A TLD-Microdosimeter for aerospace usage: Results relevant to airline pilots undertook long-haul intercontinental flights during March-May 2017

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Abstract

During high altitude long haul flights pilots, cabin crew and passengers are exposed to enhanced level of radiation originating from cosmic ray showers (CRS), produced via the interaction of very high-energy (~ GeV) primary protons with the air molecules in Earth's atmosphere. The CRS are composed of energetic particles of diverse species, i.e. neutrons, protons, electrons, muons, pions and photons. Furthermore, the magnitude of aircrew radiation exposure depends on flight altitude and duration, geographical location (latitude), geomagnetic conditions and solar activity (modulation) status. In 1990 the International Commission on Radiological Protection (ICRP) classified airline crewmembers as "radiation workers". A miniature passive microdosimeter (LiBe-14) based on LiF (TLD700) and Beryllium Oxide (BeO) thermoluminescence dosimeter chips emulating a large volume gas-filled Tissue Equivalent Proportional Counter (TEPC) was developed by one of the authors (BM). The LiBe-14 was deployed to assess the integrated ambient dose equivalent of two commercial pilots on long haul intercontinental flights during March-May 2017. The accumulated dose equivalents of 1st (38 y, Female, 148 total block hours) and 2nd (29 y, Male, 149 total block hours) pilots were evaluated to be 565 ± 105 µSv and 738 ± 137 µSv, respectively. The results agreed well within ± 20% of simulated data evaluated using the well-known EPCARD (European Program Package for the Calculation of Aviation Route Doses) aviation dosimetry code. The implementation of LiBe-14 Microdosimeter in routine long haul, high-altitude commercial flights for the estimation of dose equivalent, average LET and quality factor relevant to impinging cosmic radiation is recommended.

Keywords

aircrew-dosimetry; cosmic-radiation; radiation-exposure; TEPC; TLD-Microdosimeter

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Highlights

1. Microdosimeter (LiBe) based on LiF and BeO TLD
2. Polystyrene phantom bombarded with 180 MeV protons
3. Secondary mixed radiation field generated
4. TLD cross calibration using a gas-filled TEPC
5. Dose Equivalent, Average LET, Quality Factor
6. LiBe-Microdosimeter used in aircrew dosimetry

1. Introduction

Earth’s atmosphere is constantly bombarded with energetic particles from galactic cosmic rays (GCR) and solar cosmic radiation (SCR) [1]**.** Consequently, during long haul flights the aircrew and passengers are exposed to unignorable radiation dose governed by two sources – the continuous and isotropically distributed galactic and the sporadic solar component. In the EU countries aircrew of commercial airlines have already been classified as radiation workers [2]. The GCR is more pronounced during solar minimum occurring every 11-year solar cycle.

Long-term epidemiological studies of pilot and aircrew of both genders employed at renowned German airlines in 37 years (1960-1997) period had been carried out. The researchers performed statistical cohort studies encompassing databases of 6000 pilots and 20000 flight attendants and other flight personnel. Incidences of solid tumour, leukemia, fatal and non-fatal cancers at various organs, as well as other causes of death were statistically analyzed [3]. However, the relevant radiation exposure (dose equivalent) to the subjects was not recorded. Since 2002 in EU countries all flight personnel, including pilots and aircrew are categorized as radiation workers with mandatory assessment and recording of associated aviation doses [2]. This motivated the authors to develop a passive microdosimeter for the assessment of dose equivalent (mSv), average LET (keV/µm), and quality factor Q on long-haul commercial flights.

Airline pilots, cabin crew and passengers are exposed to mixed radiation fields composed of six major components including: neutrons, electrons, protons, photons, muons and pions [4] [5]. Hence, in order to assess the resulting ambient dose equivalent H*(10) [6] accurately, the requirement of a multitude of radiation dosimeters sensitive to individual radiation species becomes mandatory. Commercially available LiF thermoluminescence dosemeter (TLD) and CR39 solid-state nuclear track detector (SSNTD) [7] are now widely used. The tissue equivalent proportional counter (TEPC), commonly known as “Microdosimeter”, is facilitated to circumvent the usage of multiple dosimeters. A TEPC is capable of assessing the ambient dose equivalent, average “lineal energy” (keV/µm) and quality factor Q of any mixed radiation field of interest without explicitly taking account of individual radiation component. The lineal energy is an analogue of LET (linear energy transfer) (keV/µm) used in Microdosimetry [8]. A portable TEPC system for the estimation of cosmic radiation induced flight exposure is presented elsewhere [9]. The large physical size and highly inflammable propane gas filling severely restrict the use of TEPC for routine aircrew monitoring. To evade these shortcomings one of the authors (BM) had developed a mini passive microdosimeter (LiBe-14) constructed using commercially available TLD700 and BeO dosimeter chips [10].

