Children’s exposure to cosmic radiation from flight travels

Background

Ionizing radiation is a known risk factor for cancer, whereas children are particularly susceptible. The majority of most people’s exposure originates from natural background radiation, whereas flight travels account for increased exposure to cosmic radiation, as it is more intense at high altitudes.

Objective

The objective of this thesis is to quantify children’s exposure to cosmic radiation from flight travels in Switzerland based on survey data from the Childhood Cancer and Low-Dose Ionizing Radiation in Switzerland (CALIRIS) study.

Method

In an initial preprocessing, non-eligible and incomprehensible flight data from the questionnaires is removed. Realistic flight profiles then are calculated based on a great circle route and flight characteristics of typical short-, medium- and long-haul airplanes. The dose calculations are performed using EPCARD, the European Program Package for Calculation of Aviation Route Doses. Additionally, the total number of flights is estimated using different methods.

Results

The mean number of flights per child in the 12-month period is 0.844 (SD = 1.303) round trips and 1.651 (SD = 2.529) individual flights. The median is 0 (IQR = 1) and 0 (IQR = 2), respectively. The mean flight distance is 3702 (SD = 7694) km and the mean cosmic radiation dose from the flight travels accounts for 17.3 (SD = 40.5) μSv. We find that the household income, the level of education of the parents, and the grade of urbanization of the living area positively correlate with the number of flights and the cosmic radiation dose thereof. A negative correlation is found for the total household size. Moreover, French-speaking children fly more frequently than children of other language regions, and so do children with foreign citizenship compared to Swiss children.

Conclusion

The number of flight travels in children are largely in line with the findings of the Swiss Federal Statistical Office for the general population, but the observed flight distances are lower. Moreover, socioeconomic factors flight play an important role in flight behavior. For the majority of the children, the contribution of the cosmic radiation from flight travels to the total cosmic radiation dose is considered small. Hence, the effect on the cancer risk is assumed to be of minor relevance. For a minority of children with a very high number of flights, however, the contribution might become more important.

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Sehr geehrte Damen und Herren

Gerne stelle ich seitens Studiendekanat zu Handen der Fachgesellschaft der eidgenössisch anerkannten Public Health Fachärztinnen und -ärzte (SPHD) anlässlich der Teilnahme am SPHD Awards 23 folgende Bestätigung für Herrn Micha Güdel aus:

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Children's exposure to cosmic radiation from flight travels

Survey study

Master Thesis submitted by

Micha Christoph Güdel

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1 Introduction

1.1 Ionizing radiation

Ionizing radiation is a risk factor for cancer, whereas children are particularly susceptible[1,2]. The cancerogenic effects are well studied for high-dose exposure, e.g., from radiation therapy or nuclear accidents[1]. In contrast, evidence for low-dose exposure is inconclusive and the effect on cancer risk remains controversial[3].

Low-dose, natural background radiation accounts for the majority of most people's exposure[4]. This ubiquitous type of radiation consists of terrestrial gamma radiation, cosmic radiation, and residential radon. For children as a particularly vulnerable group, some studies have reported positive associations with leukemia and CNS tumors from natural background radiation in Switzerland[5]. Other relevant exposure results from medical diagnostic radiology, mainly CT scan and X-ray. The estimated average annual radiation dose in Switzerland is 5.8 mSv[6]. The contributions of the different sources of radiation are shown in Figure 1.

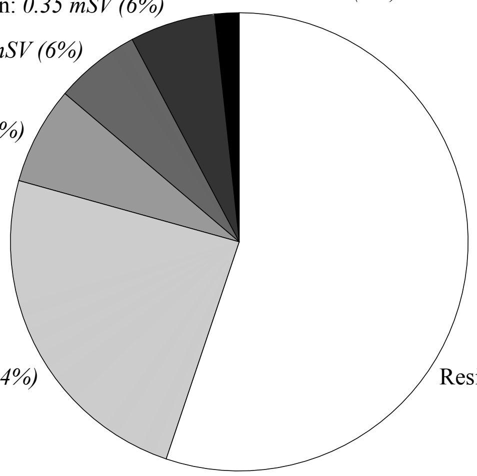

Figure 1: Contributions to the average annual dose of ionizing radiation in Switzerland (total 5.8 mSv)[6].

1.2 Cosmic radiation in flight travels

According to Figure 1, cosmic radiation accounts for approximately 7% of the annual dose of ionizing radiation in Switzerland. This type of radiation originates from high-energy particles from cosmic space, to which the earth is constantly exposed[7]. These galactic cosmic rays interact with solar winds and the earth's atmosphere and magnetic field[7]. Therefore, exposure to cosmic radiation greatly varies with time, geographic position, and altitude. In general, cosmic radiation becomes more intense at higher altitudes as the earth's atmosphere absorbs much of its energy.[8,9] As an example, at Central European latitudes the cosmic radiation accounts for approximately 0.3-0.5 mSv/y at sea level, whereas at 10'000 m above sea level values in the range of 20-50 mSv/y are observed[8,10].

For the above reasons, flight travels come with increased exposure to ionizing radiation and air passengers and crew might be at an increased risk for cancer[8]. Several studies investigate this association for aircrews and frequent air travelers as a particularly exposed group of people. It is agreed that the excess risk if it exists, is very small[7,9–14]. Findings, however, are inconsistent and further research is needed[7,9–11,14]. No studies are found for the general population and children.

1.3 Flight travels in Switzerland

According to the Swiss Federal Statistical Office (FSO), the yearly average distance traveled by airplane is 8986 km per person in Switzerland[15]. Thereof, 7163 km originate from flight travels with an overnight stay[15]. On average, 0.83 of these round trips are taken per year, whereas the amount positively correlates with household income and urbanization of the living area[15]. This number is equal in men and women, whereas the age groups 18-24 and 25-44 travel the most with 1.1 trips per year each[15]. The age group 6-17 travels less with an average of 0.6 trips per year[15]. Data for younger children is not reported. The study is based on the evaluation of over 57’000 questionnaires and does not provide information on cosmic radiation doses resulting from the flights.

1.4 Framework and aim of this thesis

The Childhood Cancer and Low-Dose Ionizing Radiation in Switzerland (CALIRIS) study consists of a nationwide survey on children living in Switzerland with three major aims: to assess the contribution to total doses of radiation from different sources, investigate lifestyle factors that modify exposure to background radiation, and improve and validate exposure models in Switzerland. The CALIRIS study is conducted at the Institute of Social and Preventive Medicine (ISPM) at the University of Bern, as part of a larger project that investigates the effects of low-dose ionizing radiation on childhood cancer. Within the framework of this study, this thesis aims at quantifying the frequency of flight travels in children and the amount of cosmic radiation exposure from these flight travels.

2 Method

2.1 Overview

Based on data collected in the CALIRIS study, this thesis aims at quantifying children's exposure to cosmic radiation from flight travels. An overview of the data processing is given in Figure 2. It consists of the initial data collection, preparation, and cleaning, the subsequent generation of flight profiles, and the actual dose calculations in EPCARD as well as the analysis of the number of flights.

