The measurement and interpretation of microdosimetric spectra recorded on commercial flights from London

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Following the ICRP's 1990 recommendations for radiological protection practices to include workers exposed to elevated levels of radiation from natural sources, the occupational exposure of aircrew increasingly drew the attention of scientific groups from around the world. This particular study began in 1999 and, to date, has performed TEPC measurements on over two hundred commercial flights travelling between London and cities in seven countries across four continents. The work presented here looks beyond the total route doses recorded during these flights to examine the microdosimetric spectra themselves, discussing differences in the results observed between different instruments and the additional information that may be drawn from the TEPC data.

1. INTRODUCTION

1.1. Aircrew as occupationally exposed workers

In 1990 the International Commission on Radiological Protection (ICRP) published recommendations that included a section on workers exposed to enhanced or elevated levels of radiation from natural sources[(1)]. Subsequently the European Union introduced a directive that included the requirement that Member States incorporate the radiological protection of aircrew into their legislation and regulations by May 2000[(2)].

1.2. Characterisation of the cosmic ray field at aircraft altitudes

Many groups around the world are involved in measuring cosmic radiation at aircraft altitudes, both in terms of the radiation field itself and of the protection quantities relevant to aircrew, using a variety of detectors from passive personal dosemeters to active instruments capable of providing dose rate measurements virtually in real time. In general, the agreement between the different techniques is good(3).

Although there now exists a large body of experimental data for many commercial air routes around the globe, there is still a need for further investigations: recent measurements over the Caribbean Sea (geomagnetic latitude ~30°) revealed dose rates that were significantly higher than expected(4), and there is precious little dosimetric data for periods of abnormal (and unpredictable) solar activity(3).

1.3. The advantages and limitations of using tissue equivalent proportional counters

Tissue equivalent proportional counters (TEPCs) are excellent instruments for monitoring cosmic radiation levels on board commercial aircraft, by virtue of the physical processes underlying their operation. Being made of tissue-equivalent media, a TEPC responds to radiation in much the same way as living tissue, undergoing similar reactions, generating secondary particle distributions and undergoing slowing down processes similar to those that would occur in real tissue. The use of a very low pressure filling gas, equivalent to 2 μm of unit density tissue, means that the dose deposited in the cavity by a charged particle traversal can be related to that particle's Linear Energy Transfer (LET). Given that radiation quality can be expressed as a function of LET in tissue(1), the TEPC pulse-height response can be converted into a value for the dose equivalent. This is not to say that the TEPC measures *ambient* dose equivalent: the physical construction of the instrument is very different to the ICRU sphere used to define H*(10)(5). However, over the energy range of interest in aircraft dosimetry, the TEPC has a very good response in terms of ambient dose equivalent(6)

As already described, the radiation field at aircraft altitudes continues to be studied with a variety of active and passive instrumentation. The relative stability of the radiation fields in terms of energy spectra, means that almost any radiation-sensitive device could serve as a monitor if suitably calibrated. In this respect, TEPCs are perhaps less well suited to routine monitoring as they have relatively low sensitivities. The real advantage of using them, however, is that their pulse-height spectra can be analysed to provide useful information in addition to simply recording the dose equivalent rate.

2. THE CAA / MSSL / NPL / VAA COLLABORATIVE STUDY

In 1999 a representative of the UK Civil Aviation Authority (CAA) contacted the Mullard Space Science Laboratory (MSSL), the UK National Physical Laboratory (NPL) and Virgin Atlantic Airways Ltd (VAA) with a view to starting a collaborative project performing measurements of cosmic ray dose rates at aircraft altitudes. The initial aim of the study was to provide data for the validation of software used to predict route doses but following the granting of funds from the Particle Physics and Astronomy Research Council (PPARC), the scope of the collaboration was extended to include the study of space weather effects on doses at aircraft altitudes. Additional funding provided by the UK Department of Trade and Industry (DTI) via the National Measurement System (NMS) enabled NPL to play a more active part in the analysis and interpretation of the collected data.