The operation principle of TLD based LiBe-14 Microdosimeter for space dosimetry of astronauts is published elsewhere [10] [11]. Consequently, in this paper the authors have presented the calibration and evaluation procedures of LiBe-14 Microdosimeter utilized to assess the cosmic ray induced radiation exposure (dose equivalent) to two commercial airline pilots (**Fig. 1**) during long-haul intercontinental flights touching 17 airports worldwide **(Table 1)** in the time period from 16 March to 01 May 2017. No ground level enhancements (GLEs) caused by solar energetic particles were identified in this time period (https://cosmicrays.oulu.fi/). The dosimetry results were verified using the EPCARD.Net (European Program package for the Calculation of Aviation Route Doses) simulation code [5]. The feasibility of TLD-based passive microdosimeter LiBe-14 in routine aircrew monitoring is presented in this work. Importance of Lithium Fluoride TLD in aerospace applications was highlighted elsewhere [12].

2. Materials and Methods

2.1 Microdosimeter Calibration

The ratio of thermoluminescent glow curve (TLGC) area of Beryllium oxide (BeO) and TLD700 (^{7}LiF: Ti, Mg) chips increases with increasing linear energy transfer (LET) of the impinging particles on the dosimeter chips [10]. This was confirmed by irradiating the TLD chips with stray (parasitic) radiations. Such radiation fields were generated by bombarding a polystyrene plate phantom (PPP) ($30 \times 30 \times 40$ cm^{3}) with 81, 119, 150, 177, 201 and 231 MeV therapeutic proton beams from the 235 MeV Medical Cyclotron operated by Westdeutsches Protonentherapiezentrum Essen (WPE) Germany.

Pairs of TLD700 and BeO chips were encapsulated in holders made of thin Mylar plates and attached to a gas-filled TEPC (Model: REM500B, Manufacturer: Health Physics Instruments, Goleta, CA 93117, USA). The TEPC was positioned at contact with the lateral wall of the polystyrene plate phantom (PPP) and aligned to the proton beam stop zone (Bragg peak BP) located at the distance R from the upper surface of the PPP (**Fig. 2**). Evidently R represents the stopping range of the proton of energy (E_P) in polystyrene. After the completion of each run the TEPC (including attached TLD pairs) was removed from the treatment room for evaluation. Subsequently a new TLD pair attached to TEPC and the irradiation procedure was repeated. A proton dose of 50 Gy (5000 Monitor Unit) at a dose rate of 2 Gy min^{-1} was delivered to PPP in all cases **(Fig. 2).** The TLGC of TLD700 and BeO chips and TEPC readouts were used to calibrate the microdosimeter [10].

After the end of radiation exposure the TEPC was taken out from treatment room and connected to a PC. The stored data was downloaded and lineal energy (y) spectrum **(Fig. 3a)** evaluated. The average lineal energy (L_{av}), Quality Factor (Q_{av}) and dose equivalent (H) were also derived [13]. The glow curves of BeO and TLD700 chips were evaluated using Risø Model DA-12 TL/OSL Reader (Manufacturer: DTU Nutech, Denmark) at a heating rate of 5 $^{o}Cs^{-1}$. The temperature interval of integrated TLGC area was (100-210 ^{o}C) and (100-250 ^{o}C) for BeO and TLD700 respectively **(Fig. 3b)**, results are summarized in **Table 4**. The calibration parameters relevant to L_{av}, Q_{av}, h_H (dose equivalent conversion factor) and dose equivalent H are presented as following linear regression functions explained in the reference [10]:

$$L_{av}\,(\text{keV}/\mu\text{m}) = 258\cdot r - 24.8 \quad (1)$$

$$Q_{av} = 60.1\cdot r - 6.46 \quad (2)$$

$$h_H\,(\text{mSv/Counts}) = 2.16\text{E-}04 - 5.59\text{E-}04\cdot r \quad (3)$$

$$H\,(\text{mSv}) = h_H\cdot A_L \quad (4)$$

Where, r) represents the TL glow curve area ratio (A_B/A_L) of BeO and TLD700 dosimeters, and A_L(counts) represents glow curve area of TLD700 **(Table 4)**.

2.2 Experimental procedure

The authors had prepared three sets of LiBe-14 microdosimeter following the procedure described elsewhere [10]. The 1st and 2nd sets were assigned to two commercial airline pilots and the 3rd set was kept at ground office of the airline. The representative picture of the aircraft cockpit (position of the pilot) is depicted in **Fig. 1.** The geographical parameters of origin and destination airports are elucidated in **Table 1.** The geomagnetic cutoff rigidity (GV) at airport coordinates was calculated using Strömer model described in the reference [14]. After the completion of the flight missions the TLD chips were evaluated and the microdosimetric quantities i.e. accumulated ambient dose equivalent H*(10) (mSv), average lineal energy L_{av} (keV/µm), quality factor (Q_{av}) were evaluated. Furthermore, the results were verified using EPCARD.Net computer simulation code [5]. The flight schedule indicating destination airports, great-circle distance between the airports, flight-time and EPCARD.Net [5] ambient dose equivalents are presented in **Table 2** and **Table 3**.