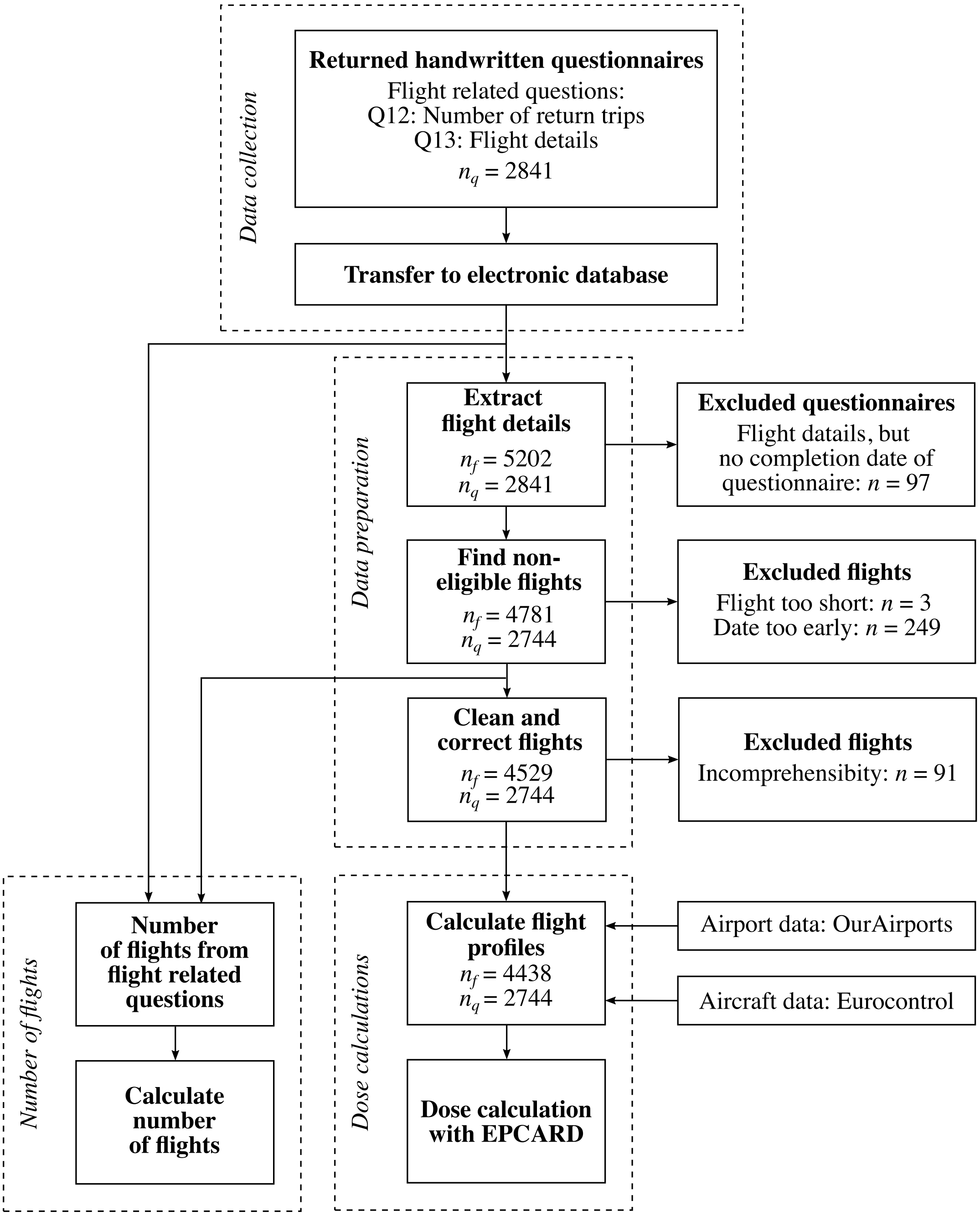

Figure 2: Overview of the data processing used to calculate the number of flights and the cosmic radiation dose from the flight travels. The number of questionnaires and flights in a step are denoted n_q and n_f, respectively.

2.2 Data collection

2.2.1 The CALIRIS study

The CALIRIS survey consisted of a nationwide cross-sectional survey of children living in Switzerland. Starting from February 2019, 8328 questionnaires are sent to households with children. The survey includes general and specific questions about current and previous places of residence, diet, outdoor activities, medical examinations, and flight travels. A total of 2841 questionnaires with completion dates from March 4, 2018, to September 21, 2019, are returned. In this thesis, these are evaluated regarding flight travels.

2.2.2 Flight-related questions

In the questionnaire, participants are asked to fill in the total number of completed flight travels (round trips) during the last 12 months (Question 12, Q12). For each flight, information about the origin, destination, date, airline, and intermediate stops is requested (Question 13, Q13). See Appendix A for the original flight-related questions.

In this work, an individual flight or simply flight is referred to as one start and one landing. A round trip, in contrast, denotes a trip from an origin to a destination and back, irrespective of the number of intermediate stops. As an example, a round trip from Zurich to Fuerteventura via Madrid and back is counted as four individual flights.

2.2.3 Non-flight-related questions

These questions request about radiation exposure from different sources as well as general information about the child. The answers to questions about the age, living area, language, nationality, parent's education, household size and income are used for reporting the results separately for different socio-economic groups.

2.3 Data preparation

Extensive data preparation is required to bring the handwritten answers in the questionnaires to a standardized format suitable for automatic dose calculations. An exemplary filled-in form is shown in Figure 3, whereas Figure 4 shows the same form after the data preparation presented in this section.

2.3.1 Eligible flight travels

Only flight travels within the 12-month before the completion of the questionnaire are eligible. No completion date is given in 97 questionnaires with filled-in flight details. These questionnaires containing a total of 421 flights are excluded from the study, as the 12-month time period cannot be checked.

Moreover, only flight travels with airplanes and a distance between origin and destination greater than 100 km are included in the study. In particular, this excludes flights with helicopters and sightseeing flights, as their flight profile cannot be approximated from the available data. In most cases, however, such flights arise from incorrectly filled in questionnaires. The effect of this restriction on the results is considered neglectable, as the number of affected flights is small and they are typically at low altitudes. A total of 3 flights in 3 questionnaires are excluded from the study due to this constraint.

Finally, a total of 249 flights in 125 questionnaires are excluded due to the flight dates not falling into the 12 months before the completion of the questionnaire.

2.3.2 Incorrectly completed questionnaires

Confused or repeated data in a total of 43 questionnaires is corrected. Most often this is related to mixed up columns and intermediate stops identical to a flight's destination. The most common mistakes are shown in Figure 3 and corrected in Figure 4.

Flights with missing origin or destination airports are excluded from the dose calculations unless the missing data is part of a round trip and can be inferred from the remaining data. In cases where only a country or city name is given, the busiest airport by passenger traffic in this area is assumed.

Misspelled data in origin and destination of a flight is corrected, if the meaning is clear or can be easily inferred from the data, i.e., from an airline's flight plan. If this is not possible or the airport's name is incomprehensible, a given flight is excluded from the study unless the affected airport is an intermediate stop. In this case, the intermediate stop is simply omitted. Misspelled dates are corrected to the most probable date.

A total of 91 flights in 34 questionnaires are excluded from the dose calculations for these reasons.

2.3.3 Date and time

As the exact time of flight is not asked for in the questionnaire, all flights are assumed to depart at 09:00 a.m. CET (10:00 a.m. UTC) on the given date, including consecutive flights resulting from intermediate stops and irrespective of changing time zones. According to Rodrigue[16], most European airports have flight departure peaks in the mornings and evenings. These correspond to short-haul flights, where passengers prefer to depart early and return late. For simplicity, only the wider morning peak at around 8-10 a.m. is considered.