2.1 Route doses measured between Jan 2000 and Feb 2001

Measurements of route doses started in January 2000 using a prototype Hawk TEPC supplied by Far West Technology, California, USA. This instrument, described in detail elsewhere[7,8], logs the accumulated pulse-height spectrum every minute, making it an ideal instrument for this type of study. By February 2001, the TEPC had made measurements on 74 flights between London and cities in China (Shanghai), Greece (Athens), Hong Kong, Japan (Tokyo), South Africa (Johannesburg) and the USA (Boston, Chicago, Los Angeles, Las Vegas, Miami, New York, Orlando and San Francisco). The route doses derived from these measurements have been reported elsewhere[8], along with the extensive calibration programme and some preliminary comparisons with CARI-6/Feb 2000. These initial findings showed that CARI predicted doses on average 22% *lower* than were measured; however, given that the TEPC is calibrated to measure ambient dose equivalent and CARI predicts effective doses, the doses predicted by CARI had been *reduced* by 25% in order to effect a comparison. A more thorough study, including the codes EPCARD and SIEVERT, has shown that this 25% reduction was excessive, and should have been between 11% and 21%, depending on the route in question (derived from predictions by EPCARD)[9].

2.2 Measurement programme to date

Using funds from the PPARC grant, the collaboration was able to purchase two commercial Hawks from Far West Technology in 2001. The first (#006) was flown in tandem with the prototype Hawk in July 2001, on two return flights from London to Boston. The second (#008) was flown in tandem with Hawk #006 in November 2001, on eight return flights to a variety of destinations. Both the CAA and NPL have acquired their own Hawk TEPCs (#007 in 2001 and #0011 in 2002 respectively), that can be used in addition to the other instrumentation if required.

One or more of the above TEPCs have now been flown on approximately 300 VAA flights to and from London, including some to Toronto, Canada. TEPCs have also been flown on two BA Concorde test flights. Full analysis of all these measurements is far from complete, and the in-flight measurement programme is expected to continue until at least 2003.

In addition to in-flight cross-calibrations, all Hawk TEPCs (except for #0011) have been calibrated at the CERF simulated cosmic ray facility at CERN[10]. There is also an ongoing programme of calibrations and characterisation using NPL's monoenergetic and radionuclide neutron sources, as well as with photon sources.

3. ANALYSIS OF SPECTRA COLLECTED BETWEEN JAN 2000 AND JUN 2001

Due to the large dynamic range of energies deposited in a TEPC, it is customary to plot the energy (or more strictly, *lineal* energy) distribution using a logarithmic scale. Lineal energy y is equal to the energy deposited ε divided by the (simulated) mean chord length of the detector cavity $<l>$: $y = \varepsilon / <l>$. Although plotting the frequency distribution in this way would be of interest, the most relevant quantity to plot for radiological protection purposes is the dose equivalent distribution, or y.h(y) spectrum. Plotting the distribution in this way means that equal areas under the histogram represent equal values of dose equivalent.

