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Cosmic Radiation Exposure and Health Risks for Passengers on Flights over Nigeria

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Abstract: This study calculated the absorbed dose and effective doses of cosmic radiation at an aviation altitude of 12 km over Nigeria. We considered galactic cosmic rays (GCR), solar energetic particles (SEP), and atmospheric cosmic rays (ACR). The results indicate that dose rates increase with altitude and latitude, reaching a maximum of 1.93 µSv/h during solar minimum and 1.63 µSv/h during solar maximum. The calculations show that a passenger flying 200 hours per year between Abuja and Lagos would accumulate 0.39 mSv/year of cosmic rays. Although this is less than the recommended dose of 1 mSv/year for non-radiation-exposed persons, passengers travelling at the same rate would accumulate 1.55 mSv in four years. This long-term exposure could be detrimental to health, potentially leading to tissue degenerative diseases and cancer. The results of this study provide insights for assessing and mitigating radiation exposure risks in aviation.

Keywords: Aviation altitude, air shower, cosmic rays, effective dose

Introduction

Radiation from outside our solar system to the Earth's atmosphere is essentially influenced by the solar cycle, the Earth's atmosphere, magnetosphere, and altitude. The size of radiation getting to the Earth somewhat depends on the sun's movement at a specific period. Every so often, the sun discharges unconstrained Electromagnetic radiation emissions in the form of gamma beams, X-rays, and radio waves. This Occurrence gets to its greatest every 11 years, i.e., solar cycle, and during this period, the Earth yields extra radiation emissions. Astonishingly, the concentration of the radiation coming to the Earth is affected by the Earth's atmosphere as well as its magnetosphere [1]. The atmosphere retains most of the particles released; the Magnetosphere repels the cosmic radiation that would have come to the Earth's surface [2-4]. These repulsions are greatest at the equator and least at the poles, where the cosmic radiation entrance is greatest [5, 6].

The exposure rate of commercial flights is estimated to be 0.06 µSv/h, and that of the Supersonic Concorde is estimated to be 6 µSv/h. Computer programs have been introduced to help with the computation of radiation dosages received by crew members and passengers on board at Aviation attitude. Now the route measurement gauges can be calculated utilizing computer Programs such as EPCARD and CARI-6, which are particularly designed to calculate route Dosage, and these programs are recognized by the United States Environmental Protection Agency [5, 7]. German Research Center for Environmental Health, Institute of Radiation Protection, with the support of the European Commission, created EPCARD 3.2 in February 2002.

The National Committee on Radiation Protection and Measurements prescribes a permissible dosage restraint of 0.5 mSv per month, and ICRP suggests a radiation limit of 1 mSv per annum during pregnancy. As it was also for flight crew members flying for a high number of hours during pregnancy according to the law, a pilot may not fly more than 85 hours a month or 1000 hours a year [8]. But we see that an average pilot works more than 100 hours a month checking ground obligations such as recording flight plans, working on reports, briefing teams, and attending training classes. The flight duration of such per annum for aircrew individuals may result in a high level of dose.

Materials and Methods

Study area

The research was conducted across the Abuja, Lagos, and Maiduguri air routes. Abuja is situated in the middle of Nigeria within the Federal Capital Territory (FCT) Abuja's geography is defined by Aso Rock; a 400-meter (1,300 ft) monolith left by water erosionLagos State is a state located in the southwestern part of Nigeria; its capital is IkejaLatitude: 6.4531° N (6° 27' 11" N) Longitude: 3.3903° E (3° 23' 25" E) Lagos state airport Murtala Muhammed International Airport (MMIA) Ikeja, Lagos State, Nigeria. Maiduguri is the capital city of Borno State in northeastern Nigeria Situated in the northeastern part of Nigeria, of Latitude: 11.8479° N (11° 50' 52" N) Longitude: 13.1567° E (13° 9' 24" E) 320 meters (1,050 ft) above sea level Maiduguri International Airport (MIU) is in Maiduguri, the capital of Borno State in Nigeria.