Whenever no specific flight date is given, default values are used. The default date is July 1, 2018, for missing or incomprehensible dates (n = 17), the default for a missing year is 2018 (n = 11). This corresponds to the year the vast majority of the flights are reported in the questionnaires and July 1 being mid-year. For a month with no specified day, mid-month, i.e., the 15th day of the month is assumed (n = 750). If only a season is reported, January 1, April 1, July 1, and October 1 are used for winter, spring, summer, and autumn, respectively (n = 21).

2.4 Total number of flights per child

In many questionnaires, the flight-related questions Q12 and Q13 contain contradictive data concerning the number of taken flights. Also, the flights are counted differently, i.e., round trips and single flights in Q12 and Q13, respectively. Therefore, the numbers are calculated separately for each question. For Q13, the number of single flights before removing incomprehensible flights is used. For Q12, if a number of return trips is given, this value is used. If Q12 is left blank or incomprehensible (n_q = 288), half of the number of the single flights counted in Q13 is used or, if the questionnaire is excluded from the dose calculations due to a missing completion date, the questionnaire is excluded from the number of flight calculations from Q12 as well.

2.5 Dose calculations

2.5.1 General

The dose calculations are performed using the "European Program Package for Calculation of Aviation Route Doses" (EPCARD.NET, ver. 5.4.3 Professional), an aviation authority-certified software. It uses measurement data from a Neutron monitor database and FLUKA Monte Carlo simulations to calculate the cosmic radiation at a given geographical position, altitude, and time[17]. Hence, the airplane's flight profile, i.e., its geographical position and altitude over time, needs to be known as a prerequisite. Usually, this data is readily available, as EPCARD is almost exclusively used by airlines to keep track of the radiation exposure of their crew. To us, however, the flight profiles are unknown.

One option is to obtain the flight profiles from flight tracking services, such as FlightAware[18] or FlightRadar24[19]. These services typically provide online real-time flight tracking for free. Many also offer profiles of historic flights as a premium service. This, however, is rather expensive. FlightAware, for instance, would charge more than 7'000 USD for our dataset. In this study, as an alternative, the flight profiles are approximated using the shortest possible flight route and a kinematics model. Using the flight characteristics, i.e., velocity profiles, of aircrafts, this approach allows for physically modeling the flight profile of an airplane.

Outbound	Example	Flight 1	Flight 2	Flight 3	Flight 4
Departure airport	Geneva	Belp	Basel	CH	GVA
Date (dd.mm.yy)	13.04.18	25.9.	Ohrid	Autumn 2018	Easter 18
Destination airport	John F. Kennedy, NY	Rhodos	6.2018	NYC	Spain
Stop airports	Frankfurt	/	-	NYC	XXX
Company	SWISS/Lufthansa	Helvetic	Wizzair	Swiss	Easyjet
Return					
Departure airport	John F. Kennedy, NY	Rhodos	Ohrid	Chicago	
Date (dd.mm.yy)	02.05.18	2.10.	Basel		
Destination airport	Geneva		8.18	Zürich	
Stop airport	Frankfurt	/	-	Paris, Boston	
Company	Lufthansa	Helvetic	Wizzair	Air France	

Figure 3: Illustrative questionnaire as it may be filled in by study participants. The entries are in a non-standardized form and possibly erroneous. The entries in red are affected in the subsequent data preparation:
***Flight 1**: No year given and missing destination airport in round trip.*
***Flight 2**:Destination and flight date entries mixed up as well as a missing day of the month in flight dates.*
***Flight 3**:Ambiguous departure, destination, and stop airports as well as missing and imprecise flight dates.*
***Flight 4**: Ambiguous destination airport and non-numeric date.*

Outbound	Example	Flight 1	Flight 2	Flight 3	Flight 4
Departure airport	Geneva	BRN	BSL	ZRH	GVA
Date (dd.mm.yy)	13.04.18	25.9.2018	15.06.2018	01.10.2018	01.04.2018
Destination airport	John F. Kennedy, NY	RHO	OHD	JFK	MAD
Stop airports	Frankfurt				
Company	SWISS/Lufthansa	Helvetic	Wizzair	Swiss	Easyjet
Return					
Departure airport	John F. Kennedy, NY	RHO	OHD	ORD	
Date (dd.mm.yy)	02.05.18	02.10.2018	15.08.2018	01.07.2018	
Destination airport	Geneva	BRN	BSL	ZRH	
Stop airport	Frankfurt			BOS,CDG	
Company	Lufthansa	Helvetic	Wizzair	Air France	

Figure 4: Illustrative questionnaire from Figure 3 after applying the data preparation described in Section 2.3. The entries in blue are affected by changes compared to the original data shown in Figure 3:
***Flight 1**: Assume default year 2018 and add most probable destination airport.*
***Flight 2**: Sort destination and flight date entries and use the default day of the month (15th)*
***Flight 3**: Use largest airports in Switzerland, New York, and Paris, assume the most probable order of intermediate stops, remove unnecessary intermediate stop and use default dates (October 1 and July 1, 2018).*
***Flight 4**: Use numeric date of Easter 2018 and largest airport in Spain (Madrid-Barajas).*

2.5.2 Flight profile generation

The flight profile generation aims at modeling the airplane's flight profile, i.e., its position and altitude over time, which is required to run the dose calculations in EPCARD. The calculations are performed in MATLAB, a numeric computing environment developed by MathWorks.

Flight route

A flight route $\boldsymbol{r}(d)$ captures the geographical position $(lat; lon)$ and altitude alt of the airplane on its way between two airports irrespective of time. We denote,

$$\boldsymbol{r}(d) = \begin{pmatrix} lat(d) \\ lon(d) \\ alt(d) \end{pmatrix}, \forall d \in [0, D] ,$$

where d is the position on the route and D denotes the route's total length.

For the geographical position, a great circle route is assumed, i.e., the airplane travels along the shortest route between two points on the earth's surface. It is calculated using MATLAB's built-in function and the airport's geographic coordinates obtained from OurAirports[20], an open airport database.

The altitude profile of the route depends on the aircraft's flight characteristics and is determined from the aircraft's velocity profile, as discussed in the following section.

Velocity profile

A typical flight consists of a climb to cruising altitude, followed by a travel at cruising altitude, and a descent to the destination airport. The horizontal and vertical velocity components during these phases depend on the type of aircraft. Three popular commercial airplane models, the ATR 72, Airbus A320, and Airbus A340 are used in this study to represent airliners typically used for short-, medium, and long-haul flights, respectively. The relevant data is obtained from Eurocontrol, the European Organisation for the Safety of Air Navigation[21]. Depending on a flight's total distance D, the characteristics of one of the three airplanes is used to model the velocity profile of the flight, as summarized in Table 1 and depicted in Figure 5. The effect of winds on the airplanes' ground velocity is not considered, i.e., no-wind conditions are assumed.

Considering a velocity vector $\boldsymbol{v}$ consisting of a vertical and a horizontal component,

$$\boldsymbol{v} = \begin{pmatrix} v_{vert} \\ v_{horz} \end{pmatrix},$$

we have the following kinematics model to obtain the traveled distance $\boldsymbol{d}$,

$$\boldsymbol{d} = \begin{pmatrix} alt \\ d \end{pmatrix} = \int \boldsymbol{v}\, dt .$$

Applying this kinematics model to the different flight phases allows for describing the position of the aircraft on the flight route as a function of time $d(t)$.

