that the fluence can be considered constant over it. The energy transport of ionizing particles with directions of motion contained in a solid angle element $d\Omega$ around $\vec{\Omega}$ through the area element dA can then, fig 2, be written:

$$\frac{d\Psi}{d\Omega} \, d\Omega \, dA \cos\theta = \frac{d\vec{\Psi}}{d\Omega} \cdot d\vec{A} \, d\Omega \qquad \text{.......... (15)}$$

where $d\vec{A} = dA \, \vec{A}$.

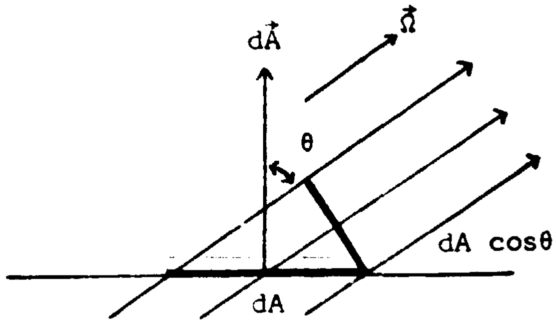

Fig 2: The energy transport through the area element dA of radiation with direction $\vec{\Omega}$ is the same as through the area dA cosθ in a plane normal to the radiation.

Integrating eq 15 over all directions gives the net transport of energy through the area element:

$$\int_{4\pi} \frac{d\vec{\Psi}}{d\Omega} \cdot d\vec{A}\, d\Omega = dA \int_{4\pi} \frac{d\vec{\Psi}}{d\Omega} \cdot \vec{A}\, d\Omega = dA\, \Psi_{pl} \qquad \ldots\ldots\ (16)$$

The net energy transport is the product of plane energy fluence and area. The energy transport is counted positive when the angle between the directions $\vec{\Omega}$ and $\vec{A}$ is acute and negative when it is obtuse.

The net energy transport through the whole of the extended plane is given by:

$$\int_S \Psi_{pl}\, dA \qquad \ldots\ldots\ldots\ (17)$$

where S is the surface of the plane.

The plane fluence is a useful quantity in problems with plane geometries as, for instance, in slab penetration problems, or the determination of energy imparted to a plane detector that is thick for the incident radiation.

In eqs 15 - 17 the symbols for the different energy fluences Ψ, $\vec{\Psi}$ and Ψ_{pl} include all types of ionizing particles. In practical work it is sometimes necessary to determine the energy fluence of each type, <u>i</u>, of ionizing particles present. That is:

$$\Psi = \Sigma\Psi_i \qquad (18)$$

IV. Comparison of energy fluence and plane energy fluence

The difference between energy fluence and plane energy fluence is illustrated in fig 3, where perpendicularly incident radiation is deviated in a slab of a non-absorbing material in the direction θ without any energy degradation. The two thick horizontal lines represent a unit area perpendicular to the direction of the incident radiation, while the two circles represent spheres with cross-sections of unit area (CARLSSON and LIDÉN, WHYTE).

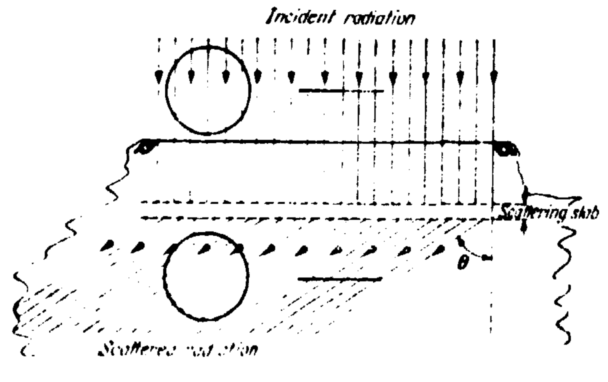

Fig 3: The difference between energy fluence and plane energy fluence (CARLSSON and LIDÉN).

