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PAPER

New operational dose quantity ambient dose H^* in the context of galactic cosmic radiation in aviation

Daniel Matthiä*, Matthias M Meier and Kai Schennetten

German Aerospace Center, Institute of Aerospace Medicine, Linder Höhe, 51147 Cologne, Germany

* Author to whom any correspondence should be addressed.

E-mail: Daniel.Matthiae@dlr.de

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Abstract

The International Commission on Radiation Units and Measurements recently proposed new operational quantities for external radiation exposure. Among those, the ambient dose is intended to replace the ambient dose equivalent as estimator for the effective dose. Following its definition, the measurement of the ambient dose requires a much more detailed knowledge about the radiation field than the ambient dose equivalent. The implications for radiation protection in aviation concerning galactic cosmic radiation that would follow the adoption of the ambient dose as operational quantity at flight altitudes were investigated in this work using model calculations. It was found that the ambient dose is about 10% higher than the ambient dose equivalent for conditions relevant in commercial aviation and overestimates the effective dose by about 30%.

1. Introduction

The occupational radiation exposure of aircrew due to cosmic radiation has been legally regulated in the European Union (EU) and several other countries for many years (EU 1996, 2013). A fundamental legal requirement consists in the assessment of the exposure of the crews concerned in terms of the protection quantity effective dose E (ICRP 2007). Although E is not a measurable quantity, it can be well assessed using model calculations, e.g. PANDOCA (Matthiä *et al* 2014, Meier *et al* 2018) for operational purposes and legal obligations. In Germany, the PANDOCA model has been authorised by the competent authority, the Luftfahrtbundesamt (LBA, Federal Aviation Office) and has been used for dose assessment, e.g. at Lufthansa German Airlines, for many years. Furthermore, high quality and safety standards require regular measurements at flight altitude for the quality assurance of the model calculations. Since the radiation protection quantity E is not measurable, the ambient dose equivalent $H^*(10)$ (ICRU 1993) is defined as operational quantity and can be used for comparison with model calculations and dose assessment with suitable dosimeters. It was shown in Meier and Matthiä (2019) and Dumouchel *et al* (2016) that for galactic cosmic radiation (GCR) conditions encountered in aviation the ambient dose equivalent is a conservative estimator for the effective dose in its current definition which was adopted in ICRP (2007). In the PANDOCA model, both dose quantities are based on the energy dependent fluxes of different particles, i.e. protons, neutrons, photons, e^-, e^+, μ^-, μ^+, π^-, and π^+. The dose quantities E and $H^*(10)$ are derived from the same particle fluxes by multiplication with corresponding conversion factors, which are different for these quantities, and subsequent summation over all particle components. Therefore, the comparison of calculated values and dose rates for $H^*(10)$ with measurements provides also information about the quality of E based on the assumption that the respective conversion factors are correct. The experimental assessment of $H^*(10)$ can be achieved with tissue equivalent proportional counters (TEPCs).

Recently, the International Commission on Radiation Units and Measurements (ICRU) proposed new operational quantities (ICRU 2020). Among those, the ambient dose H^* is intended to replace the ambient dose equivalent $H^*(10)$ as estimator of the effective dose in the future. This represents a notable paradigm shift, since the new quantity H^* is not based on the linear energy transfer (LET) and the derived quality factor Q but on energy and particle type, which requires the sensitivity and calibration of measuring instruments for a single particle component within a defined range of energies only. As a consequence, direct, independent measurements in complex radiation fields, e.g. at aviation altitudes, as with the dose quantity $H^*(10)$ using a TEPC are not possible with the quantity H^* anymore. In this work, the relations between effective dose, ambient dose equivalent and ambient dose are investigated for the radiation field at aviation altitudes caused by galactic cosmic rays. For this purpose, model calculations were performed covering the relevant ranges of altitude, geomagnetic shielding and solar modulation.