In the climb phase, let $\boldsymbol{v}_c$ denote the velocity,

$$\boldsymbol{v}_c = \begin{pmatrix} v_{c\_vert} \\ v_{c\_horz} \end{pmatrix}.$$

Using kinematics, we get for the climb phase,

$$\boldsymbol{d}_c = \begin{pmatrix} alt_{cruise} - alt_{origin} \\ D_{c\_horz} \end{pmatrix} = \int_0^{T_c} \boldsymbol{v}_c \, dt \,,$$

where D_{c_horz} is the horizontally travelled distance in the climb phase, and $alt_{cruise} - alt_{origin}$ is the difference in altitude between the origin airport and the cruising altitude. T_c is the time it takes the airplane for the climb.

Similarly, for the decent phase, we have the velocity $\boldsymbol{v}_d$,

$$\boldsymbol{v}_d = \begin{pmatrix} v_{d\_vert} \\ v_{d\_horz} \end{pmatrix},$$

and the kinematics,

$$\boldsymbol{d}_d = \begin{pmatrix} alt_{cruise} - alt_{destination} \\ D_{d\_horz} \end{pmatrix} = \int_0^{T_d} \boldsymbol{v}_d \, dt \,,$$

where D_{d_horz} is the horizontally travelled distance in the descent phase, $alt_{cruise} - alt_{destination}$ is the difference in altitude between the destination airport and the cruising altitude, and T_c is the time it takes the aircraft for the decent.

Finally, for the cruising phase at constant altitude alt_{cruise} and constant velocity v_{cruise}, we have,

$$D = D_{c\_horz} + D_{d\_horz} + \int_0^{T_{cruise}} v_{cruise} \, dt \,,$$

where T_{cruise} denotes the total time in the cruise phase.

Combining these equations of motion of the climb, cruise, and descent flight phases, we have generated the desired flight profile, i.e., we have described $alt(t)$ and $d(t)$ $\forall t \in [0, T = T_c + T_{cruise} + T_d]$, such that $d(T) = D$.

2.5.3 EPCARD configuration

We use the standard minimal configuration of EPCARD, where each flight is characterized by four waypoints, which represent the flight's origin, top of climb (TOC), top of decent (TOD), and destination. The model is shown in Figure 6. It is a slightly simplified model compared to the one used for the flight profile generation. To perform the dose calculations, EPCARD uses linear interpolation in-between the waypoints and estimates geographical position from the great circle route.

Table 1: Flight characteristics of the three airplane models used to generate the velocity profiles[21].

	ATR 72		**Airbus A320**		**Airbus A340**	
Ascent	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal
0 – 5’000 ft	1’500 fpm	140 knot	2’500 fpm	175 knot	1’500 fpm	175 knot
5’000 – 15’000 ft	1’000 fpm	210 knot	2’000 fpm	290 knot	1’200 fpm	290 knot
15’000 – 24’000 ft	1’000 fpm	210 knot	1’400 fpm	290 knot	1’000 fpm	290 knot
24’000 ft – Cruise alt.			1’000 fpm	Mach 0.78	600 fpm	Mach 0.81
Cruise						
Speed	250 knot		Mach 0.79		Mach 0.82	
Altitude	24’000 ft		33’000 ft		36’000 ft	
Decent						
Cruise alt. – 24’000 ft	1’500 fpm	250 knot	1’000 fpm	Mach 0.78	1’000 fpm	Mach 0.81
24’000 – 10’000 ft			3’500 fpm	290 knot	2’000 fpm	290 knot
10’000 – 0 ft	1’500 fpm	210 knot	1’500 fpm	250 knot	1’500 fpm	250 knot
Flight distance used for						
Flight distance D	$D \leq 500$ km		500 km $< D <$ 3’000 km		$D \geq$ 3’000 km	

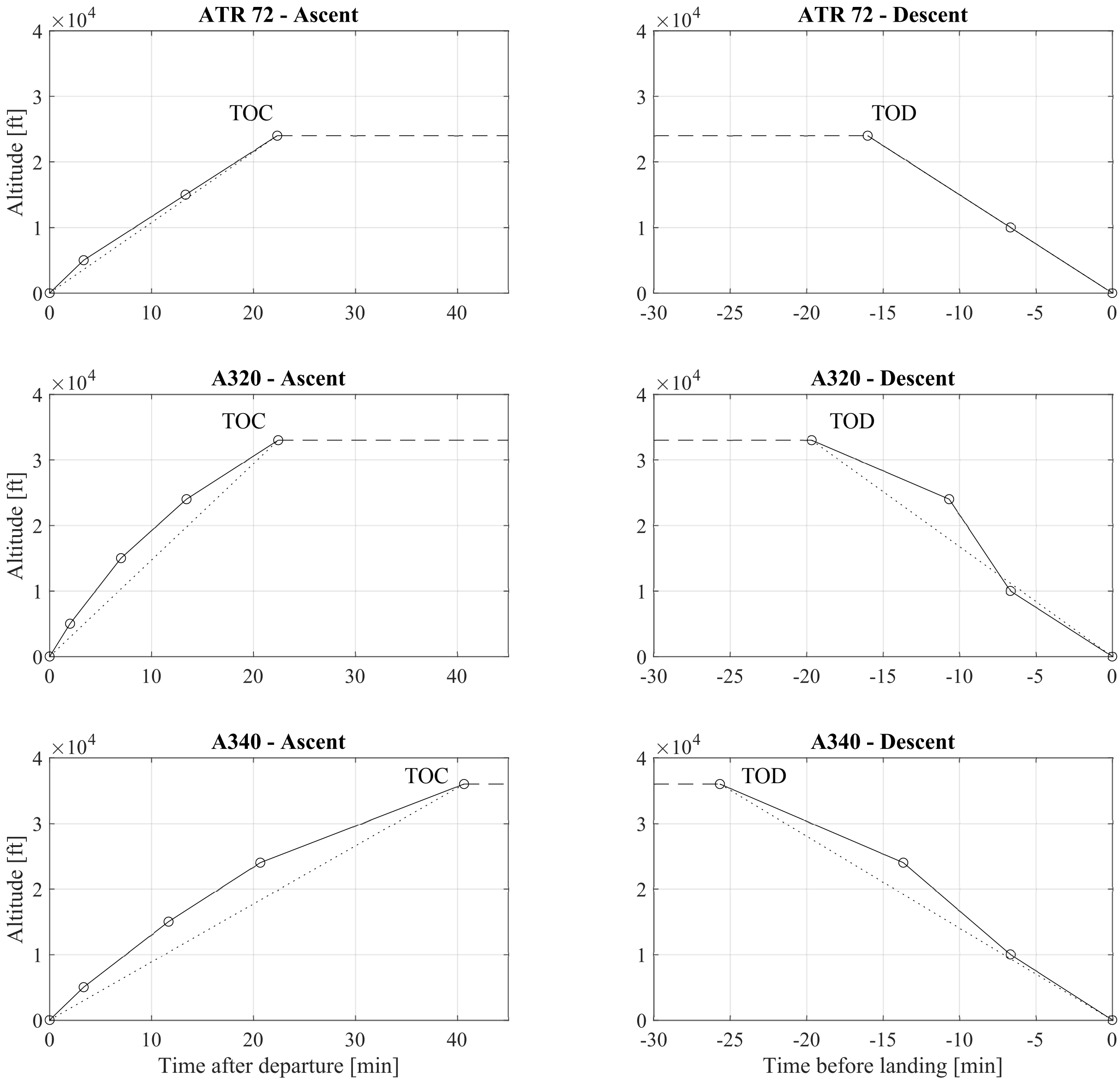

Figure 5: Flight profiles of the three airplane models (solid line). The dotted lines correspond to the simplified profiles used in EPCARD. TOC and TOD denote the top of climb and top of descent, respectively.