In this hypothetical case the plane energy fluence is the same on both sides of the scattering slab whereas the energy fluence is increased due to the scattering.

The plane energy fluence is equal the energy fluence when the radiation direction is the same as the direction $\vec{A}$ of the plane. Evidently plane as well as vectorial energy fluences are zero for isotropic radiation.

V. Energy transport through a closed surface

Consider a closed surface, fig 4, and a surface element dA small enough to be regarded as plane. The area vector $d\vec{A}$ perpendicular to the surface element is pointed into the volume described by the closed surface. The net energy transport through the surface element is $\vec{\Psi}\cdot d\vec{A}$ (cf eq 15).

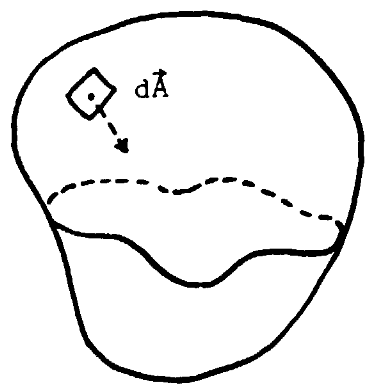

Fig 4: The net energy transport by ionizing particles through a closed surface S(V) gives the mean energy imparted to the described volume from external radiation sources provided no nuclear or elementary particle reactions are initiated within the volume.

The net energy transport through the whole surface is equal to the mean energy imparted, $\bar{\varepsilon}$, to the volume when no internal radiation sources are present and no transformations of nuclei or elementary particles occur in the volume:

$$\bar{\varepsilon} = \oiint_{S(V)} \vec{\Psi} \cdot d\vec{A} = \oiint_{S(V)} \vec{\Psi}_{in} \cdot d\vec{A} + \oiint_{S(V)} \vec{\Psi}_{out} \cdot d\vec{A} =$$

$$= \overline{\Sigma T}_{in} - \overline{\Sigma T}_{out} \qquad \text{..........} \quad (19)$$

Here, $\overline{\Sigma T}$ is the expectation value of the sum of kinetic energies of ionizing particles, <u>in</u> indicates particles entering the volume and <u>out</u> particles leaving the volume. S(V) is the surface circumscribing the volume V.
The definition of energy imparted follows ICRU, but the symbols and nomenclature is modified after ALM CARLSSON 1978.

In measurements of mean energy imparted to an object (patient) from an external radiation source, it is practical to determine the energy transport in to and out from the object separately.

A totally absorbing detector, screened to receive radiation only through its surface, measures the scalar product of the vectorial energy fluence and the area vector of the detector surface integrated over the surface area of the detector. If this detector describes a convex surface circumscribing the radiation source and the irradiated object, the radiation energy escaping from the object is measured, fig 5 (provided the material between the object and the detector attenuates the radiation only negligibly).

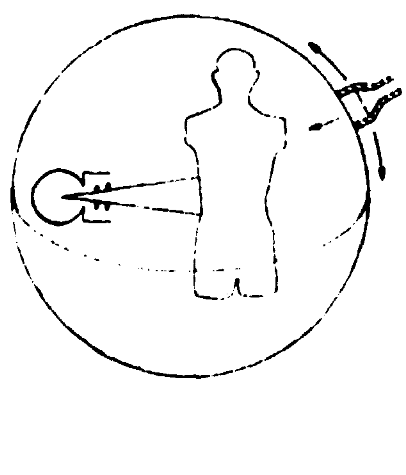

Fig 5: Measurement of the energy scattered and transmitted by a phantom. The totally absorbing detector has to describe the whole sphere, circumscribing the phantom and roentgen unit, CARLSSON 1964.

VI. Quantities describing back-scattering of ionizing particles

The back-scattering properties of a medium can be expressed in terms either of its albedo or its reflection-coefficient (backscatter-coefficient). Here, these quantities are discussed in order to derive useful relations between the plane energy fluence and the energy fluence at points on an extended plane surface.