2. Methodology

2.1. Operational quantities

Radiation protection in aviation is based on the protection quantity effective dose E, which is defined as the weighted double sum over the absorbed dose from different types of radiation and over a number of organs in a reference phantom using specific weighting factors for the different types of radiation and organs (ICRP 2007). The effective dose is not measurable and the International Commission on Radiological Protection (ICRP) defines an operational quantity to assess the effective dose: 'Operational quantities aim to provide a reasonable estimate, generally conservative, for the value of the protection quantities related to an exposure or potential exposure of persons under most irradiation conditions.' (ICRP 2010) Currently, the ambient dose equivalent $H^*(10)$ is used to estimate the effective dose E (ICRP 2007). $H^*(d)$, with $d = 10$ mm for $H^*(10)$, is defined as 'the dose equivalent that would be produced by the corresponding aligned and expanded field, in the ICRU sphere at a depth d, on the radius opposing the direction of the aligned field' (ICRU 1985, 1993). The dose equivalent, which is the underlying quantity for $H^*(10)$ is based on the quality factor Q(LET) which is a function of the unrestricted LET. For radiation protection, the LET can often be approximated by lineal energy which allows to determine the quality factor and the dose equivalent experimentally without prior knowledge about type and energy of the measured radiation, for instance with a TEPC. This is in contrast to the effective dose E, which is based on radiation weighting factors, defined by particle type and for neutrons also by energy (ICRP 2007). The newly proposed operational quantity H^* is based on fluence-to-dose conversion coefficients that are particle and energy dependent using the maximum value of several different irradiation geometries (ICRU 2020).

2.2. Dose measurements at aviation altitudes

Cosmic particles interact with the constituents of the upper atmosphere and generate a complex secondary radiation field at aviation altitudes which consists of different particle types with a large range of energies. Therefore, instruments for assessing the radiation dose are used, which do not need prior knowledge about type and energy of the radiation component. The fundamental dose quantity is the absorbed dose, which describes the absorbed energy per mass. This dose quantity depends on the absorber material. For a TEPC the energy deposition is similar to that in human tissue with a size of a few micrometers. A TEPC usually uses a spherical detection volume that is filled with a gas at low pressure and surrounded by tissue equivalent plastic (e.g. A-150). Operated as a proportional counter, this detector measures deposited energy per mean chord length of the detector volume. The spectra of lineal energy are good approximations of the unrestricted LET. The dose equivalent is obtained by applying the radiation quality factor Q(LET) to the LET spectra. An appropriate calibration of the instrument is necessary to obtain the ambient dose equivalent $H^*(10)$ from dose equivalent.

2.3. PANDOCA

The PANDOCA model (Matthiä *et al* 2014) was developed to calculate the radiation exposure in aviation. It is authorised by the German Federal Aviation Office (Luftfahrtbundesamt LBA) for the official assessment of radiation exposure of aircrew. Approved implementations of the model calculate the total ambient dose equivalent and effective dose according to different definitions of radiation and organ weighting factors (ICRP 1991, 2007) for a defined flight route; other versions for scientific applications additionally calculate total absorbed dose in water, tissue or silicon for defined flight routes and their rates along the flight path or for arbitrarily defined points in the atmosphere. PANDOCA has been validated against experimental data (Matthiä *et al* 2014, Meier *et al* 2018) and has shown agreement to measurements within 10%. For this work, fluence-to-dose conversion factors provided by ICRU (2020) have been used to additionally implement the calculation of the ambient dose H^* and its rate equivalently to the methodology described in (Matthiä *et al* 2014).