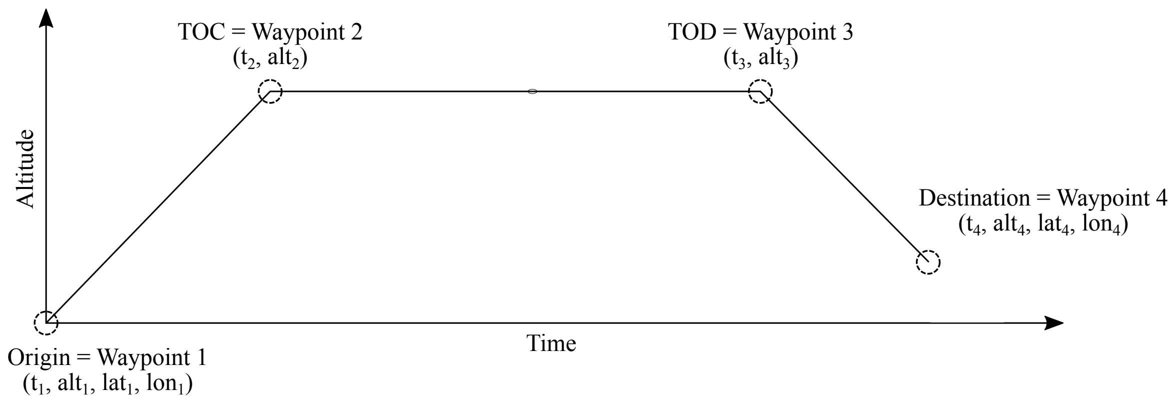

Figure 6: Structure of the simplified flight profiles used in EPCARD consisting of four waypoints. Origin and destination are specified by geographic coordinates, altitude, and time. The intermediate points representing TOC and TOD are specified by altitude and time. Their coordinates are interpolated on the great circle route between origin and destination.

3 Results

3.1 Overview

3.1.1 Flight patterns in children

The results for the number of flights are summarized in Table 2. The values are calculated as described in Section 2.4 and correspond to the total number of flights per child in the 12-month period. Additionally, the final number of flights after exclusions due to incomprehensible data is given (see Figure 2). The corresponding histograms for the total number of flights from Q12 and Q13 are shown in Figure 7.

The mean number of reported round trips from Q12 is 0.844. The number of flights from the flight details given in Q13 is 1.651, whereas about 45% of the children took at least one flight and 22% took more than two flights. Accordingly, 55% of the children did not fly at all in the 12-month period. Within the children with flights, the mean number is 1.820 round trips and 3.694 flights from Q12 and Q13, respectively.

The most frequented airports by starts and landings are shown in Table 3. The table also includes a ranking of the most frequented routes (irrespective of the direction of travel) reported in the questionnaires. A total of 382 unique airports and 898 unique routes are reported, based on the flight data used for the dose calculations.

3.1.2 Total flight distance

Based on the flight data used for the dose calculations, the mean total flight distance per child in the 12-month period is 3702 km, with a standard deviation of 7694 km. The median is 0 km with an interquartile range of 3564 km. The results are summarized in Table 4 and the histogram is shown in Figure 8.

3.1.3 Total cosmic radiation dose

Based on the flight data used for the dose calculations, the mean total cosmic per child from flight travels in the 12-month period is 17.3 μSv, with a standard deviation of 40.5 μSv. The median is 0 μSv with an interquartile range of 13.5 μSv. The results are shown in Table 4 and the corresponding histogram is shown in Figure 8.

Table 2: Total number of flights per child in the 12-month period. Refer to the overview given in Figure 2 for details on the different data sources.

Data source n_q = 2744 questionnaires (if not mentioned otherwise)	**Quantity**	n_f	**Number of flights** Mean (SD) $Q_{0.25}$, Median, $Q_{0.75}$ *min - max*
From number of flights (Q12)	Round trips	2317	0.844 (1.303) 0, 0, 1 0 - 20
From flight details (Q13)	Flights	4529	1.651 (2.529) 0, 0, 2 0 - 26
From flight details (Q13) after exclusions due to incomprehen-sible data, i.e., from the flights for which a dose is extracted	Flights	4438	1.617 (2.493) 0, 0, 2 0 - 26
From Q12, only questionnaires with flights (n_q = 1273)	Round trips	2317	1.820 (1.372) 1, 1, 2 1 - 20
From Q13, only questionnaires with flights (n_q = 1226)	Flights	4529	3.694 (2.602) 2, 2, 4 1 - 26

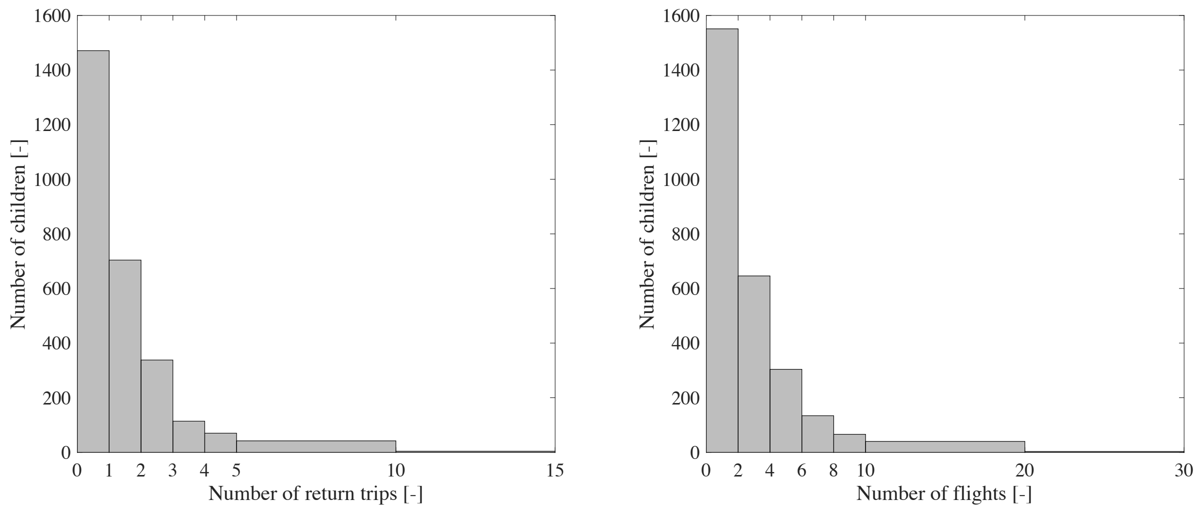

Figure 7: Total number of flights per child in the 12-month period from Q12 (left) and Q13 (right). A total of 1471 (54%) and 1518 (55%) children reported no flights in Q12 and Q13, respectively.

Table 3: Most frequented airports (by starts and landings) and routes (irrespective of direction) based on the flight data used for the dose calculation (n_f = 4438 flights). A total of 382 unique airports and 898 unique routes are reported.

Rank	**Most frequented airports**		**Most frequented routes**	
	Airport	% of all	Route	% of all
1	ZRH	19.66	ZRH - PMI	2.28
2	GVA	12.26	GVA - LHR	1.62
3	BSL	5.52	GVA - OPO	1.28
4	PMI	2.53	BSL - PMI	1.19
5	MXP	2.33	ZRH - HAM	1.19
6	MAD	1.95	ZRH - DXB	1.13
7	LHR	1.89	GVA - LIS	1.13
8	DXB	1.45	GVA - MAD	1.06
9	LIS	1.44	ZRH - BER	1.04
10	FRA	1.24	GVA - BCN	1.01

Table 4: Total flight distance and total cosmic radiation per child in the 12-month period.