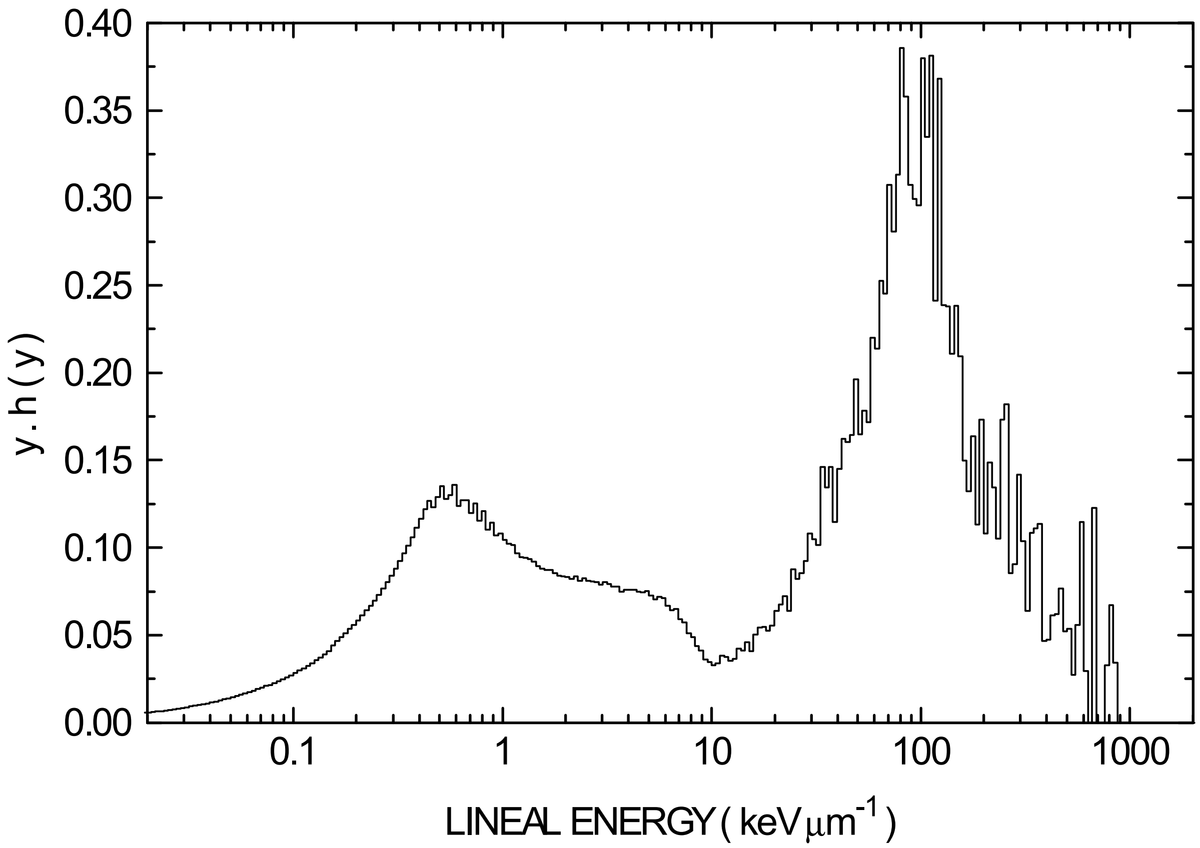

Figure 1. Microdosimetric spectrum measured with the prototype Hawk TEPC during a flight from Tokyo to London, showing the dose equivalent distribution in terms of lineal energy.

Figure 1 shows the y.h(y) (*i.e.* dose equivalent) spectrum recorded by the prototype Hawk during a single flight from Tokyo to London on April 5th 2000. The route dose was measured at 62.2 µSv, which is the highest value recorded on any flight (yet analysed) in this study. Even so, the statistics at higher lineal energies are quite poor. Nevertheless, the basic structure of the spectrum is apparent. Up to 10 keV μm^{-1} the spectrum is dominated by the lightly ionising particles, *i.e.* electrons and muons. Between roughly 10 keV μm^{-1} and 150 keV μm^{-1}, the spectrum is dominated by protons (both primary and recoil). Between roughly 150 keV μm^{-1} and 400 keV μm^{-1} the majority of the dose equivalent comes from α-particles and above 400 keV μm^{-1} the spectrum is dominated by heavy recoils such as carbon and oxygen.

3.1 Comparison between spectra measured with prototype and commercial Hawks

The cross-calibration flights between London and Boston performed in June 2001 for the prototype and Hawk #006 highlighted some interesting differences between the instruments. Although the total dose equivalent recorded for the two units during the first of these flights (London – Boston, June 6th 2001) were very similar (32.3 ±0.8 and 30.3 ±1.0 respectively), the quality factors for the two spectra differed by 20% (2.23 ±0.05 for the prototype and 2.70 ±0.06 for the commercial unit).