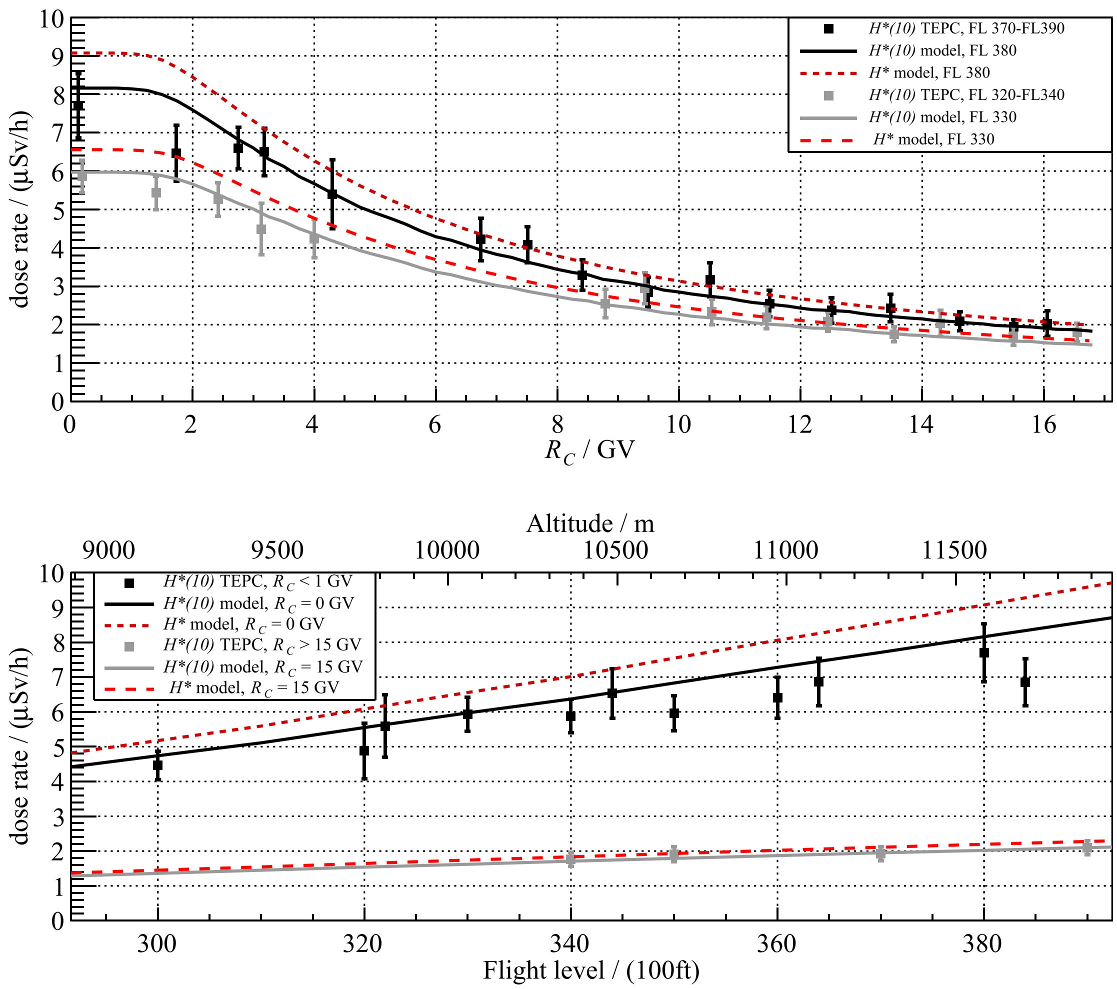

Figure 1. Measured and calculated dose rates from GCR of $H^*(10)$ in comparison to calculated dose rates of H^*. Top panel: dose rates vs cut-off rigidity R_c for two altitude regions; bottom panel: dose rates versus altitude for two cut-off rigidity regions. (Matthiä *et al* 2014) John Wiley & Sons.

The major factors impacting the dose rates in aviation are the atmospheric shielding provided by the residual atmosphere above the point of interest quantified by the flight altitude, the geomagnetic shielding from Earth's magnetic field parameterised by the effective vertical cut-off rigidity R_C, and the varying solar modulation of the primary galactic cosmic rays during the solar activity cycle; for details see (Matthiä *et al* 2014). In this work, it is investigated how the ambient dose compares to ambient dose equivalent and effective dose over the relevant range of these impact parameters, i.e. altitude ranges from FL280 to FL410 (28 000 ft to 41 000 ft; FL = flight level = 100 ft), geomagnetic shielding from $R_C = 0$ GV to 17 GV (Smart and Shea 2009) and solar maximum and solar minimum activity conditions. The lowest and highest geomagnetic shielding is reached at high and low latitudes, respectively. Values of W parameter of the galactic cosmic ray model (Matthiä *et al* 2013) applied in PANDOCA for solar minimum and maximum conditions were $W = 0$ and $W = 150$, respectively. These values of W correspond to extremes of the GCR intensity reached for instance in December 2009 and April/May 1990. The GCR intensity maximum during the recent solar activity minimum in 2020 was comparable to 2009 but GCR intensity minima during the more recent activity maxima were not as low as 1990.