Prior to exposure, all TLD chips were heated for 1 hour at 400°C in air in a muffle furnace. Pilot 1 and Pilot 2 carried the TLD chips belonging to the 1st and 2nd batch respectively, and the 3rd batch was kept as control (background subtraction). The TLD chips were evaluated by heating to 350 ^{o}C at a rate of 5 $^{o}Cs^{-1}$ using Risø Model DA-12 TL/OSL Reader. The region of TLGC integration was (100-210 ^{o}C) and (100-250 ^{o}C) for BeO and TLD700 chips, respectively.

2.3 Data evaluation

All three batches of TLD (LiBe-14 microdosimeter) were delivered to the participating pilots on 16 March, returned on 01 May after in-flight exposure and readout on 20 June 2017. Thus, the total time span of the aviation dosimetry project was 96 days (2304 h). The dosimeters were safely stored at pilots ground quarter situated in Frankfurt a. M. International Airport **(Fig. 1)** and evidently, exposed to natural-background radiation at a rate of 0.8 mSv/y (in Frankfurt area) according to German National Radiation Protection Office [14]. The 3rd batch (control) received the natural background exposure throughout the entire time span of 2304 hours, whereas, the dosimeter batches carried by Pilot 1 and Pilot 2 received less natural background exposure depending on respective integrated flight duration (block-hours). The background-count correction factor k is given in **Eq. (5)**:

$$k = (T_t - T_b)/T_t \qquad (5)$$

where, T_t (2304 h) is the total time span of the dosimetry project, T_b the block hour relevant to Pilot 1 (148 h) and Pilot 2 (149 h). By substituting the numerical values in **Eq. (5)** the background count correction factor (k) for Pilot 1 and Pilot 2 are evaluated to be 0.937 and 0.935, respectively.

The TLD-readouts of LiF (4048 counts) and BeO (3846 counts) chips of the 3rd batch (control) originated from natural background radiation [13] were corrected for Pilot 1 (k = 0.937) and Pilot 2 (k = 0.935) as follows: Pilot 1 (corrected BeO, 3615 counts; corrected LiF, 3805 counts) and Pilot 2 (corrected BeO, 3577 counts, corrected LiF, 3765 counts). The corrected TLD-readouts (background) as derived above were subtracted from the TL outputs of the 1st and 2nd batch carried by Pilot 1 and Pilot 2. For Pilot 1, the background subtracted TL-output (TLGC area) of BeO (A_B = 3042 counts) and TLD700 (A_L = 10487 counts) chips and TLGC area ratio A_B/A_L (r = 0.290) were evaluated (**Fig. 4a)**. For Pilot 2 the values of A_B, A_L and A_B/A_L were calculated to be 2719 counts, 10441 counts and 0.260, respectively (**Fig. 4b)**.

By substituting the value of “r” in **Eq. (1)** the average LET (L_{av}) for Pilot 1 and Pilot 2 was evaluated to be: 99.6 and 91.9 keV/µm, respectively. Furthermore, by substituting the value of “r” in equation 2 the quality factor (Q_{av}) for Pilot 1 and Pilot 2 was calculated to be 11.0 and 9.2, respectively. Entering the value of “r” in equation 3 the dose equivalent conversion factor (h_H) for Pilot 1 and Pilot 2 was calculated to be 5.39×10^{-5} (mSv/Counts) and 7.07×10^{-5} (mSv/Counts), respectively. By substituting the values of h_H and A_L (**Fig. 4)** in **Eq. (4)** the dose equivalent H for Pilot 1 and Pilot 2 was calculated to be 565 and 738 µSv, respectively. The results are presented in **Table 5**.

2.4 EPCARD.Net calculations

Authors had used the latest version of the EPCARD (European Program package for the Calculation of Aviation Route Doses) code available as EPCARD.Net 5.4.3 Professional [5] to simulate aviation doses. The German Aviation Authority (LBA) has approved the official use of EPCARD.Net program for dose assessment of radiation exposure due to secondary cosmic radiation at aviation altitudes in 2010. The EPCARD.Net solution is based on the results of extensive Monte Carlo (MC) calculations taking into account all physical processes that govern the interaction of cosmic radiation with air molecules in the Earth's atmosphere, using well-known FLUKA Monte-Carlo code [15]**.** The EPCARD.Net data outputs explicitly include ambient dose equivalents from all secondary particles; neutrons, protons, photons, electrons, muons, and pions.