Data source n_f = 4438 flights n_q = 2744 questionnaires	**Total flight distance** [km] Mean (SD) *min*, $Q_{0.25}$, Median, $Q_{0.75}$, *max*	**Total cosmic radiation** [µSv] Mean (SD) *min*, $Q_{0.25}$, Median, $Q_{0.75}$, *max*
From dose calculations	3702 (7694) 0, 0, 0, 3564, 83002	17.3 (40.5) 0, 0, 0, 13.5, 468
From dose calculations, only questionnaires with flights (n_q = 1212)	8383 (9737) 555, 2088, 4126, 11869, 83002	39.2 (53.4) 1, 7.2, 15.8, 47.8, 468

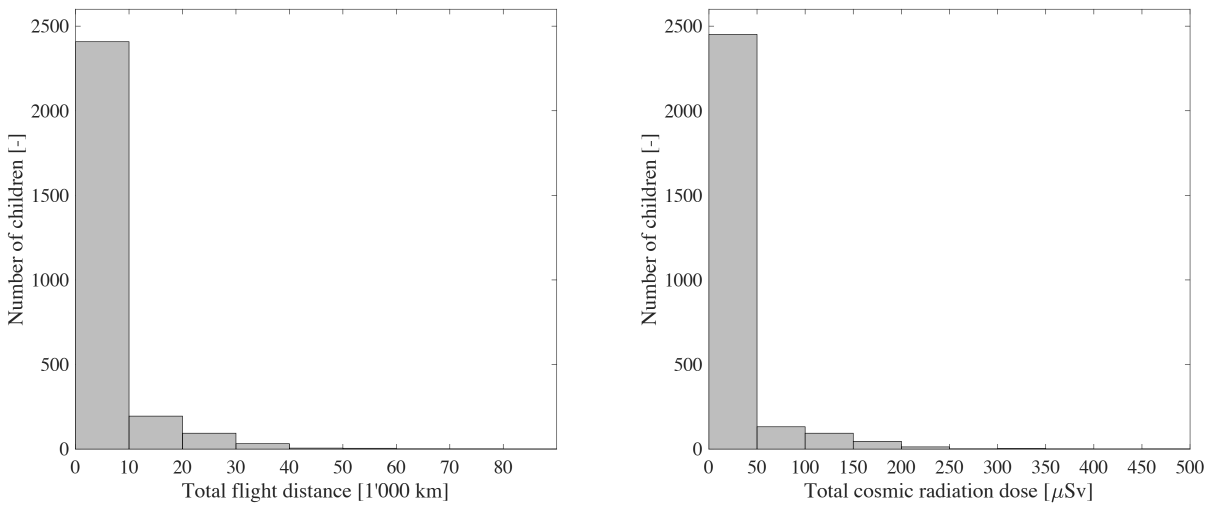

Figure 8: Total flight distance (left) and total cosmic radiation from flight travels (right) per child in the 12-month period.

3.2 Results by socioeconomic factors

The results by socio-economic factors are summarized in Table 5. It is observed that in most subgroups, a higher number of flights corresponds to a longer total flight distance and a higher total cosmic radiation dose. Therefore, for simplicity, sometimes only the number of flights is mentioned in the following.

Considering the different age groups, the results suggest that children tend to fly more often the older they are. As an exception, the children aged 0-2 almost fly as much as those aged 6-8. Similarly, the total gross household income positively correlates with the number of flights. Here, the income class CHF 3'000 - 4'499 is an exception, with almost as many flights as the CHF 9'000 - 12'999 income class. The flights of the former, however, tend to be shorter, resulting in a comparably lower cosmic radiation dose.

Children from three person households fly the most, followed by those from a two person household. For larger households, the results show that the number of flights declines with increasing household size. In terms of parent's education, children from the highest educated parents (university) travel the most, followed by those from the lowest educated (≤ 7 years of compulsory education). Children from parents of the second lowest education class (> 7 years of compulsory education) fly the least.

Considering the living area, children from cities almost fly twice as much as children from rural areas. In terms of language area, it is found that children from the French speaking parts of Switzerland fly the most, followed by children Italian and German speaking regions. Finally, children with a foreign nationality fly 1.8 times more often than their Swiss counterparts, which results in a 1.6 times higher total cosmic radiation dose.

Table 5: Flight patterns by socioeconomic factors (continues on next pages).

		n_q	**Number of flights**[1] Mean (SD)	**Total flight distance**[2] [km] Mean (SD)	**Total cosmic radiation**[3] [μSv] Mean (SD)
Overall		2744	1.651 (2.529)	3702 (7694)	17.3 (40.5)
By age group	0 - 2	505	1.57 (2.6)	3282 (7632)	14.6 (40.2)
	3 - 5	609	1.48 (2.38)	3134 (6698)	14.4 (36.1)
	6 - 8	561	1.56 (2.62)	3532 (7846)	15.2 (35.0)
	9 - 11	557	1.76 (2.47)	3923 (7687)	19.3 (42.2)
	12 - 14	512	1.92 (2.58)	4741 (8569)	23.5 (47.9)

[1] Flights per child in the 12-month period (from Q13), including flights with incomprehensible flight details.
[2] Per child in the 12-month period.
[3] From flight travels per child in the 12-month period.

Table 5: Flight patterns by socioeconomic factors (continued).

		Sample size n_q	**Number of flights** Mean (SD)	**Total flight distance** [km] Mean (SD)	**Total cosmic radiation** [μSv] Mean (SD)
By household size	2	57	1.91 (2.41)	4084 (7077)	17.5 (35.1)
	3	499	2.31 (3.17)	5159 (9558)	23.4 (46.7)
	4	1386	1.62 (2.30)	3765 (7574)	17.9 (40.5)
	5	591	1.35 (2.54)	2882 (6784)	13.4 (37.7)
	> 5	210	1.08 (1.84)	2053 (5090)	10.2 (29.6)
	N/A	1	0 (0)	0 (0)	0 (0)
By total gross household income [CHF]	< 3'000	39	0.56 (1.17)	934 (3215)	4.2 (14.4)
	3'000 – 4'499	100	1.43 (2.69)	2857 (6039)	11.4 (27.0)
	4'500 – 5'999	227	1.01 (1.79)	1649 (3666)	6.7 (18.6)
	6'000 – 8'999	687	1.14 (1.98)	2472 (6300)	12.0 (35.2)
	9'000 – 12'999	779	1.58 (2.36)	3615 (7265)	17.0 (38.9)
	≥ 13'000	612	2.68 (3.12)	6273 (9978)	29.9 (53.6)
	N/A	300	1.6 (2.67)	3698 (8138)	16.1 (36.5)
By education[4]	≤ 7y compulsory education	19	1.74 (2.35)	4652 (9076)	16.8 (32)
	> 7y compulsory education	52	1.08 (1.98)	1620 (3741)	7.0 (17.9)
	Basic vocational education	524	1.18 (1.97)	2402 (5351)	11.1 (29.9)
	Higher secondary general education	231	1.33 (2.1)	2986 (6985)	13.3 (35)
	Advanced professional training	597	1.21 (1.98)	2565 (5467)	12.1 (30.3)
	University	1278	2.15 (2.95)	5021 (9282)	23.8 (48.8)
	N/A	43	0.93 (1.75)	2094 (6549)	7.0 (20.5)
By area	Urban	1488	1.96 (2.67)	4165 (7809)	19.2 (41)
	Semi-urban	680	1.49 (2.61)	3816 (8735)	17.8 (44.7)
	Rural	572	1.02 (1.82)	2364 (5689)	11.7 (32.8)
	N/A	4	2.5 (2.52)	3835 (4251)	14 (15.9)

[4] The highest completed educational level of a parent.

