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DOSE EQUIVALENT AND QUALITY FACTOR OF RADIATION FROM HIGH ENERGY ACCELERATORS

M. Höfert

A B S T R A C T

Health Physics measurements around high energy accelerators are difficult because of the varying composition of radiation fields. The presence of neutrons as well as charged particles above 10 MeV contributing considerably to the total dose means another complication. Thus concepts in the field of radiation protection are under constant review and have to be adapted to the assessment of radiation risks in accelerator installations.

Some criticism voiced in the past and concerning the application of quantities has been overcome to a great extent with the Publication 15 of the ICRP. Definitions of dose equivalent and quality factor are now unambiguous and straightforward and different propositions for the assessment of the two quantities in mixed radiation fields including high energy are outlined in this publication.

Taking radiation protection measurements made near the CERN accelerators as an example, it will be shown that there is no need for introducing new concepts like the dose equivalent index as presented recently in the ICRU Publication 19. Practical results will rather call for logical simplifications allowing for better correlations between survey methods (anticipatory measurements) and methods used for the control of exposure to individuals (simultaneous measurements) than justify the introduction of new complications.

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1. INTRODUCTION

In the early days of radiation protection it was readily accepted that the risk for a person in a radiation field should be related to the amount of radiation he is exposed to. Subsequently the idea of defining a quantity "exposure" for x- and γ-radiation was born and radiation protection standards were given in units of "Röntgen".

Refinements of dosimetric quantities at a later stage saw however:

(a) The introduction of "absorbed dose" and
(b) the consideration of a higher biological efficiency for more densely ionizing radiations like α-particles and neutrons.

The first modification - to introduce the energy absorbed in body tissue as a measure of radiation dose - was born out of requirements in radiation therapy and the need of depth dose distributions. Subsequently the "rad" was adopted in radiation protection work, although it becomes rather complicated to relate external exposure to absorbed dose in tissue, the latter not being directly measurable in the body.

The second refinement was necessary due to the existance of a Relative Biological Efficiency for different radiations. Difficulties arose when experimental RBE values were examined to derive factors for a modification of absorbed dose, thus becoming the dose equivalent for radiation protection purposes. In their extensive and scrutinized report the RBE Committee gave only meagre support to the ICRP practice of linking the so-called Quality Factor to Linear Energy Transfer: as the recommended values are admittedly based on scanty evidence they saw no reason to depart from the well-known table relating QF and stopping power in water[1].

Although Health Physics voluntarily accepted ideas and dosimetric quantities from radiotherapy and radiobiology the direction of work at that stage was already largely separated.

Radiobiologists interested in radiation protection work and with them the ICRP tend to regard the dose equivalent still to be rather an equivalent dose leading to the same late effects. Furthermore, when regarding large populations the term "manrad" is more often employed than "manrem".

Health Physicists, however, see a whole world of research activities linked to the definitions of dose equivalent and quality factor in terms of stopping power ranging from Monte-Carlo calculations in complex body phantoms to LET-spectroscopy.

2. THE DEVELOPMENT OF HEALTH PHYSICS

In its Publication 19 the ICRU has given its blessing to the physical approach and for the first time defined dose equivalent as a physical field quantity varying throughout the body of a person exposed to an external radiation field[2]. Already in the past efforts by health physicists centred around the determination of a maximum value of dose equivalent in the body or rather in a suitable body phantom. It is, however, worthwhile to note that the ICRP never really cared for this kind of activity but was rather worried about doses to critical organs, for example bone marrow and gonads in case of an approximately uniform irradiation of the whole body[3]. As it is difficult or even impossible to determine the dose equivalent at the points of interest (the critical organs) for any radiation condition, the maximum dose equivalent in the body is an acceptable approximation although it tends to over-estimate the radiation risk.

Further overestimations, however, were introduced by attempts to do the physics correctly[4]. The method of solving the problem of maximum dose equivalent in the body by means of neutron spectroscopy seems straightforward but is doomed to failure around high energy accelerators due to several reasons:

(a) Neutron spectroscopy in situations of daily practice can hardly

be performed and, if at all, resulting spectra are ambiguous with current techniques.

(b) Stray fields encountered routinely have several components and the non-neutron components are generally ignored.