3. Results

It was shown in earlier work that values of ambient dose equivalent $H^*(10)$ calculated with PANDOCA agree with experimental data taken with a TEPC within approximately 10% (Matthiä *et al* 2014). In figure 1, the comparison of experimental data and model calculations from Matthiä *et al* (2014) was expanded to include values of H^* calculated in this work over a wide range of geomagnetic shielding (cut-off rigidity $R_C = 0$ GV to 17 GV) and altitudes (FL290 to FL390). It is clear that H^* is consistently greater than the calculated values of $H^*(10)$ and the corresponding measurements of the TEPC. Figure 1 shows that if the TEPC is to be used

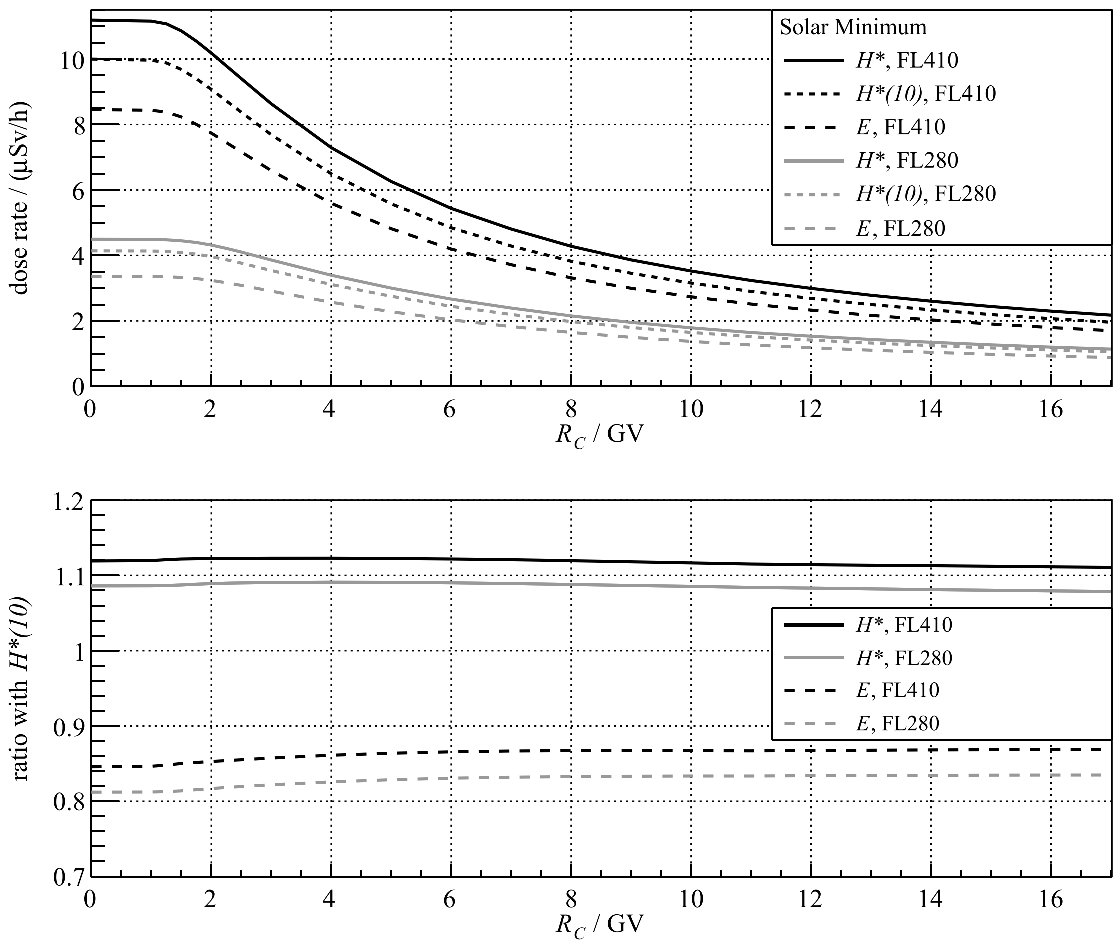

Figure 2. Calculated dose rates from GCR for ambient dose H^*, ambient dose equivalent $H^*(10)$ and effective dose E for solar minimum conditions at FL280 and FL410 as a function of cut-off rigidity R_C (top); corresponding ratio of H^* and E with $H^*(10)$ (bottom).

to measure H^*, a correction factor needs to be applied. In order to investigate this correction factor in more detail, a systematic calculation has been performed for solar minimum conditions (figure 2) and solar maximum conditions (figure 3) over flight altitudes from FL280 (28 000 ft) to FL410 (41 000 ft) and geomagnetic shielding quantified by the effective vertical cut-off rigidity R_C.