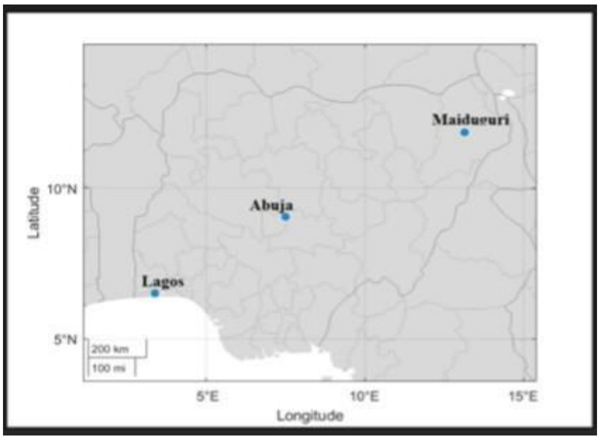

Figure 1: Map of Nigeria showing the study area

Data collection method

Using the open-access code EXPACS (ver.4.09) based on the PARMA model [9]. The computation of the atmospheric cosmic ray flux and dosimetry is performed at several geographic locations (latitudes), altitudes, and phases in the solar cycle. Moreover, the cosmic ray fluxes of protons, negative and positive muons, neutrons, Positrons, electrons, and photon flux were computed using EXPACS by providing the Evaluated depth (d) of the atmosphere and vertical cut-off rigidity Rc for the period between 1986 and 2021. EXPACS code also enables computation of the cosmic ray fluxes of Atoms having a charge up to 28; however, their contributions are very insignificant at Ground and were consequently ignored in the present work. It must be noted that the EXPACS code has been upgraded to version 4.10 by including the solar modification data updated to March 21, 2021, using a PHITS-based Analytical Radiation Model in the Atmosphere (PARMA) version 4.0 (Sato, 2015). It's an analytical model for calculating the cosmic ray spectrum in the atmosphere for all types of cosmic particles.It is also applied for all global conditions and altitudes below 63 km with energy ranging from 1 MeV and 200 GeV. The program may also calculate the angular distributions of cosmic rays in the Terrestrial atmosphere [3, 9].

When "Km-MSIS" is chosen, atmospheric depth is calculated from input altitude, considering the latitude dependence based on NRLMSISE [10]. In this software, the latitude (-90◦ ∼90◦, north+) and longitude (-180◦ ∼+180◦, east+) are used to specify the geographic location or vertical cut-off rigidity. Using the database integrated into the MAGNETOCOSMICS code, EXPACS computes the vertical cut-off rigidity automatically, with values between 1 and 20 GV. In addition to the previous parameters, the solar modulation parameter W-index and the density of water should be provided to EXPACS for estimating cosmic ray flux on the Earth.

When the time is in years, months, and days, EXPACS automatically calculates the force field potential, which is an index of solar activity, based on the count rate of the different neutron monitor observations at the ground on the same date. However, the force field potential in the high and low solar activity periods is approximately 300 and 1200 MV, for the period from 1951 to 2020, the mean value is= 648.8 MV. For this purpose, we have used the recent experimental data published by the World Data Centre, which produces, preserves, and disseminates In the Matthiä model, the energy-differential GCR fluxes at 1 AU for particle type i with energy for solar modulation index, $\emptyset_{i,1AU}(E, W)$, can be calculated based on force field formalism as follows:

$$\emptyset_{i,1AU}(E,W) - \frac{a_{1,i}\beta^{a_{2,i}}}{R(E)^{a_{3,i}}} \left\{\frac{R(E)}{R(E)+[0.37+0.0003W^{1.45}]}\right\} a^{4W+a_5}\frac{A_i}{|Z_I|}\frac{1}{\beta} \qquad (1)$$

where A_i and Z_i are the mass and charge numbers of the particle, respectively, $R(E)$ is the rigidity of the particle in GV, and β is the speed of the particle relative to that of light. W is generally calculated from the sunspot number; however, in the Matthiä model, it is determined from cosmic ray measurements and neutron monitor count rates, as described later. The parameters $a_{1,}$ to a_{3i} are free parameters depending on particle type i, while a_4 and $a_5$are constant for all particles [11].