During this aviation dosimetry research the pilots had recorded the geographical location of the origin and destination airports **(Table 1)**. The flight date, take-off and landing time, maximum flight altitude and flight duration were taken from flight-log and implementing EPCARD.Net program the total ambient dose equivalent for Pilot 1 and Pilot 2 was calculated **(Table 2** and **Table 3)**. However, a confidentiality agreement with the participating airline prevented the inclusion of flight date, take-off and landing times in the above tables.

3. Results and discussions

The calibration results of the LiBe-14 microdosimeter based on TLD-700 and BeO chips are presented in **Table 4**. The chips were irradiated with 81, 119, 150, 177, 201 and 231 mono-energy protons from a medical cyclotron [10]. In **Fig. 5** the average lineal energy (L_{av}) and average Quality factor (Q_{av}) as linear functions of TLGC area ratio (A_B/A_L) are depicted. The average lineal energy (keV/µm), Quality (Q_{av}) and dose equivalent H (mSv) relevant to Pilot 1 and Pilot 2 were evaluated using the TLGC area ratio (A_B/A_L) and **Eq (1)**, **Eq (2)** and **Eq (4)** [11] and presented in rows 8-10 of **Table 5**, respectively.

The latest version of the well-established aviation dose simulation code EPCARD.Net was used [5] to simulate the ambient dose equivalent H*(10) relevant to Pilot 1 and Pilot 2. The geographical coordinates of the starting and landing airports **Table 1**, great-circle distance and flight-time were taken into consideration, the results are summarised in **Table 2** and **Table 3**. The overall ambient dose equivalents received by Pilot 1 and Pilot 2 during 16 March-01 May 2017 period were evaluated to be 520 µSv and 737 µSv, respectively. The values are presented in row 7 of **Table 5**. Important parameters including gender and age of the pilots, flight plan, flight time (block hours) and total distance covered are presented in rows 2-6 of **Table 5**.

The uncertainty of ambient dose equivalent evaluated using EPCARD.Net was ± 20 % [5]. The overall uncertainty (± 18.5 %) in evaluated ambient dose equivalent ($^{Total}H$) relevant to LiBe-14 microdosimeter [10] was comprised of (**a**) uncertainty in TLD readouts: LiF (± 3.5%), BeO (± 2.5%) and (**b**) REM500 TEPC data: Lav (± 12.5%), Q (± 12.5%).

4. Conclusions

The findings of this research (LiBe-14 microdosimeter) and EPCARD.Net results are summarised in **Table 5**. Authors had used EPCARD.Net code to simulate the ambient dose equivalent accumulated during long-haul flights undertaken by a male (29y) and a female (38y) pilot covering 23 **Table 2** and 14 **Table 3** routes, respectively. The simulation results were compared with the estimated values obtained from LiBe-14 microdosimeter **Table 5**. The aircrew dosimetry study reported in this paper commenced on 16 March 2017 (dosimeter handed over date) and ended on 20 June 2017 (dosimeter readout date). This corresponds to a project time span of 96 days, or 2304 hours. Evidently, the LiBe-14 microdosimeters carried by Pilot 1 (1st Batch) and Pilot 2 (2nd Batch) were exposed to radiation fields at aviation altitude exclusively during the flights lasting 148 (Table 2, column 5) and 149 (Table 3, column 5) block hours respectively. Otherwise, the microdosimeters were kept in airport ground office while not in use. This results in a significant radiation exposure from natural background radiation [14]. Hence, by curbing the "idle-time", i.e. time gap between "dosimeter-handover" and "TLD-read-out" dates one could reduce the accumulated background counts resulting in higher net TLD counts (A_B, A_L in **Fig. 4ab**) and lower statistical error. The error analysis relevant to LiBe-14 microdosimeter was explained elsewhere [10].

At aviation altitude a mixed radiation field made of neutrons, protons, electrons, photons, pions and muons prevails [4]. Hence, for pilots and aircrew a microdosimeter becomes necessary to assess the ambient or personal dose equivalents encompassing all radiation species [9]. However, due to high cost, large size and potential fire hazard from propane gas filling a conventional TEPC type microdosimeter [13] [8] is unsuitable for personal monitoring of the aircrew. The miniature, TLD based passive microdosimeter LiBe-14 was found to be ideal candidate.

Sophisticated computer code like EPCARD.Net [5] is based on powerful computer modelling and large databases. Simulation codes are unable to sense the dose escalations caused by sporadic occurrence of solar particle events [1]. The passive integrating type LiBe-14 microdosimeter is capable to record such events. The EPCARD.Net [5] code simulated the radiation exposure relevant to the Pilot 1 and Pilot 2 as "ambient dose equivalent" H*(10) (mSv) [6] based on the concept of: dose equivalent produced by the expanded and aligned (unidirectional) field of strongly penetrating radiations at 10 mm depth of a 30 cm diameter ICRU sphere made of “tissue equivalent” material of a density of 1 g.cm^{-3}, whereas; the LiBe-14 microdosimeter physically estimated the “dose equivalent” (H: mSv) based on quality factor Q [10]. The concepts of H*(10) and H are explained in details elsewhere [16]. The values of H*(10) and H estimated in the framework of this research **Table 5**, columns 7 and 8 agree with each other within the expected uncertainty of ± 20% of EPCARD.Net code.