(c) As Monte-Carlo calculations with an experimentally determined spectrum are cumbersome the method relies on the availability of fluence-to-dose equivalent conversion factors for mono-energetic neutrons giving the maximum dose equivalent for mono-directional parallel beams in specifically chosen body phantom geometries. As in most practical cases (stray fields) incident neutrons are largely isotropic and in reasonable equilibrium with their secondaries, the values determined with the above mentioned conversion factors are a gross overestimation for the true maximum of dose equivalent in the body.

(d) Anticipatory measurements performed with this method hardly bear any relation to simultaneous measurements, i.e. to results of personal dosimeters worn on the body surface in external radiation fields.

Dosimetry methods and techniques in radiation protection on the contrary should be uncomplicated and easy to perform in practice. At the same time basic features of the irradiation conditions encountered can be taken into consideration. The fact that in nearly all cases stray fields have to be assessed around high energy accelerators leads to several consequences:

(1) Fluence-to-dose equivalent conversion factors for particles in equilibrium with their secondaries as endorsed by the ICRP in the past are more realistic than those for mono-energetic beams. The response of the ANDERSON and BRAUN rem counter is based on these figures. This instrument gives good estimations for the dose equivalent of the neutron component up to 10 MeV.

(2) Maximum values of dose equivalent in stray fields are encountered near the body surface due to the isotropic character and the equilibrium condition of the external radiation field. Mono-energetic parallel beams where considerably build-up is

present are a feature of radiation therapy and hardly a problem in routine protection work.

(3) The critical organs in case of a whole-body irradiation lie near to the body surface. This is the place where personal dosimeters are worn. Thus the dose equivalent to which a person in an external stray field of mixed composition is exposed is rather well correlated to simultaneous measurements at the body surface.

It will be shown that CERN radiation survey practice takes the above mentioned facts into account but first new quantities introduced by the ICRU will be discussed in the light of their usefulness in routine health physics work.

3. THE DOSE AND DOSE EQUIVALENT INDEX

Recently the ICRU has proposed two new quantities in their Report 19: dose index and dose equivalent index. These quantities are defined as the maximum of dose, resp. dose equivalent in a tissue equivalent sphere of 30 cm diameter of unit density. Three remarks made by the ICRU are worthwhile to be mentioned in this context:

(a) The index quantities characterize the radiation field for protection purposes.

(b) They are regarded to be an approximation to the maximum dose and dose equivalent respectively in the human body in case of a whole body irradiation.

(c) They are not to be employed as a basis for a different formulation of permissible dose levels.

Difficulties to assess these index quantities in routine practice have already been mentioned elsewhere [5]. In this case it would be much better if efforts were diverted from the determination of this integral quantity to acquire complete differential information of the spectral composition. The latter not only gives a better characterization of the radiation field but also allows for the evaluation of any integral quantity.

As for the approximation to the dose equivalent in the human body in case of a whole-body irradiation it is clear from the remarks made above that H_I is not equal to the true dose equivalent maximum and any other approximation H_{meas} acquired by a suitable measurement method may be a better fit to H_{true} than H_I. It can be argued that there is still a benefit in this index quantity as - when used generally in different installations - it will allow for the comparison of results, although in the characterization of radiation risk everybody will make the same error. If this holds and the dose equivalent index is meant to characterize the radiation risk, then the need for the quantity dose index is hardly understood.

The ICRU states that permissible dose levels should not be employed in terms of index quantities. This is a safeguard against the fact that in the future entries in legal records have to be made in terms of H_I . However, the temptation for physicists exists to realize this physical quantity in its own right and to its utmost precision when on the other hand it might bear but a small correlation with radiation risk.

4. A PRACTICAL SYSTEM FOR MEASUREMENTS AROUND HIGH ENERGY ACCELERATORS (see table)

The CERN radiation survey measurement set makes use of the principle of additivity for the dose equivalent [6]. The neutron component is determined with an ANDERSON and BRAUN rem ionization chamber which follows in its characteristics the ICRP fluence-to-dose equivalent conversion curve for particles in equilibrium with their secondaries. Particle equilibrium around thick outside shielding of a high energy accelerator is always present.