Primary cosmic ray fluxes in the atmosphere

$\emptyset_{I,PRI}(E,\ d,\ W) = \emptyset_{i,1AU}(E + S_i(E)d,\ W)(4\pi{-}\Omega_E) \times \{b_{1,i}(d)\exp(-b_{2,i}d) + [1 - b_{1,}(d)]\exp(-b_{3,i}d)\}$ (2)

where $\emptyset_{i,1AU}$ is the primary cosmic ray flux at $1AU$, as calculated using Eq (3), and its unit is $cm^{;2s^{-1}}(MeV/n^{;1r^{-1}})$. (E) is the stopping power of particle i with energy E in the atmosphere, and its unit is $(MeV/n)(g/cm^2)^{;1}$. ΩE is the solid angle of the Earth from a point at the top of the atmosphere in our EAS simulation, and $b_{1,}ib_{3,i}$ are free parameters depending on particle type i as well as d in the case of b_1. The value of $(E + (E)d$ indicates the back-calculated primary cosmic ray energy at $1AU$ under the assumption that the stopping power is constant at higher energies and the cosmic ray is vertically incident on the atmosphere. The numerical values of $b_{1,i} - b_{3,i}$ were determined from the $L_{s,q}$ fitting to the $b_{1,i}EAS$ data only for high energies and low cut-off rigidities. The value of $S_i(E)$ calculated using $PHITS$ was adopted in the $L_{s,q}$ fitting [9, 12, 13].

Secondary cosmic ray fluxes in the atmosphere

$\phi_{i\ \mathrm{sec},}(E,\ d,\ r_c,\ W) = \phi_i(d,\ r_cW)\varphi_{i,all}(E,\ d) for Z \leq 2 = (d,\ r_cW)\varphi_{i,eva:rec}(E) for 3 \leq Z \leq 8 = 0 for 9 \leq Z$ (3)

where $\phi_i(d,\ r_cW)$ is the normalization flux in $cm^{;2s^{-1}}$, and $\varphi_{i,all}(E,\ d)$ and $\varphi_{i,eva:rec}(E)$ are the normalized energy spectra of the secondary particles i in (MeV/n), which are produced by all three reaction mechanisms and only by the evaporation and recoil processes, respectively. The flux of particle i at 1 (MeV/n) was selected as the numerical value of ϕ_i because the contributions of the primary particles are almost negligible for such a low energy level. Note that the symbols ϕ, φ, and ϕ are used for representing absolute fluxes, normalized energy spectra, and fluxes used for normalization, respectively [12].

Combining primary and secondary ion fluxes

In the same manner as our previous study, we employed the following function to calculate the total ion fluxes of particle $i\phi_{i,}$

$$\phi_i(E,\, d,\, r_c,\, W) = \frac{\emptyset_{I,PRI}(E,d,W)\{\tan h\{O_{1,i}[E/E_{s1,I}(r_c,d)-1]\}+1\}}{2} + \frac{\phi_{i,}\sec,(E,d,r_c,W)\{\tan h\{O_{2,i}[1-E/E_{s2,i}(r_c,d)]\}+1\}}{2} \quad (6)$$

where $\emptyset_{I,PRI}$ and $\phi_{i,}$ sec, are the primary and secondary fluxes calculated using Eqs (3) and (4), respectively, $E_{s1,i}$ and $E_{s2,i}$ are the switching energies between the primary and secondary spectra, and $O_{1,i}$ and $O_{2,i}$ are free parameters that influence the smoothness of spectrum switching.

Neutron fluxes

Thus, we express the neutron fluxes below 20 km, $\emptyset_n$,<20 km $(E,\, d,\, r_c,\, W)$ using a function like Eq. (5) as follows:

$\emptyset_{n,<20Km}(E,\, d,\, r_c,\, W) = \emptyset_n(d,\, r_c,\, W)\psi_n(E,\, d,\, r_c)$ (7)

where $\emptyset_n(d,\, r_c,\, W)$ is the normalization flux in $cm-^2$, and $\psi_n(E,\, d,\, r_c)$ is the normalized energy spectrum of neutrons in (MeV/n), which depends not only on the atmospheric depth, d, but also on the cut-off rigidity, rc [9].

Table 1: Parameters of Lagos, Abuja and Maiduguri

S/N	Parameter	Lagos	Abuja	Maiduguri
1	Atmospheric depth (g/cm^2)	97.815	9. 7.815	197.815
2	Cut-off rigidity (GV)	14.55	14.90	15.10
3	Solar activity index during solar minimum	0.0	0.0	0.0
4	Local Effect MASS (100) ton	0.75	0.75	0.75

Total Effective dose during the flight at 12 km altitude along the flight route in terms of vertical cut-off rigidity (R) during solar max. and solar min, respectively.