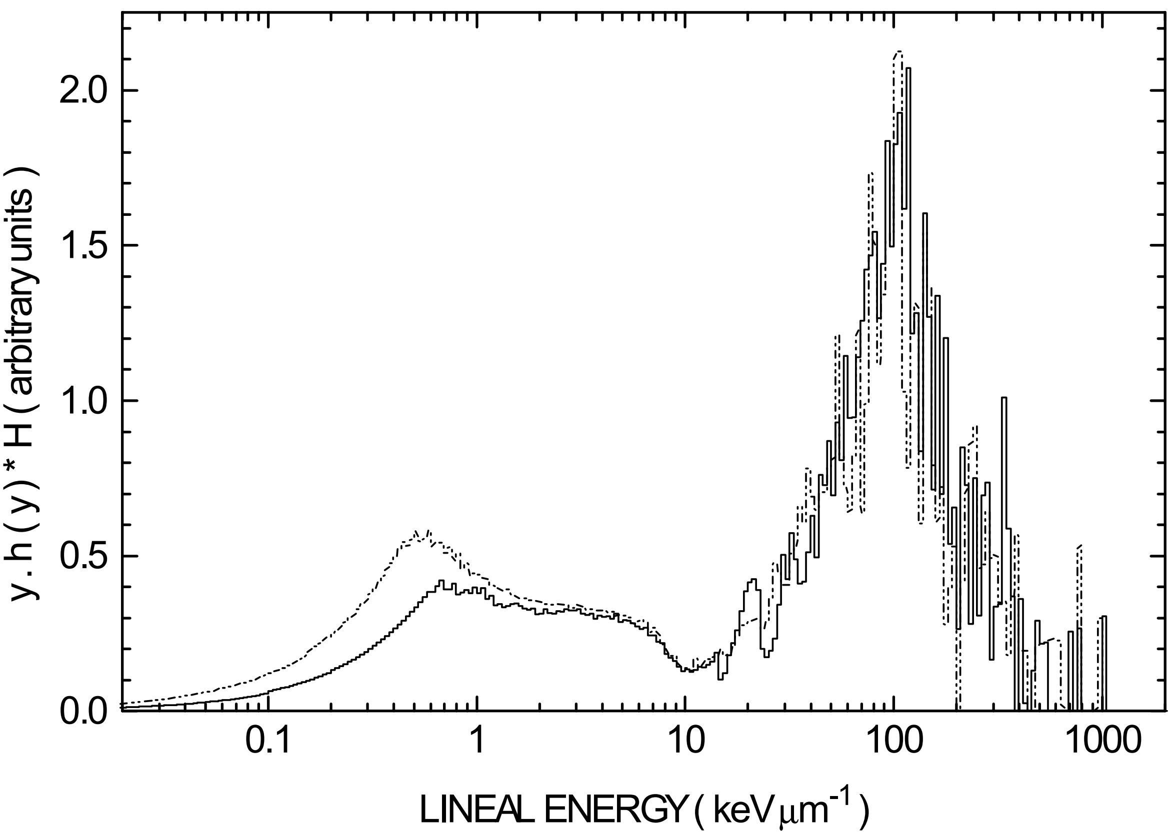

Figure 2. Comparison of microdosimetric spectra measured with the prototype and Hawk #006, during the first cross-calibration flight between London and Boston.

The spectra recorded during this flight are shown in Figure 2. The most obvious difference can be seen below 10 keV μm^{-1}, where Hawk #006 records ~30% less dose equivalent than the prototype. Although differences in construction may account for some of this, the bulk of it is thought to be caused by the reduced power consumption of the commercial instrument, resulting in a worse signal to noise ratio and hence higher low level discriminator setting. Consequently the unit appears to be 'missing' some low LET events. This conclusion is corroborated by the results from other studies: Grillmaier and Gerdung report quality factors for northern hemisphere routes of 2.23 and 2.24, measured with HANDI TEPCs(11), and Saez Vergara *et al.* report that commercial Hawk TEPC underestimated the low LET component when compared to other instrumentation(4).

Above 10 keV μm^{-1}, the shape of the two spectra are essentially the same, apart from an apparent peak in the commercial unit's spectrum at 20 keV μm^{-1}. After some investigation this was attributed to non-linearities in the MCA card used for the low gain segment of the lineal energy spectrum. Furthermore, it appears to be an artefact common to all commercial Hawk units, as demonstrated in Figure 3, which compares data from a selection of radiation fields from four commercial Hawks with in-flight data from the prototype instrument. Although its presence is far from ideal, the artefact does appear in a relatively unimportant part of the spectrum and can be corrected, if required, by adjusting the quality factors used over that region.