In EU countries air crew and flight attendants are placed in category of radiation workers of nuclear or particle accelerator facilities [2]**.** We herewith propose the usage of LiBe-14 microdosimeter **(Fig. 2 inset)** for aircrew dosimetry [16] as a substitute of conventional TLD albedo dosimeter cards based on TLD700 and TLD600 chips and CR39 SSNTD [7]. The evaluation protocol, record and database keeping of the system described in the references [10] [11] could be implemented after minor modification.

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Figure and Table Captions

Figure 1. A representative picture of the aircraft cockpit showing pilot's position.

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Figure 2. Principle of TLD Microdosimeter calibration set up showing the proton beam delivery nozzle, polystyrene plate phantom (PPP) and the TEPC (REM 500B) with LiF (TL700) and BeO pairs attached to it. The TEPC was aligned to proton stopping (Bragg Peak-BP) zone by manipulating the vertical movement of the height adjustable table (HAT). The distance between BP zone and the PPP surface (R) depends on proton beam energy (E_P). The sketch of the TLD holder is depicted inset.

Figure 3. (a) LET spectrum downloaded from the REM500B TEPC. Average LET, bombarding proton energy and ambient dose equivalent are shown inset. **(b)** The TL glow curve (TLGC) of BeO and TLD700 (^{7}LiF: Ti,Mg) dosimeters co-irradiated with the TEPC (Figure 2). TLGC area ratio (A_B/A_L) is shown inset.

Figure 4. (a) Background corrected Thermoluminescence glow curves of the TLD-700 (^{7}LiF: Ti,Mg) and BeO (Thermolux) dosimeter chip pairs (LiBe-14) exposed during intercontinental flights undertaken by Pilot 1. The TL (counts) is plotted as a function of temperature. The TLGC area of BeO (A_B) and LiF (A_L) dosimeters and TLGC area ratio (A_B/A_L: r) are shown in the inset). **(b)** TLD glow curves relevant to Pilot 2.

Table 1: The name, country of origin, geographical coordinates and corresponding EPCARD.Net [5] calculated Vertical geomagnetic cut-off rigidity (VCR) of the airports used by the participating commercial airline pilots during 16 March - 01 May 2017 period.

Table 2: Summarizing the flight data relevant to Pilot 1 showing the flight routes (take-off and landing airports), great-circle distance between the airports, flight time, and calculated ambient dose equivalent (EPCARD.Net). Total ambient dose equivalent, distance covered and flight time (block hours) during the investigation period (16 March-01 May 2017) were evaluated to be 520 µSv, 1.07×10^5 km and 148 hours respectively.

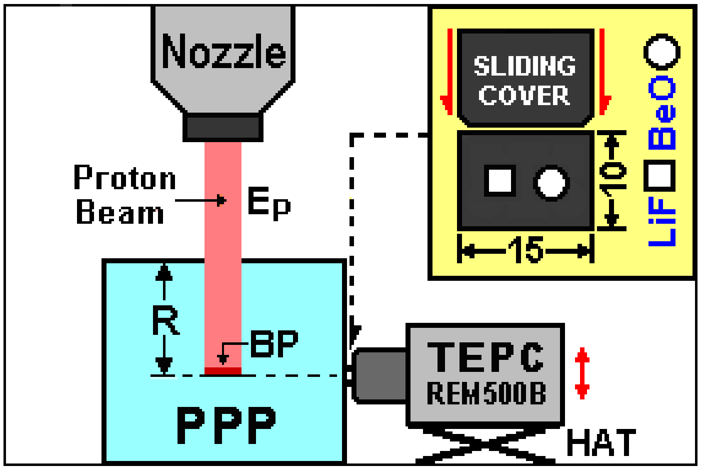
Table 3: Summarising the flight data relevant to Pilot 2 showing the flight routes (take-off and landing airports), great-circle distance between the airports, flight time, and calculated ambient dose equivalent (EPCARD.Net). Total ambient dose equivalent, distance covered and flight time (block hours) during the investigation period (16 March-01 May 2017) were evaluated to be 737 µSv, 1.20×10^5 km and 149 hours respectively.

Table 4: Calibration results, the energy (E_P) of the protons bombarding the polystyrene phantom, microdosimetric quantities (H, L_{av} and Q_{av}), TL glow curve areas of LiF (A_L) and BeO (A_B) dosimeters and corresponding glow curve area ratio A_B/A_L (r).

Table 5: Summary of the studies encompassing the age and gender of the participating pilots, flight schedules and experimental (LiBe-14 microdosimeter) and computer simulated (EPCARD.Net) results. Average LET and Quality factors are also included.