Albedo is defined as the fraction of a physical quantity that is reflected. Only two quantities are appropriate to use (CARLSSON 1969).

1. Number albedo, A_N

$$A_N = \frac{N_{refl}}{N_{in}} \qquad \text{.......... (20)}$$

where N is the number of ionizing particles traversing a fix plane. Indices in stands for incident radiation and refl for reflected radiation.

The fix plane is usually the surface of a semiinfinite medium, but may be a plane on the same side of an arbitrary body as the radiation source (CARLSSON 1969).

2. Energy albedo, A_E

$$A_E = \frac{E_{refl}}{E_{in}} \qquad \text{.......... (21)}$$

where E is the sum of kinetic energies of all ionizing particles traversing a fix plane and the indices have the meaning given above.

Buildup factors and reflection coefficients are defined according to (3)-(6):

3. Number buildup factor, B_N

$$B_N = \frac{\Phi_p + \Phi_s}{\Phi_p} \qquad \text{(22)}$$

Here Φ is the fluence of primary, p, and secondary, s, ionizing particles. The buildup factors vary with depth in the medium.

4. Number reflection coefficient, R_N

$$R_N = B_{N_0} - 1 = \frac{\Phi_{s_0}}{\Phi_{p_0}} \qquad \text{(23)}$$

Here index 0 stands for depth zero in the medium.

5. Energy buildup factor, B_E

$$B_E = \frac{\Psi_p + \Psi_s}{\Psi_p} \qquad \text{(24)}$$

where Ψ is the energy fluence.

6. Energy reflection coefficient, R_E

$$R_E = B_{E_0} - 1 = \frac{\Psi_{s_0}}{\Psi_{p_0}} \qquad \text{(25)}$$

Presume a case with a plane interface between a medium and vacuum and the radiation incident from the vacuum. The medium is homogeneously irradiated by the incident radiation over the whole plane (field area ∞). Then, all field quantities of scattered radiation are constant over the same plane field area and the albedos and reflection coefficients can be written:

$$A_N = \frac{\Phi_{pl_{refl}}}{\Phi_{pl_{in}}} \qquad \text{..........} \quad (26)$$

$$R_N = \frac{\Phi_{refl}}{\Phi_{in}} \qquad \text{..........} \quad (27)$$

$$A_E = \frac{\Psi_{pl_{refl}}}{\Psi_{pl_{in}}} \qquad \text{..........} \quad (28)$$

$$R_E = \frac{\Psi_{refl}}{\Psi_{in}} \qquad \text{..........} \quad (29)$$

The special case with the incident radiation perpendicular to the surface gives:

$$\Psi_{pl_{in}} = \Psi_{in} \qquad \text{..........} \quad (30)$$

and

$$\frac{A_E}{R_E} = \frac{\Psi_{pl_{refl}}}{\Psi_{refl}} \qquad \text{..........} \quad (31)$$

VII. Backscattering of photons from water

The backscattered radiation from a water surface irradiated with perpendicularly incident, heavily filtered roentgen radiation, with mean energy 114 keV, is approximately isotropic, fig 6 (HETTINGER), at the center of a 50 cm^2 irradiated field.

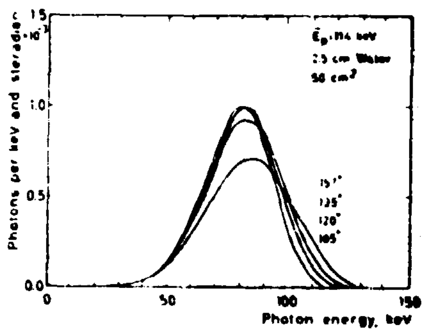

Fig 6: Spectra of radiation backscattered in different directions (θ = 105°, 120°, 135° and 157°) for a primary photon with $\bar{E}_p$ = 114 keV (HETTINGER).