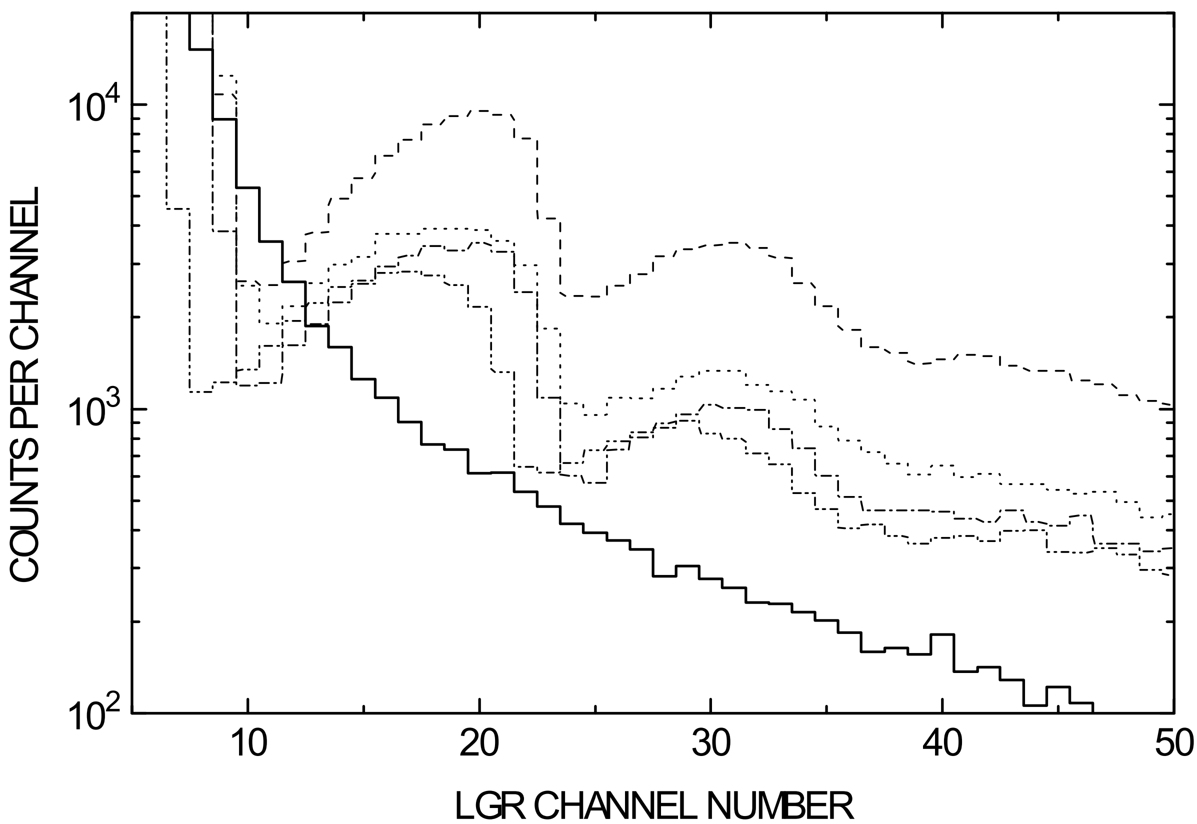

Figure 3. Comparison of the pulse-height spectra recorded in four commercial Hawk TEPCs compared to summed flight spectra recorded using the prototype instrument (solid line): (- · -) Hawk #006 [summed flight spectra]; (· · ·) Hawk #007 [CERN measurement]; (- · · -) Hawk #008 [summed flight spectra]; (- - -) Hawk #011 [Am-Be spectrum]

3.2 Comparison of route spectra from the prototype instrument

Having identified significant differences in the data collected from the prototype and commercial Hawk TEPCs, the rest of this study will concentrate on the prototype unit. A more comprehensive study will follow when the above issues have been fully resolved.