Figures and Tables

Figure 1. A representative picture of the aircraft cockpit showing pilot's position.



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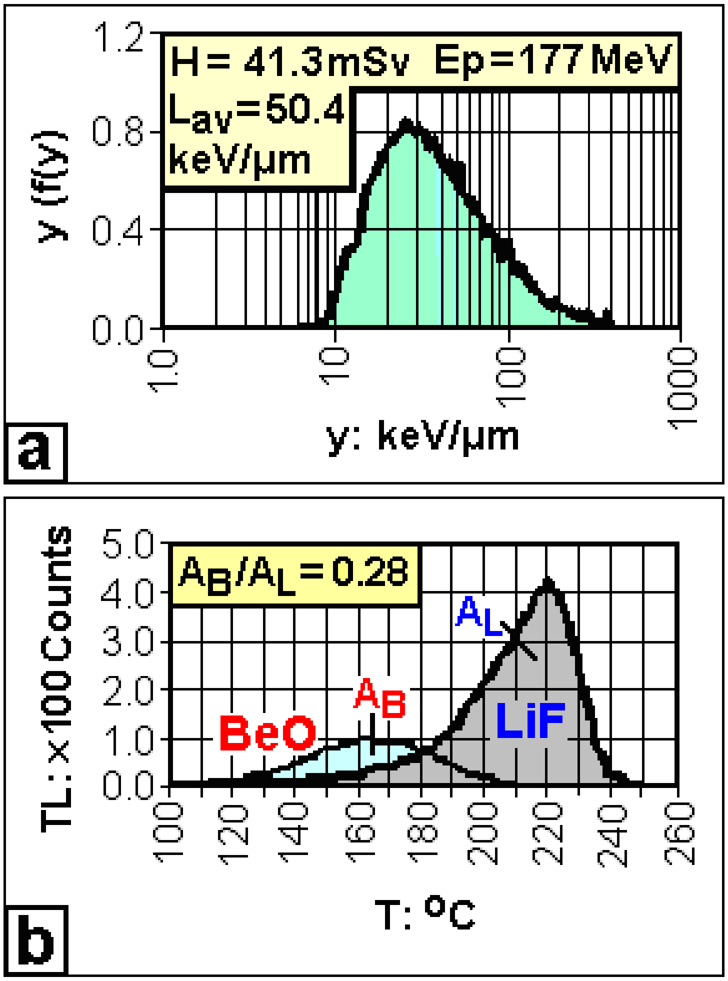

Figure 3. (a) Lineal Energy spectrum downloaded from the REM500B TEPC representing event distribution as a function of lineal energy. Average lineal energy (L_{av}), bombarding proton energy (E_P) and ambient dose equivalent (H) are shown inset. **(b)** The TL glow curve (TLGC) of BeO and TLD700 (^{7}LiF: Ti,Mg) dosimeters co-irradiated with the TEPC **(Fig. 2)**. The TLGC area ratio (A_B(counts)/A_L(counts)) is shown inset.