In the case of isotropic radiation the ratio between the plane energy fluence and energy fluence is

$$\frac{\Psi_{pl}}{\Psi} = \frac{\iint \frac{\partial^2 \Phi(T,\vec{\Omega})}{\partial T \partial \Omega} \, T\vec{\Omega}\cdot\vec{A} dT d\Omega}{\iint \frac{\partial^2 \Phi(T,\vec{\Omega})}{\partial T \partial \Omega} \, T dT d\Omega} =$$

$$= \frac{\int_0^{2\pi} 2\pi \sin\theta \, \cos\theta \, d\theta \quad \int T \frac{d\Phi(T)}{dT} \, dT}{\int_0^{2\pi} 2\pi \sin\theta \, d\theta \, \int T \frac{d\Phi(T)}{dT} \, dT} = \frac{1}{2} \qquad \text{.......... (32)}$$

A comparison (CARLSSON and LIDÉN) of Monte Carlo calculations of energy albedos (BERGER and RASO) and reflection coefficients (BERGER and DOGGETT) of normally incident photons on a semi-infinite water layer show in the overlapping energy region that the energy albedo is about half of the energy reflection coefficient.

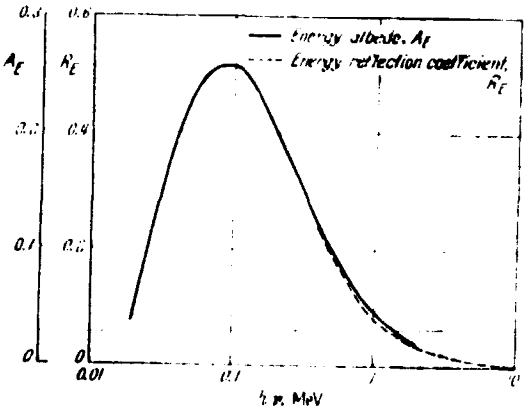

Fig 7: A comparison between the energy albedo (A_E calculated by BERGER and RASO, 1960) and the energy reflection coefficient, R_E, calculated by BERGER and DOGGETT (1956). The semi-infinite medium is water and a plane-perpendicular source has been used. In overlapping regions the two curves almost coincide in the ordinate scales given. (CARLSSON and LIDÉN).

This means that the plane energy fluence, under these circumstances, is about half of the energy fluence, eq 31. In turn, this indicates that the reflected (backscattered) radiation is isotropic, cf. eq 32. The conditions at the center of the 50 cm^2 irradiated field approaches the conditions at the surface of the semi-infinite medium.

VIII. Examples of erroneous use of energy fluence instead of vectorial or plane energy fluence

ZIELER attempted to determine the mean energy imparted, $\bar{\varepsilon}$, (integral absorbed dose) to patients undergoing roentgen diagnostic examinations. In calibration experiments he used parallell-epipedic water phantoms and measured the product of exposure, X, and area for the escaping as well as for the incident radiation. He determined the energy fluence from the relation:

$$X = \left(\frac{\overline{\mu_{en}}}{\rho}\right)_{air} \cdot \Psi \cdot \frac{e}{\bar{W}} \qquad \text{.......... (33)}$$

where e is the electronic charge and $\bar{W}$ is the mean energy expended in a gas per ion pair formed. The average value of the mass energy absorption coefficient was that valid for monoenergetic photons with the same exposure half value layer as the actual radiation.

From these measurements he wrongly estimated the mean energy imparted to a patient as:

$$\bar{\varepsilon} = \int \Psi_{in}\, dA - \int \Psi_{out}\, dA \qquad \text{.......... (34)}$$

The true expression is given in eq 19, that is, both energy fluence and area should be vectorial. In this case with plane sides the escaping radiation could from each side be calculated as the product of plane energy fluence and area, eq 17.