This is verified when studying the high energy particle component measured by the activation of ^{11}C from ^{12}C in a scintillation crystal. A fluence-to-dose equivalent conversion factor of 10 $cm^{-2}s^{-1}mrem^{-1}h$ is used to attain the high energy dose component of the total dose equivalent. In particle equilibrium the high energy component determines the accompanying secondaries. Thus

from experience a conversion factor of 3 $cm^{-2}s^{-1}mrem^{-1}h$ for the high energy component gives a rather good approximation for the total dose equivalent.

Finally the gamma and the charged particle components are deducted from a combined measurement with an air and a TE chamber.

The thus determined components of dose equivalent are added up for the total and by dividing with the TE dose an apparent quality factor may be calculated. This quality factor is found to be high (4-6) sidewards of the thick shielding showing the predominance of the neutron component, it is low (1-2) in the forward direction of the primary beam, where a minor component generally accompanies the stray field and thus reflects the physical radiation conditions expected.

A TE chamber working well below 1 mrad/h with excellent stability is the backbone of the CERN survey set for the following reasons:

(1) In looking into the value of the apparent quality factor a quick check on the validity of any complete measurement is performed.

(2) When multiplying the reading of the TE-chamber by five, a rather good (mostly over-) estimation of the dose equivalent is attained.

(3) Incorporated in a stationary monitor system - working in experimental areas around external targets at CERN - it allows for continual checks on the development of the radiation situation since apparent quality factors determined by a complete survey at the place of the monitor are rather stable and may be used to convert the reading of the TE chamber into dose equivalent values.

The CERN radiation survey system is based on a straightforward approach, it is simple to operate and gives reliable results in daily routine work.

5. CONCLUSIONS

The problems with the assessment of dose equivalent around high energy accelerators call for developments of dosimetry in several directions.

A further advancement of the TE chamber into an energy-independent tool for the measurement of absorbed dose would facilitate the dosimetry in mixed radiation fields considerably. This is important in view of the fact that trends are visible to separate the quality factor from its strict relation with LET.

There are two main reasons for this development:

(a) As evidence for a precise numerical dependence of biological risk on LET is lacking, it would be logical to return to the original meaning of quality factor, namely to assign specific factors to specific radiations. This practice already endorsed in Recommendation 4 of the ICRP could, for example, be extended to neutron sources of known energy and furthermore simplified by limiting oneself in most other circumstances to quality factors of 1, 3 and 10[7].

(b) The Linear Energy Transfer, on the whole far from describing some specific energy density absorbed locally (as the ICRP recommends using the stopping power instead), may lose its significance completely in the case of nuclear interactions which can hardly be described by this concept.

Before the ICRU provides us with new physical quantities we would rather like to have the ICRP voice its opinion on dose equivalent. The maximum dose equivalent in a body will surely always overestimate the dose to the critical organs but due to some synergistic effects on those organs the integral dose may imaginably play an important role and give a better correlation to radiation risk.

In the good old times health physicists sometimes found it difficult to understand what the ICRP meant by dose equivalent but

we were able to assess values which we thought were relevant to the radiation risk. Now we understand what the ICRU means by dose equivalent index but we are left with the difficulty that this quantity cannot be measured and still question ourselves as to its relevance to radiation risk.