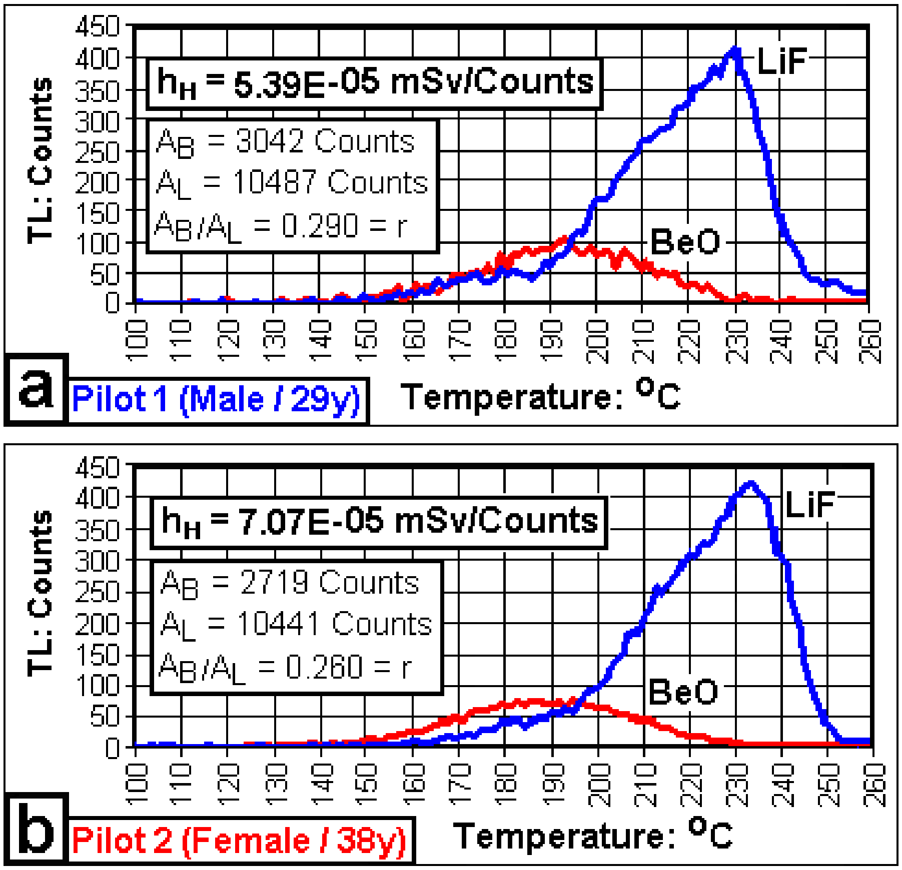

Figure 4. Background corrected Thermoluminescence glow curves of the TLD-700 (^{7}LiF: Ti,Mg) and BeO (Thermolux) dosimeter chip pairs (LiBe-14) exposed during intercontinental flights undertaken by Pilot 1 **(a)** and Pilot 2 **(b)**. The TL (counts) is plotted as a function of temperature. The TLGC area of BeO (A_B) and LiF (A_L) dosimeters, TLGC area ratio (A_B/A_L: r) and dose equivalent conversion factor (h_H) are shown in the inset).

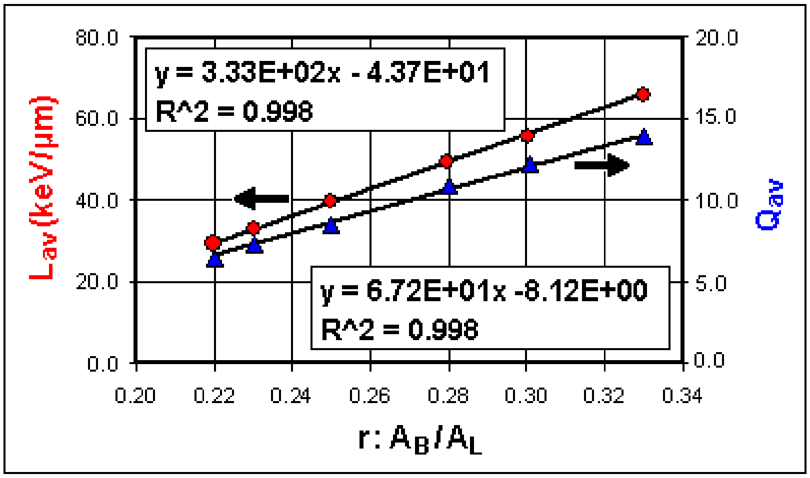

Figure 5: Average lineal energy Lav) and average Quality factor (Qav) are depicted as functions of TLGC area ratio (A_B/A_L) of the BeO and LiF TLD. The linear fitting functions are shown as inset.

Table 1. The name, country of origin, geographical coordinates and corresponding EPCARD.Net [5] calculated Vertical geomagnetic cut-off rigidity (VCR) of the airports used by the participating commercial airline pilots during 16 March - 01 May 2017 period.

IATA Code	Airport Name	Country of Origin	Longitude	Latitude	VCR (GV)
ALA	Almaty International	Kazakhstan	77^{o}02’26”E	43^{o}21’07”N	6.030
ASB	Ashgabat International	Turkmenistan	58^{o}21’39”E	37^{o}59’13”N	8.375
ATL	Atlanta International	USA	84^{o}25’40”W	33^{o}38’21”N	3.687
BLR	Bengaluru International	India	77^{o}42’20”E	13^{o}11’56”N	17.157
BOM	Chatrapati Sivaji International	India	72^{o}52’05”E	19^{o}05’19”N	16.243
DEL	Indira Gandhi International	India	77^{o}07’05”E	28^{o}34’10”N	13.412
DFW	Dallas International	USA	97^{o}02’17”W	32^{o}53’49”N	4.039
DKR	Yoff-Senegal International	Africa	17^{o}29’25”W	14^{o}44’23”N	14.161
EZE	Ministro Pistarini International	Argentina	58^{o}23’02”E	34^{o}36’02”S	7.955
FRA	Frankfurt a. M, International	Germany	08^{o}41’04”E	50^{o}07’03“N	3.392
GYD	H. A. International	Azerbaijan	50^{o}02’48”E	40^{o}28’03”N	6.830
HKG	Hong Kong International	China	113^{o}54’53”E	22^{o}18’32”N	15.731
HYD	Rajiv Gandhi International	India	78^{o}25’41”E	17^{o}14’24”N	16.688
JFK	John F. Kennedy International	USA	74^{o}00’21”W	40^{o}42’46“N	2.468
MEX	Juarez International	Mexico	99^{o}04’19”W	19^{o}26’10”N	7.437
SHJ	Sharjah International	UAE	55^{o}31’02”E	25^{o}19’43”N	14.294
PEK	Beijing (Peking) International	China	116^{o}35’05”E	40^{o}04’21”N	8.646

Table 2. Summarizing the flight data relevant to Pilot 1 showing the flight routes (take-off and landing airports), great-circle distance between the airports, flight time, and calculated ambient dose equivalent (EPCARD.Net) [5]. Total ambient dose equivalent, distance covered and flight time (block hours) during the investigation period (16 March-01 May 2017) were evaluated to be 520 μSv, 1.07×10^5 km and 148 hours respectively.