Given the relative stability of the radiation fields at flight altitudes, it is possible to integrate the spectra acquired on each route to create a generic spectrum for that route. Figure 4 shows just such a comparison for the following eight routes out of London: Boston, Miami, New York, Tokyo, Los Angeles, Athens, Hong Kong and Johannesburg. Although there appear to be some small differences between the majority of the routes, the London – Johannesburg route stands out as being quite unique, having a significantly softer lineal energy spectrum. This reflects the fact that Johannesburg is the only destination in the southern hemisphere, hence the majority of the flight is at low latitudes. The observed spectrum is, therefore, entirely consistent with the known physics of cosmic radiation levels at aircraft altitudes. The uniqueness of the London – Johannesburg route is shown more clearly in Figure 5, which compares this route spectrum with the summed of all the northern hemisphere routes.

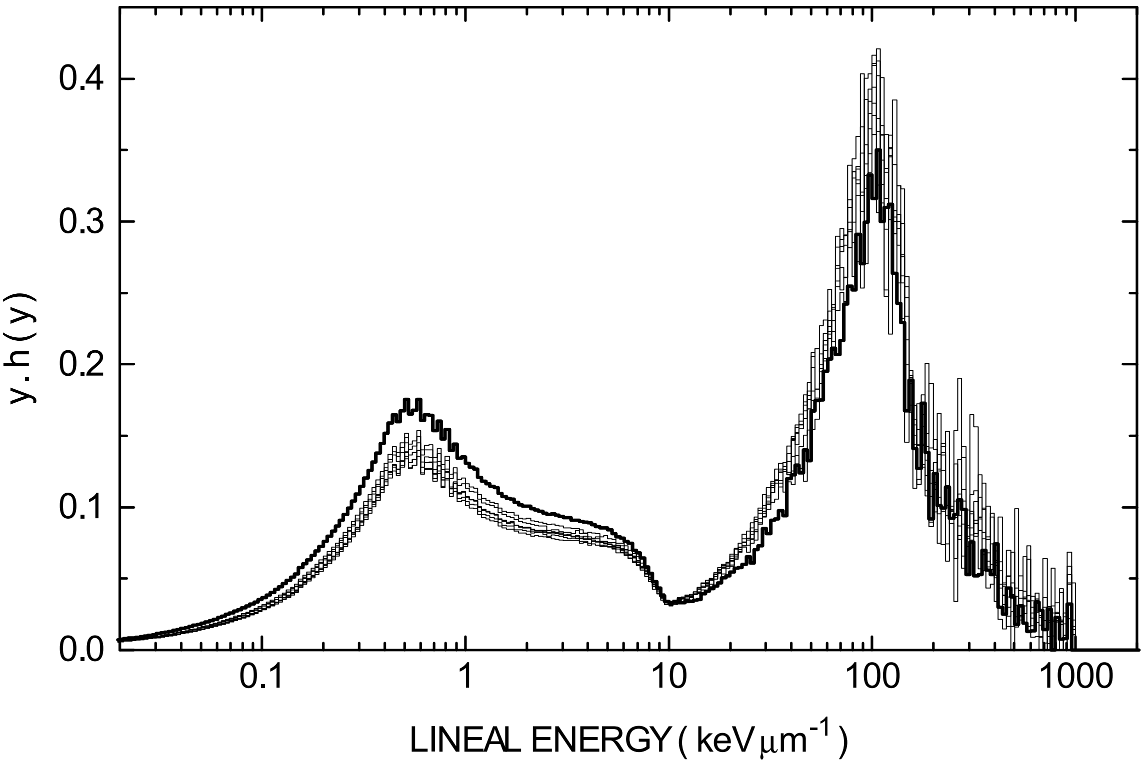

Figure 4. Comparison of summed spectra for specific routes, showing the difference between London – Johannesburg (dark line) and the other, northern hemisphere, routes.