Average effective dose between Abuja-Lagos during solar max = 1.63 µSv/hr

Average effective dose between Abuja-Lagos during solar min = 1.93 µSv/hr

Annual effective dose between Abuja-Lagos during solar minimum per annum for 200 hours of flight is given as,

200 × 1.93 µSv/hr = 386 µSv

386 µSv/hr = 0.386 mSv

Annual effective dose between Abuja-Lagos during solar maximum per annum for 200 hours of flight is given as,

200× 1.63 µSv/r= 326 µSv

326 µSv = 0.326 mSv

From the calculation of the linear regression, the average effective dose at solar maximum is 0.326 mSv and at solar minimum is 0.386 mSv, respectively.

Results and Discussion

It can be observed from Table 2 above that the total energies of the secondary particles are the sum of each secondary particle. Therefore, it reveals that a passenger travelling along these air routes would have absorbed such ionizing energies recorded in Table 2. Abuja-Maiduguri air routes have the highest absorbed doses at solar minimum, which is 2.422 μ Sv/h. While Lagos-Abuja air routes also have a lesser absorbed dose of 1.954 μSv/h at solar minimum compared to that of Abuja-Maiduguri routes. A passenger travelling along these air routes would have absorbed a maximum of 2.422 μSv/h, which is a quite disturbing number for a regular passenger to be exposed to due to frequent travel.

Table 2: Absorbed dose for Lagos, Abuja, and Maiduguri

Cosmic rays	Lagos solar max (uSv/h)	Lagos solar min (uSv/h)	Abuja solar max (uSv/h)	Abuja solar min (uSv/h)	Maiduguri Solar max (uSv/h)	Maiduguri Solar min (uSv/h)
Total	2.114	1.954	2.076	2.451	2.055	2.422
Neutron	6.459	6.124	6.273	7.790	6.174	7.660
Proton	2.807	3.592	2.746	3.343	2.712	3.291
He ion	1.336	2.406	1.299	1.559	1.279	1.531
Moun+	6.236	6.613	6.148	6.996	6.099	6.933
Moun-	5.844	6.225	5.765	6.588	5.721	6.531
Electron	5.224	2.318	5.170	5.898	5.140	5.852
Position	3.671	2.086	3.630	4.146	3.608	4.115
Photon	1.756	3.898	1.735	1.959	1.723	1.942
Other ions	1.590	2.152	1.543	1.842	1.518	1.807

Table 3: Effective dose for Lagos, Abuja, and Maiduguri

Cosmic rays	Lagos Solar Max (uSv/h)	Lagos Solar Min (uSv/h)	Abuja solar max (uSv/h)	Abuja solar min (uSv/h)	Maiduguri Solar Max (uSv/h)	Maiduguri Solar min (uSv/h)
Total	1.648	1.954	1.618	1.913	1.601	1.889
Neutron	4.931	6.124	4.789	5.945	4.713	5.845
Proton	2.938	3.592	2.875	3.499	2.840	3.446
He ion	2.027	2.406	1.975	2.336	1.946	2.297
Moun+	5.796	6.613	5.714	6.509	5.669	6.450
Moun-	5.431	6.225	5.358	6.130	5.317	6.076
Electron	2.026	2.318	2.005	2.287	1.993	2.269
Position	1.823	2.086	1.803	2.059	1.791	2.043
Photon	3.439	3.898	3.399	3.838	3.376	3.804
Other ions	1.793	2.152	1.740	2.080	1.710	2.040

The total energies of the secondary particles are the total of each particle as represented in Table 3, revealing to us the number of effective doses passengers travelling along these air routes will be exposed to. Lagos-Abuja air routes have the highest effective dose exposure at solar minimum, which is 1.954 μSv/h. Abuja-Maiduguri air route also has a high effective dose of 1.9131μSv/h at solar minimum, but less than that of the Lagos-Abuja air route. These high-energy secondary particles can cause cancer mortality and memory loss after long-term exposure due to frequent travel.

Cosmic ray spectrum

Figures 2 -5 show results for the cosmic ray spectrum for the Lagos-Abuja air route.