Table 5: Flight patterns by socioeconomic factors (continued).

		Sample size n_q	Number of flights Mean (SD)	Total flight distance [km] Mean (SD)	Total cosmic radiation [μSv] Mean (SD)
By language	de	1764	1.48 (2.3)	3414 (7205)	16 (38.1)
	fr	817	2.01 (2.94)	4346 (8676)	20.4 (44.1)
	it	163	1.64 (2.57)	3593 (7432)	15.7 (45.1)
By nationality	Swiss	2341	1.48 (2.31)	3378 (7340)	15.9 (39)
	Other	402	2.68 (3.37)	5602 (9289)	25.6 (47.3)
	N/A	1	0 (0)	0 (0)	0 (0)

3.3 Sensitivity analysis

A sensitivity analysis is performed in order to evaluate the impact of some assumptions made in the data preparation process. The results of the sensitivity analysis are shown in Table 6. In each analysis, a single parameter is changed in the calculations and its effect on the results is quantified. In particular, the effect of the assumed day of time of the flights and the default flight dates is looked at.

Table 6: Sensitivity analysis for different scenarios. In each analysis, a single parameter is changed to quantify its influence.

Changes	**Sample size** n_q n_f	**Number of flights**[5] Mean (SD) $Q_{0.25}$, Median, $Q_{0.75}$	**Total flight distance**[6] [km] Mean (SD) $Q_{0.25}$, Median, $Q_{0.75}$	**Total cosmic radiation**[7] [μSv] Mean (SD) $Q_{0.25}$, Median, $Q_{0.75}$
Overall results (for reference)	2744 4438	1.651 (2.529) 0, 0, 2	3702 (7694) 0, 0, 3564	17.3 (40.5) 0, 0, 13.5
Change default time for flights to 10 a.m. CET	2744 4438	1.651 (2.529) 0, 0, 2	3702 (7694) 0, 0, 3564	17.3 (40.5) 0, 0, 13.5
Change default time for flights to 9 p.m. CET	2744 4438	1.651 (2.529) 0, 0, 2	3702 (7694) 0, 0, 3564	17.3 (40.5) 0, 0, 13.5
Assume 1st instead of 15th day of the month for missing days	2744 4407	1.639 (2.5210) 0, 0, 2	3684 (7665) 0, 0, 3516	17.2 (40.1) 0, 0, 13.5
Instead of excluding the questionnaires with no completion date, assume March 20, 2019,[8] and proceed as with all other questionnaires	2841 4838	1.738 (2.584) 0, 0, 2	3892 (7842) 0, 0, 3858	18.4 (42.2) 0, 0, 14.3

[5] Flights per child in the 12-month period (from Q13), including flights with incomprehensible flight details.
[6] Per child in the 12-month period.
[7] From flight travels per child in the 12-month period.
[8] This corresponds to the mean date of completion of the questionnaires.

4 Discussion

4.1 Quality of survey data

The dataset consists of 2841 questionnaires with a total of 5202 flights. For the dose calculations, 97 questionnaires with 421 flights as well as 343 additional flights are excluded from the dataset. This corresponds to 3.4% of all questionnaires and 7.2% of the remaining flights being excluded.

Incompletely filled-in questionnaires are an issue with a negative effect on the amount and quality of the data. After removing the said 97 questionnaires, in the remaining questionnaires, there are 59 cases where flight details are filled in but no number of flights is given in Q12. Vice versa, in 4 questionnaires Q12 is filled in but no flight details are given. Most likely, this is for convenience or participants did not remember all flights or flight details. The overall effect of this missing data is not expected to be of great relevance, as only a small percentage of the questionnaires are affected and some of the missing values are inferred from the remaining data. The effect of incompletely filled-in flight dates is addressed in a sensitivity analysis and discussed in Section 4.5.

Incorrectly filled-in questionnaires result in a total of 249 flights being excluded from the dose calculations for not falling into the 12 months before the date of completion of the questionnaire. This corresponds to 5.2% of the flights. As Q12 is not affected by these exclusions, the number of flights from this data may be overestimated.

A total of 91 flights, corresponding to 2% of all flights, are excluded due to incomprehensible flight details. Deciphering the handwriting and accounting for misspellings was a major challenge in the data preparation. For the 382 unique airports, a total of 1038 alternative spellings are used, i.e., every airport is spelled in almost three different ways across the questionnaires. Considering this, the number of exclusions seems to be modest. Nonetheless, the values obtained in the dose calculations are expected to be lowered by the exclusions by about 2%.

4.2 Quality of flight profiles

As described in Section 2.5, a flight profile model is used for the dose calculations due to the lack of real flight data. In Table 7, for a few illustrative examples, this modeled flight profile is compared to real flights from July 30, 2021, based on data from FlightRadar24[19]. Comparison to real flights on the original date given in the questionnaires is not possible, as the real flight data from this source is only available for free a few days back.

The actual flight times between two airports can vary considerably from flight to flight, e.g., due to (seasonal) winds, air traffic, and weather-dependent re-routing. This becomes evident when comparing the duration of the inbound and outbound flights in Table 7, where differences of up to one hour are observed. These parameters are not reproduced in the flight profile model.

Table 7: Comparison of flight profiles generated by the flight profile model with real flights. The flight data is obtained from www.flightradar24.com, date of access July 31, 2021.

Route	**Flight profile model**			**Real flight on July 30, 2021**[19]		**Relative modeling error**
	Distance [km]	Duration [hh:min]	Model	Flight number / Aircraft	Duration [hh:min]	
ZRH - MUC MUC - ZRH	261	00:39	ATR 72	LX1110 / A220 LX1101 / E290	00:40 00:37	-2.5% +5.4%
ZRH - CDG CDG - ZRH	476	01:07	ATR 72	LX632 / A320 LX633 / A320	00:57 00:49	+17.5% +36.7%
BSL - AMS AMS - BSL	561	00:49	A320	KL1988 / E190 KL1987 / E190	01:04 00:56	-23.4% -12.5%
ZRH - PMI PMI - ZRH	996	01:20	A320	LX2156 / B777 LX2157 / B777	01:34 01:30	-14.9% -11.1%
ZRH - HEL HEL - ZRH	1'778	02:15	A320	AY1514 / A320 AY1513 / A320	02:17 02:37	-1.5% -13.1%
ZRH - DXB DXB - ZRH	4'768	05:38	A340	EK88 / A380 EK87 / A380	05:32 06:03	+1.8% -6.9%
ZRH - JFK JFK - ZRH	6'310	07:22	A340	LX14 / B777 LX15 / B777	08:02 06:41	-8.3% +10.2%
ZRH - SIN SIN - ZRH	10'306	11:53	A340	SQ345 / A350 SQ346 / A350	11:48 12:24	+0.7% -4.2%

Nonetheless, as can be seen in Table 7, our flight profile model well approximates the real flights with errors below 15% in most cases. The differences tend to be larger in shorter flights with distances around 500 km. Besides that it is assumed that delays, e.g., due to air traffic congestion, have a stronger relative effect on shorter flight distances, the choice of aircraft seems to be crucial in this distance range. This becomes evident in the ZRH-CDG and BSL-AMS flights in Table 7, where a different type of aircraft is used than expected by the model, i.e. a medium-haul instead of a short-haul aircraft and vice versa, respectively. As a result, the flight time is overestimated in one and underestimated in the other flight. It is observed on FlightRadar24 that even within an airline, the type of aircraft serving these short routes sometime changes daily. This makes an accurate modeling very hard. The overall effect on the dose calculations, however, is considered small, as the absolute errors are small and the majority of flights cover longer distances (see Chapter 3), where the type of aircraft is less critical.