Flight No.	From	To	D: km	T: min	H* (10): μSv
1	FRA	JFK	6200	723	60.7
2	JFK	MEX	3364	521	30.6
3	MEX	DFW	1508	144	8.2
4	DFW	FRA	8274	588	71.6
5	FRA	BOM	6571	485	21.5
6	BOM	FRA	6571	549	23.1
7	FRA	DEL	6126	465	28.0
8	DEL	BLR	1708	165	4.4
9	BLR	HYD	455	65	0.6
10	HYD	SHJ	2532	220	4.8
11	SHJ	HKG	5926	430	14.3
12	HKG	ALA	4135	365	6.4
13	ALA	FRA	5099	425	24.9
14	FRA	ASB	4120	306	15.2
15	ASB	GYD	766	95	3.2
16	GYD	FRA	3372	298	21.8
17	FRA	EZE	11490	838	37.1
18	EZE	DKR	6997	530	21.1
19	DKR	FRA	4573	350	16.0
20	FRA	JFK	6200	496	35.3
21	JFK	ATL	1222	123	6.3
22	ATL	DFW	1175	136	9.0
23	DFW	FRA	8274	589	56.0

Table 3. Summarising the flight data relevant to Pilot 2 showing the flight routes (take-off and landing airports), great-circle distance between the airports, flight time, and calculated ambient dose equivalent (EPCARD.Net) [5]. Total ambient dose equivalent, distance covered and flight time (block hours) during the investigation period (16 March-01 May 2017) were evaluated to be 737 µSv, 1.20×10^5 km and 149 hours respectively.

Flight No.	**From**	**To**	**D: km**	**T: min**	**H* (10): µSv**
1	FRA	IAH	8417	644	55.0
2	IAH	FRA	8417	565	66.2
3	FRA	SFO	9173	718	75.1
4	SFO	FRA	9173	642	72.0
5	FRA	DEL	6126	455	30.3
6	DEL	FRA	6126	514	33.0
7	FRA	SIN	10278	712	30.1
8	SIN	FRA	10278	762	27.3
9	FRA	SFO	9173	690	73.7
10	SFO	FRA	9173	655	84.5
11	FRA	HKG	9184	672	48.0
12	HKG	FRA	9184	713	42.6
13	FRA	PEK	7805	551	53.4
14	PEK	FRA	7805	621	46.2

Table 4. Calibration results, the energy (E_P) of the protons bombarding the polystyrene phantom, microdosimetric quantities (H, Lav and Q), TL glow curve areas of LiF (A_L) and BeO (A_B) dosimeters and corresponding glow curve area ratio A_B/A_L (r).

Ep: MeV	H: mSv	L_{av}: (keV/µm)	Q_{av}	A_L: (counts)	A_B: (counts)	r: A_B/A_L
81	27.8	29.3	6.50	2.52E+05	5.47E+04	0.22
119	31.8	32.9	7.40	3.31E+05	7.63E+04	0.23
150	34.8	39.5	8.50	5.08E+05	1.28E+05	0.25
177	41.3	50.4	11.1	8.08E+05	2.27E+05	0.28
201	51.1	55.2	12.1	1.11E+06	3.33E+05	0.30
231	50.0	66.3	13.8	1.71E+06	5.61E+05	0.33

Table 5. Summary of the studies encompassing the age and gender of the participating pilots, flight schedules and experimental (LiBe-14 microdosimeter) and computer simulated (EPCARD.Net) results. Average LET and Quality factors are also included.

Results	**Pilot 1**	**Pilot 2**
Gender	Male (Caucasian)	Female (Caucasian)
Age: y	29	38
Flight schedule	16 March - 01 May 2017	16 March - 01 May 2017
Flight time (block hours): h	148	149
Total distance covered: km	1.07×10^5	1.20×10^5
$^{Total}H^*(10)$ (EPCARD): µSv	520 ± 104	737 ± 147
$^{Total}H$ (LiBe-14): µSv	565 ± 105	738 ± 137
Lav (LiBe-14): keV/µm	99.6 ± 12	91.9 ± 11
Qav (LiBe-14)	11.0 ± 1.4	9.2 ± 1.2