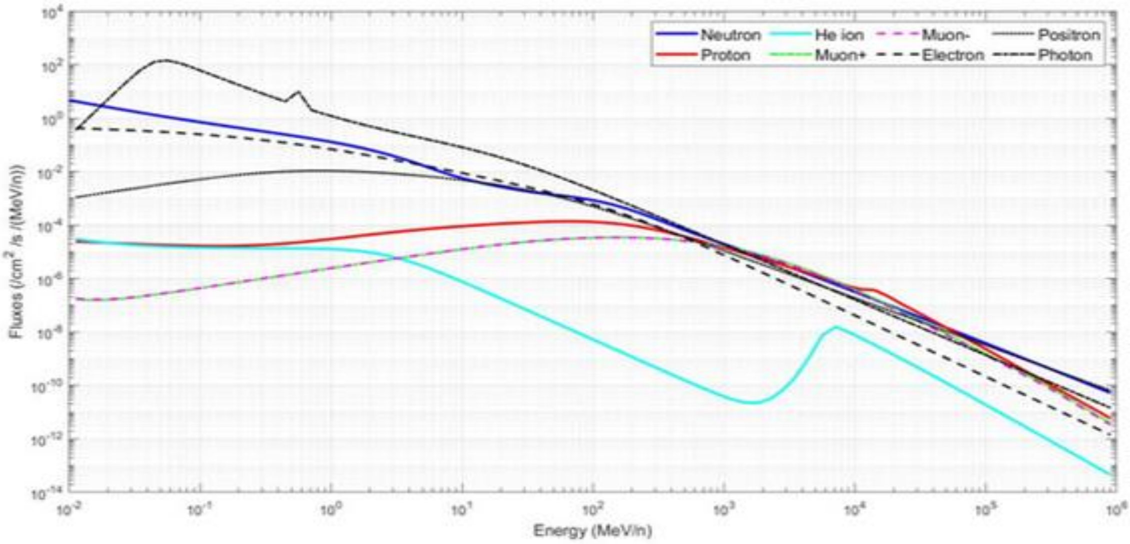

Figure 2: Lagos ray flux at solar min

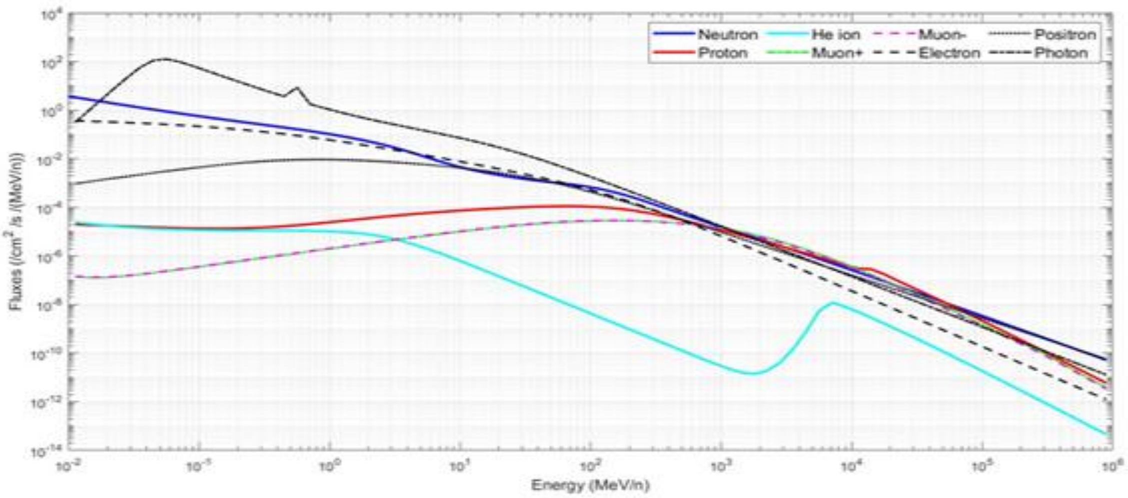

Figure 3: Lagos ray flux at solar max

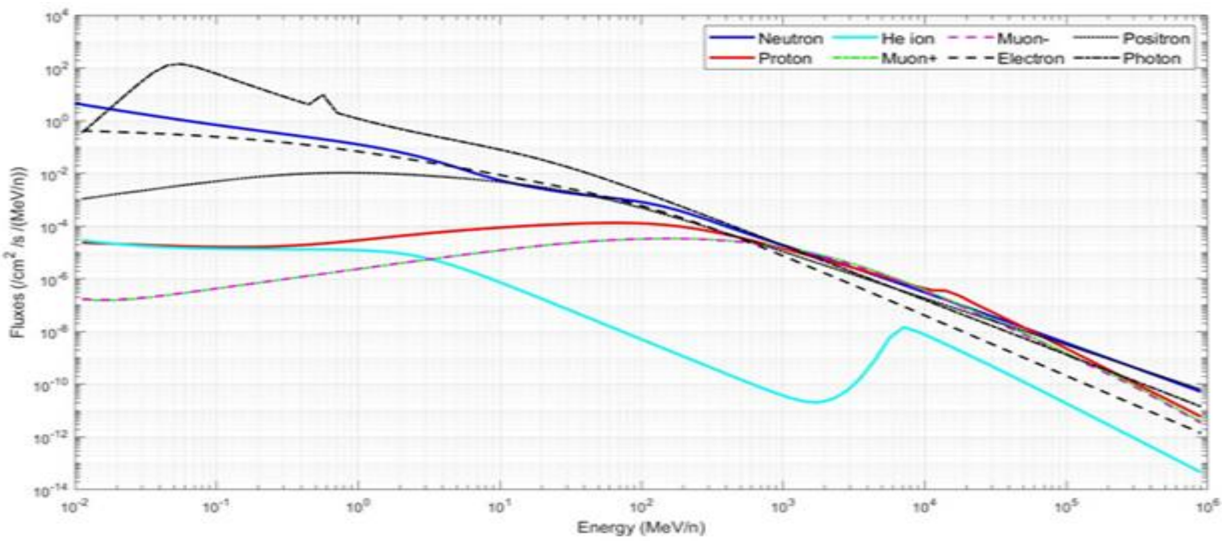

Figure 4: Abuja ray flux at solar min

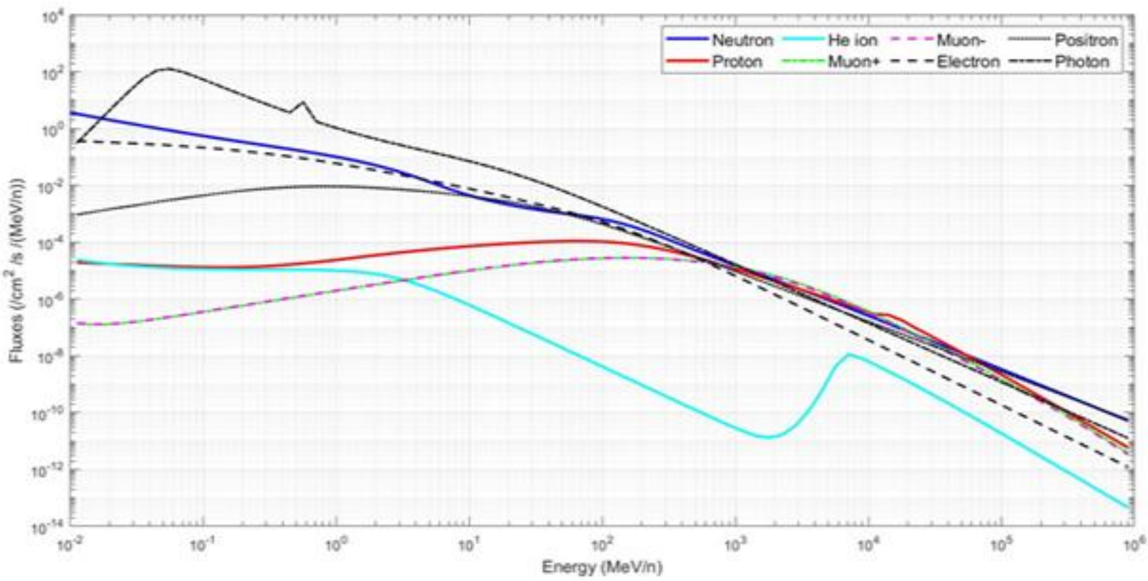

Figure 5: Abuja ray flux at solar max

Figures 3-6 show the components of the cosmic ray spectrum along the air routes. We can see that the photons, neutrons, and electrons are the largest contributors to space radiation at aviation altitude. While primary neutrons may not pose a great problem, the secondary neutrons, after interacting with matter, may create a radiation field that is detrimental to human tissues and organs. Energetic electrons can cause memory loss and damage to devices.

The alpha particles can be particularly harmful because of their very high ionizing power.