According to section VII and assuming the scattered radiation to be isotropic at all the plane surfaces of the parallell-epipedic phantom ZIELER overestimated the escaping energy with a factor of about two. He used two radiation qualities, 60 kV and 100 kV and received with increasing voltage, decreasing mean energy imparted per unit of the product of exposure and field area of the incident radiation, fig 8 (CARLSSON, 1963). If he had increased the voltage further he could easily received negative values of the mean energy imparted.

STRID made two experiments in order to determine the effect of scattered as well as of primary roentgen radiation on the intensifying screens used in diagnostic radiology.

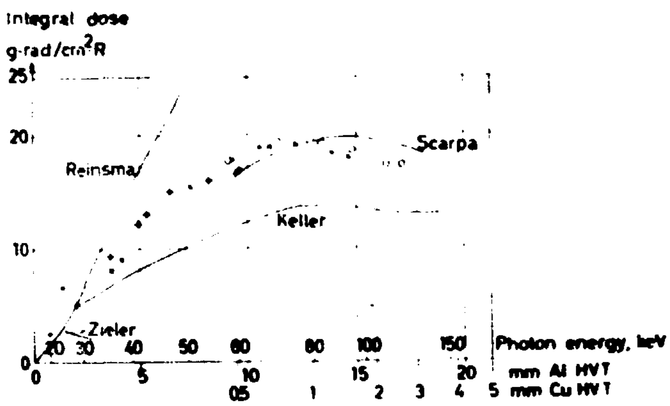

Fig 8: Mean energy imparted to a slab of 20 cm water per unit area and exposure calculated by different authors. The symbols are the results by CARLSSON 1963.

When measuring the optical density of the film between the intensifying screens, he found, that in his geometry, the scattered radiation contributed to the mean energy imparted to the screens with a factor of 6.6 more than the primary radiation did. No secondary radiation grid was used.

As the screens absorbs much more than half of the scattered radiation (nearly totally absorbing), this experiment gave results approximately proportional to the quotient between the plane energy fluences of the scattered and the primary radiation at the screens.

In the second experiment he used a thin ionization chamber as detector. The detector received collimated scattered radiation emitted from a small area on the back side of the scattering water phantom. He determined the exposure caused by the angular distribution of scattered radiation and integrated it over the solid angle 2π. He concluded that the scattered radiation contributed to the effect on roentgen film between screens with a factor of [illegible].5 more than the primary radiation did, in disagreement with his first experiment. The latter experiment, however, gives results approximately proportional to the quotient between the energy fluences of the scattered and primary radiation at the screens as the exposure is proportional to the energy fluence, eq 33. STRID had problems to explain this difference, but again the mistake was to use the quantity energy fluence when plane energy fluence is correct (eq 34 instead of eq 19 or eq 17). As the scattered radiation at the rear of a water layer is not as isotropic as the backscattered radiation (BJÄRNGARD and HETTINGER 1961) the results from eqs 34 and 19 should deviate less than a factor of two.

In an interesting article about image information content and exposure MOTZ and DANOS conclude that "the basic quantity for information is the number of X-ray photons per area of the spatial resolution element that are detected at the image plane by the imaging system". In their following mathematical treatment of the problem, they incorrectly set this number proportional to the fluence when it is proportional to the plane fluence.

In ICRU Report 14 the total beam energy is explained to be "the energy fluence integrated over the area of the incident beam". This explanation is correct only if the beam area is perpendicular to all the rays in the beam. Evidently ICRU discussed primary radiation and there is no reason for misunderstanding. MOTZ and DANOS, however, used the same method for diagnostic radiation including scattered radiation created in the transport through the patient.

It is my impression that mistakes of this kind is more frequent today than before. The explanation is perhaps that medical radiology now benefits by more physics experts with other background than radiation physics. To prevent further mistakes it could be valuable if ICRU introduced vectorial and plane fluences in their compilation of important radiation physical quantities. Awaiting these quantities and problems being introduced in text books in radiation dosimetry, this report hopefully may help to prevent further mistakes like them examplified.

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