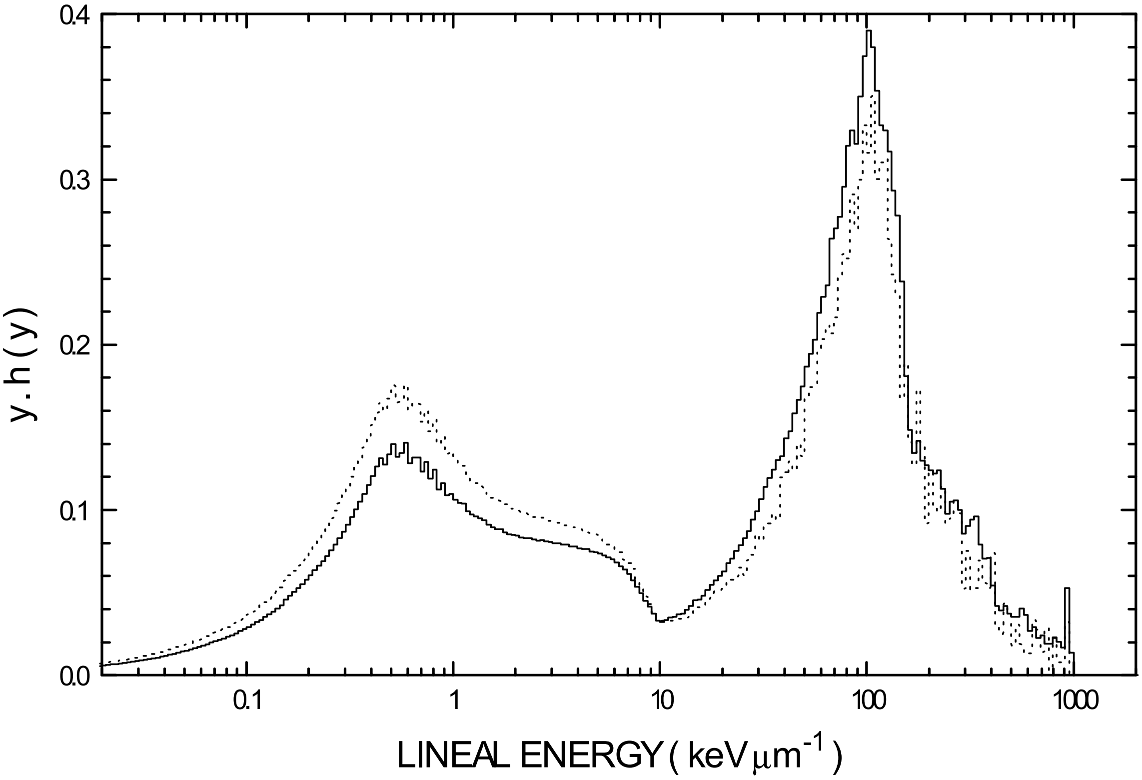

Figure 5. Comparison between London – Johannesburg (dotted line) and the sum of the northern hemisphere routes.

The summed data in Figure 5 shows even more clearly the different parts of the dose equivalent spectrum in terms of lineal energy, *i.e.* electrons and muons up to 10 keV μm^{-1}, protons between roughly 10 keV μm^{-1} and 150 keV μm^{-1}, α-particles between roughly 150 keV μm^{-1} and 400 keV μm^{-1} and carbon and oxygen recoils above 400 keV μm^{-1}. The single channel peak at the top of the spectrum contains events that would ordinarily be recorded beyond the 1000 keV μm^{-1} cutoff of these instruments.

3.3 Deriving effective dose data directly from the TEPC

As indicated earlier, an important part of this study is the evaluation of software used for predicting route doses. One result of this evaluation was that the ratio of effective dose to ambient dose equivalent E/H*(10) (as predicted by EPCARD) appeared to be route dependent, *with the ratio for the London – Johannesburg route being significantly lower than for the other routes*. Investigating this point further indicates that information derived from the TEPC spectra could be used to estimate effective dose as well as ambient dose equivalent, as shown in Figure 6. Although this figure simply superimposes the EPCARD E/H*(10) ratio for various flights over analogous data for the mean quality factors derived from the TEPC measurements, the relationship is quite apparent and work is under way to refine this observed relationship.