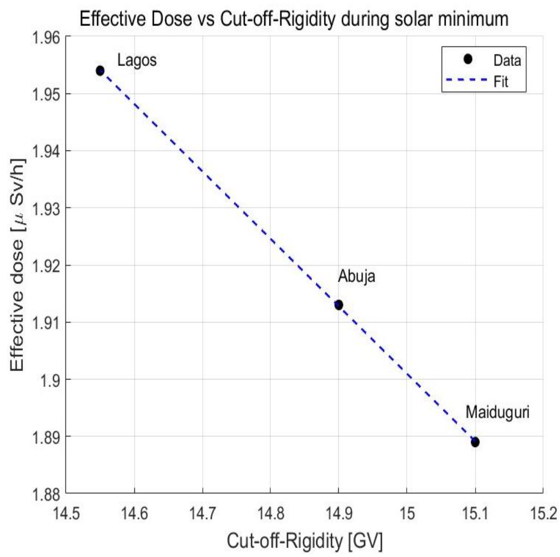

Figure 6: Effective dose, linear regression plot

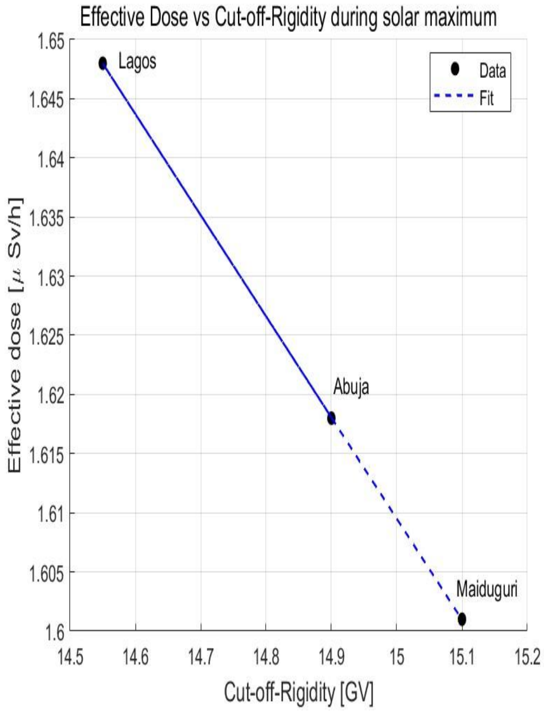

Figure 7: Effective dose, linear regression plot during solar maximum

During Solar maximum, i.e., Solar cycle, the effective dose is observed to be less along this air route compared to Solar minimum, and it can be observed that the Dose is still high for travelers at Lagos and reduces as it approaches Maiduguri.

The linear regression below fits the data well in the aircraft cabin.

$Y_{EFF\_max}= -0.0855R + 2.8918$

$Y_{EFF\_min}= -0.1181R + 3.6719$

Where R is the cut-off rigidity

$R = 14.9cos^4\omega$ (8)

ω is the geomagnetic latitude

Therefore, with the above equation, if the geomagnetic latitude is known, the cutoff rigidity for any place on earth could be determined. If you have a traveler between Lagos and Abuja at least 2 times a week between Lagos and Abuja, he/she would have accumulated about 200 hours of flight in a year. Therefore, a regular passenger who flies at an average of 200 hours per annum and is not active radiological personnel travelling at aircraft altitude along the Lagos – Abuja air route would have been exposed to an effective dose of 0.386 mSv at Solar minimum and 0.326 µSv at Solar maximum per annum.

The above results for the effective dose at both Solar minimum and Solar maximum indicate that the dose the passenger is exposed to is within the recommended dosage approved by ICRP, but considered high for average non-radiological passengers if such a passenger makes such journeys for 4 years, he /she would have accumulated a dose of 1.55 mSv So therefore over the periods of 4 years he/she has exceeded the ICRP recommendation per annum and slowly accumulated high does over time which has increased the risk of cancer mortality and other radiation-associated risks [14]. The ICRP recommends a radiation permissible limit of 1 mSv per annum for the public [15].

Conclusion

The Effective dose and absorbed dose were calculated to be within the ICRP permissible doses, but considered high for a regular passenger flying at an aircraft altitude for an average of 200 hours per annum for four years. These results are above the standard permissible limits set for the public and pregnant women who are aircrew members, but below the limit set for occupationally exposed persons. Long-term continuous exposure to cosmic radiation at the aviation routes between Lagos, Abuja, and Maiduguri is likely to increase the overall risk.

Recommendation

In General, such persons travelling for such a high number of flights per annum are exposed to high doses of cosmic radiation, which in turn will increase the cancer mortality rate and illnesses that are caused by exposure to high-energy particles. We recommend that individuals reduce the flight time across this route to minimize or avoid being exposed to radiation. In order to increase life expectancy and reduce cancer mortality rates.

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