Top panels of figures 2 and 3 show the variation of calculated rates of H^*, $H^*(10)$ and E as a function of the cut-off rigidity R_C for the two different altitudes. The lower panels in the figures give the corresponding ratios of H^* and E with respect to $H^*(10)$, i.e. the current operational quantity. As H^* is intended to replace $H^*(10)$, the figures were chosen to show the quantities relative to $H^*(10)$ rather than the ratio to the effective dose. It is obvious that for both solar minimum and maximum conditions, the different quantities show very uniform behaviour in terms of geomagnetic shielding and altitude dependence with decreasing values from low to high geomagnetic cut-off rigidity and from high to low altitudes. H^* is again consistently greater than $H^*(10)$ and E. The ratios between the different quantities show only a very weak dependency on the cut-off rigidity regardless of altitude and solar activity (lower panels of figures 2 and 3). The ratios show a slight dependence on altitude increasing by about 3%–4% from FL280 and FL410. Absolute values of the ratios are between 0.81 (FL280, $R_C = 0$ GV, solar minimum) and 0.87 (FL410, $R_C = 17$ GV) for $E/H^*(10)$ and between 1.08 (FL280, $R_C = 17$ GV) and 1.12 (FL410, $R_C = 0$ GV) for $H^*/H^*(10)$. To our knowledge no estimate of H^* from other models is available at present. Previous investigations on the change of ICRP weighting factors, however, showed very similar results, specifically E being 80% to 90% of $H^*(10)$, for an alternative mode, Predictive Code for Aircrew Radiation Exposure (PCAIRE), (Dumouchel *et al* 2016); a similar agreement between PCAIRE and PANDOCA (c.f. section 2.3) can be expected for the relation of the new operational quantity with E. Also, a comprehensive study of models calculating $H^*(10)$ from GCR at aviation altitudes showed that most models agree within 20% (Bottollier-Depois *et al* 2012). It is reasonable to assume that differences between models for H^* and $H^*(10)$ go in the same direction and that differences in the ratio $H^*/H^*(10)$ are well below the cited 20%. This, however, remains to be confirmed, when H^* will be included in other models.