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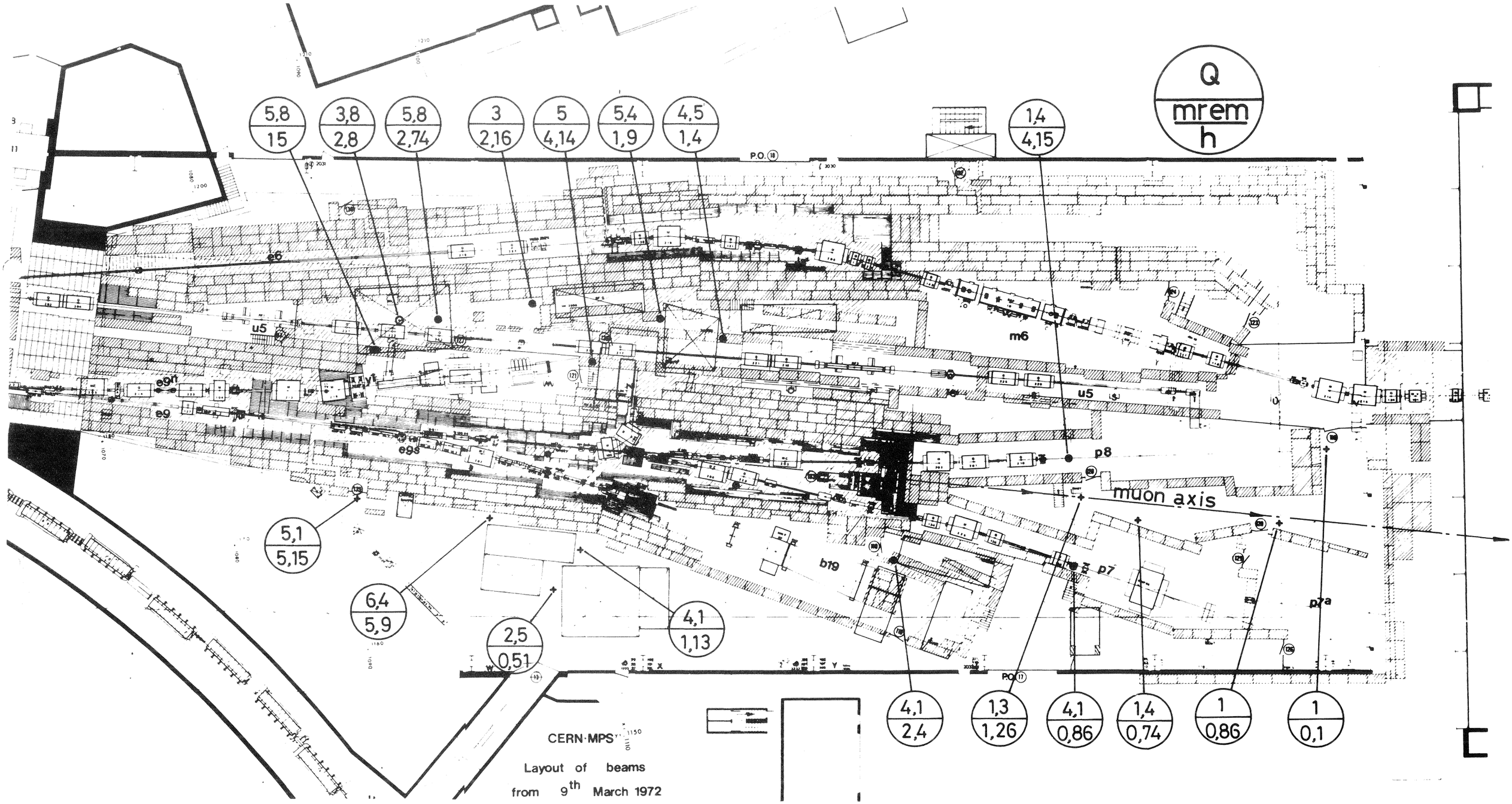
Table

CERN HEALTH PHYSICS MEASURING METHODS

Purpose (Instrument)	Features	Radiation measured				Total $\dot{H}$ or H evaluation	Apparent quality factor Q
		Neutrons <14 MeV	HE particles >20 MeV	γ	Absorbed dose		
Rapid survey (Search Monitor)	Portability Duty cycle independent	All radiations: H_2 filled ionization chamber			-	Direct reading of $\dot{H}_{Rapid}$	-
Routine survey (Cerberus)	Accurate analysis	$\dot{H}_{RIC}$ Rem Ion Chamber (RIC) or counter (RC)	$\dot{\phi}_{HEP}$ Flux density using C-11 activation	$\dot{D}_\gamma$ with CO_2 or air chamber (neutron correction with TE chamber)	$\dot{D}_{TE}$ with TE chamber	$\dot{H}_{total} = \dot{H}_{RIC} + 0.1\,\dot{\phi}_{HEP} + \dot{D}_\gamma$	$Q = \frac{\dot{H}_{total}}{\dot{D}_{TE}}$
Low-level continuous monitoring (Site Monitor Stations)	Sensitivity Reliability	H_{RC} with Rem counter (RC)	By correction (10% of H_{RC})	5 l 20 atm Argon/Air ion chamber	-	$H_{total} = 1.1\,H_{RC} + D_\gamma$	-



Routine Radiation Survey

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