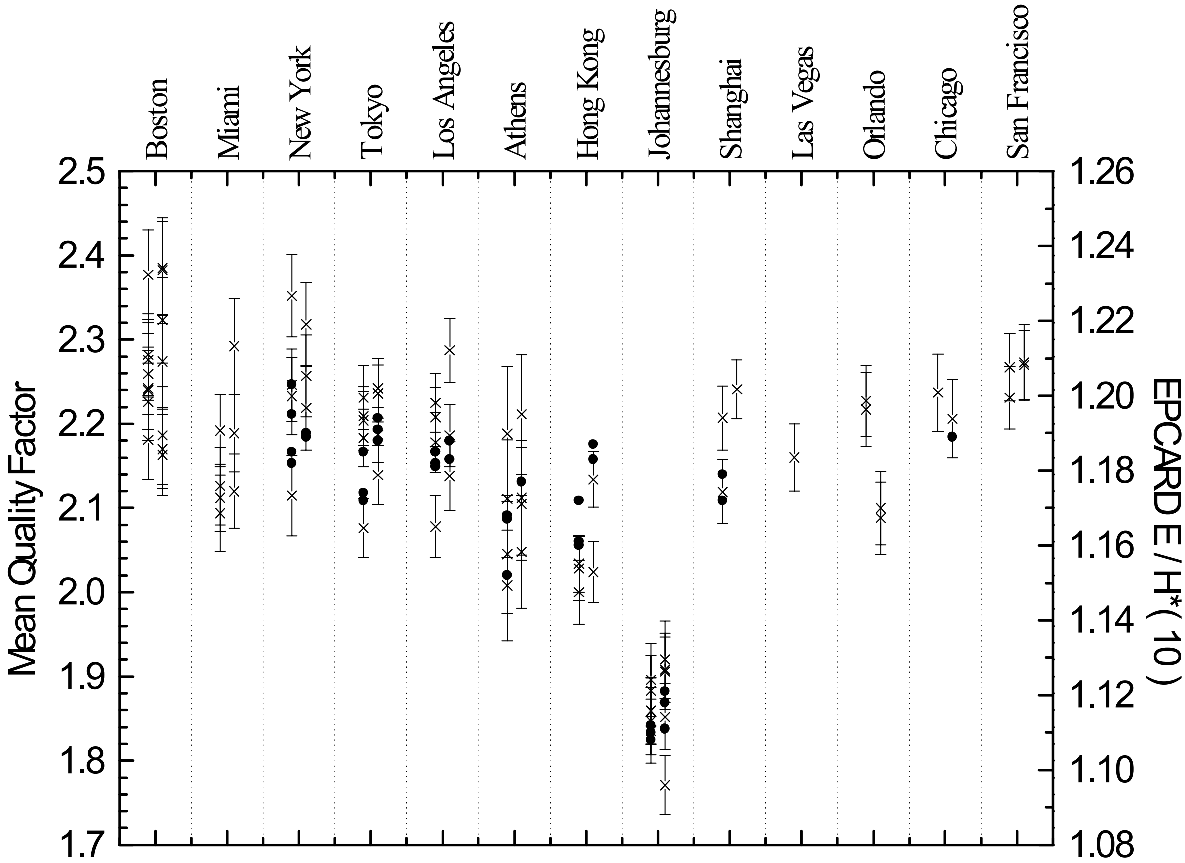

Figure 6. Superimposition of route quality factors (x) measured using the prototype Hawk TEPC, with E/H*(10) ratios (•) predicted by EPCARD where flight profiles were available.

4. CONCLUSIONS

Significant differences have been found between the prototype and commercial Hawk TEPCs, with the prototype instrument appearing to measure a better quality microdosimetric spectrum. However, the commercial unit still works well as a dose equivalent meter once suitable calibration data has been applied.

Microdosimetric spectra collected on different routes show differences in the low to high LET components, with the London - Johannesburg route being quite distinct from the rest.

A study of the effective dose to ambient dose equivalent ratio predicted by EPCARD for different routes shows similar trends to those observed in the TEPC spectra, and a clear relationship between the E/H*(10) ratio from EPCARD and the mean quality factor derived from measurements has been established. Exploiting this relationship may result in TEPCs being able to provide measurements of both ambient dose equivalent *and* effective dose.

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