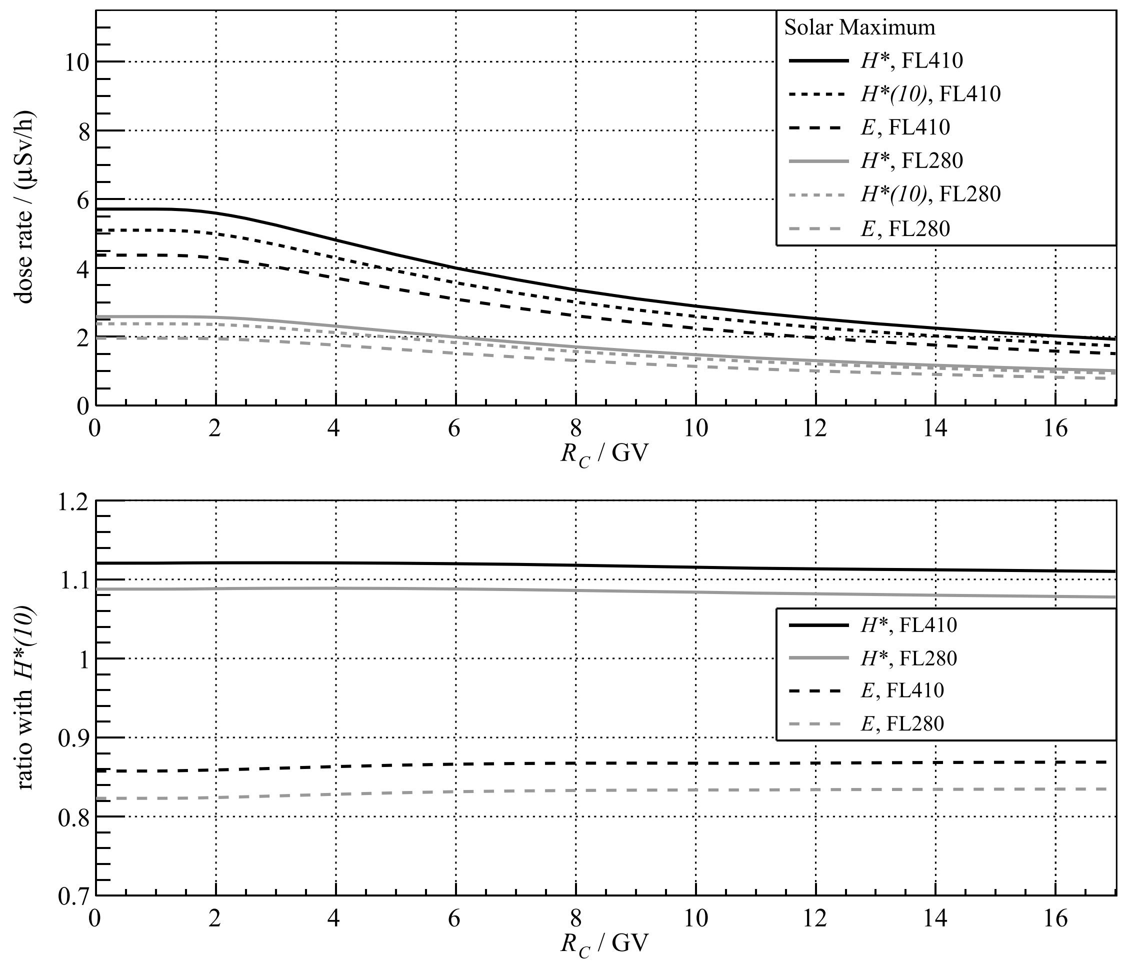

Figure 3. Calculated dose rates from GCR for ambient dose H^*, ambient dose equivalent $H^*(10)$ and effective dose E for solar maximum conditions at FL280 and FL410 as a function of cut-off rigidity R_C (top); corresponding ratio of H^* and E with $H^*(10)$ (bottom).

4. Summary

The numerical atmospheric radiation model PANDOCA (Matthiä *et al* 2014), which describes the radiation field at aviation altitudes, was applied to estimate the newly proposed operational quantity ambient dose H^* (ICRU 2020), which is intended to replace the ambient dose equivalent $H^*(10)$ as estimator for the effective dose. It was found that H^* consistently overestimates both the current operational quantity $H^*(10)$ and the protection quantity effective dose E over the whole range of altitudes and geomagnetic shielding relevant for commercial aviation. While it was calculated in earlier work (Meier and Matthiä 2019) that the current operational quantity $H^*(10)$ is a conservative estimator of the effective dose E ($E/H^*(10)$ is between 0.81 and 0.86), the newly proposed H^* is again a factor of 1.08–1.12 greater than $H^*(10)$. In total, H^* overestimates E by 30% to 35% depending on altitude, geomagnetic shielding and solar modulation. The result implies that a measuring device calibrated to measure $H^*(10)$ in the radiation field relevant for radiological protection in aviation may be used to derive H^* by applying a correction factor of 1.1 to the measurement. Accordingly, the adoption of the ambient dose as operational quantity and as estimator of the effective dose will make the dose assessment in aviation less accurate and will lead to higher dose values of exposed persons in the identical radiation field, i.e. at the identical level of biological impact, if measurements of H^* are used for the dose assessment. Furthermore, it should be borne in mind that the use of H^* instead of E to characterise the radiation field at aviation altitudes for epidemiological dose-response studies would lead to downward-biased results due to the discussed overassessment of E.

ORCID iDs

Daniel Matthiä https://orcid.org/0000-0003-1507-0143
Matthias M Meier https://orcid.org/0000-0003-0918-6473
Kai Schennetten https://orcid.org/0000-0001-7342-1576

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