Moreover, in Table 7 it is observed that the modeled flight times tend to be at the lower range of the observed flight times. This comes as no surprise, as the model represents an optimal case, where no potential disturbances or delays are considered. Consequently, the calculated cosmic radiation doses should also be looked at as minimal values.

4.3 Flight patterns in children

The mean number of flights reported in Q12 is 0.844 (SD = 1.303) round trips. The mean number from the flight details in Q13 is 1.651 (SD = 2.529) individual flights, which is 1.96 times the value from Q12. It is tempting to conclude that a round trip consists of roughly 2 flights, i.e., an outbound and inbound flight. The numbers, however, cannot be compared directly. The ratio is expected to be > 2 as there are around 600 intermediate stops and only a few non- round trip flights given in the flight details in Q12. This, however, is counterbalanced by the flights excluded for the various reasons discussed in Section 2.3. The number of flights in Q12, in contrast, is not checked for eligibility and therefore expected to be tendentially overreported, as discussed in Section 4.1. All things considered, but it remains unclear, which method better estimates the actual number of flights.

The Swiss Federal Statistical Office (FSO) reports 0.83 round-trip flight travels with an overnight stay in the general population in Switzerland in 2015[15]. For the 6-17 years old, 0.6 of these round-trips are reported[15]. Data for children younger than 6 years is not available. No measures of uncertainty are given in the publication.

In our study, we find a number of round trips for children that is slightly higher than reported by the FSO. It closely matches the number for the general population found by the FSO. Our data, however, also includes flight travels without an overnight stay. Their contribution, though, is expected to be small, as this segment is assumed to mainly consists of business trips. In total, from our data, we find that the total number of flights in children is largely in line with the number for the general population in Switzerland.

Not surprisingly, the ranking of the most frequented airports and routes in Table 3 is dominated by flights from and to one of the major Swiss airports and the nearby airport Milano-Malpensa (MXP). The most popular destinations include classical beach holiday and city trip destinations in Europe, such as Palma de Mallorca (PMI), London (LHR), Madrid (MAD), Lisbon (LIS), and Porto (OPO), as well as large hub airports for longer travels, such as Dubai (DXB), London (LHR), and Frankfurt (FRA).

4.4 Flight distance

According to the Swiss Federal Statistical Office (FSO), in Switzerland, the yearly average distance traveled by airplane is 8986 km[15]. Thereof, 7163 km originate from round-trip flight travels with an overnight stay[15]. Separate data for different age age-groups is not available.

For the children investigated in this study, a total flight distance of 3702 (SD = 7694) km in the 12-month period is found. This is considerably lower than the number reported by the FSO for the general population. Given that the number of flights is not significantly lower than in the general population, it is assumed that children tend to take shorter flights than adults. One reason might be that sitting still for long periods is difficult and boring for most children. Therefore, long-haul flights and long car drives are troublesome for both, children and parents, such that a short flight may be the best option to go on holiday.

4.5 Cosmic radiation dose from flight travels

To my knowledge, there are no published studies that quantify the cosmic radiation exposure from flight travels in children. Also, no studies on cosmic radiation exposure from flight travels in the general populations of Switzerland are found. A study from the United Kingdom estimates an annual cosmic radiation dose of 30 μSv from flight travels for the general population[22]. Such numbers, however, can only be extrapolated with care to different populations, as flight habits may greatly vary between different regions and countries[23].

The mean cosmic radiation dose from flight travels is found to be 17.3 (SD = 40.5) μSv per child in the 12-month period. This corresponds to only 4.3% of the total annual dose of cosmic radiation in Switzerland, which is 0.4 mSv as discussed in Chapter 1. The percentage, however, is much larger when looking at the most frequently flying children. In our dataset, the average of the 10 highest observed cosmic radiation doses is 0.31 mSv with a mean flight distance of 51'260 km. Here, the cosmic radiation dose from flight travels corresponds to 77.5% of the total annual cosmic radiation dose of the general population.

In total, except for a small percentage of children with extreme numbers of flight travels, the cosmic radiation dose from flight travels is considered rather small compared to the total annual cosmic radiation dose of the general population.

4.6 Impact of socioeconomic factors

It can be assumed that socioeconomic factors play a crucial role in flight behavior. This is confirmed by our study. The results split up with regard to different factors are shown in Table 5.

We find that older children tend to fly more frequently than their younger peers. In particular, this effect becomes strong in the age groups of the above 8 years old. In younger children, the number of flights does not appear to greatly depend on the children's age. Reasons that contribute to this increase may be that families have more money available as the parents can work more with the children getting more independent, that flying itself may become less burdensome with older children, and that older children become increasingly interested in exploring different regions and cultures.

According to the FSO, the annual number of round-trip flight travels with an overnight stay in the general population positively correlates with the total household income[15]. People living in a household with a total income greater than CHF 12'000 are said to travel 5 times more often by airplane than people living in a household with a total income of less than CHF 4'000[15]. These findings are confirmed in our study for children. As can be seen in Table 5, the number of flights in children from a household with a total income above CHF 13'000 is 4.8 times greater than that of those living in a household with a total income below CHF 3'000.

Similarly, we find that a smaller household size and a higher level of education of the parents generally results in a higher number of flights in the children. These socioeconomic factors are strongly interlinked to the household income, whereas generally a smaller household size means a higher income per capita and a higher level of education results in a higher income. An exception are two-person households, i.e., a single parent with a child, which are financially often not as well-positioned as households with two adults.

A high number of flights is correlated with a high grade of urbanization of the children's living area. As can be seen from Table 5, children living in an urban area travel about twice as frequently by airplane as their peers living in a rural area. Likewise, children from semi-urban neighborhoods take 1.5 times more flights per year than those from rural areas. Factors contributing to this difference may be differences in lifestyle and income, as well as the proximity to airports.

Considering the language regions, children from French-speaking parts of Switzerland fly most frequently, followed by Italian and German-speaking children. The "Röstigraben" seems to hold for flight travels in children as well.

In terms of nationality, children with a Swiss passport fly only about half as frequently as their counterparts living in Switzerland with a citizenship of a foreign country. Visiting friends and relatives in their country of origin most likely contributes to this difference.

According to Table 5, a higher number of flights generally results in a longer total flight distance and a higher total radiation dose from flight travels. Consequently, it is concluded that the flight lengths, i.e., the distances of the individual flights, do not greatly vary with the socioeconomic factors presented in this section.

4.7 Effects on cancer risk

It is generally accepted that for a given dose of ionizing radiation, children are more at risk for tumor induction than adults. For exposed children, the lifetime cancer risk might be 2-3 fold compared to the population exposed at all ages[2]. It is found that the radiation sensitivity, i.e., the rate of radiogenic tumor induction, is particularly increased in certain types of cancer, including leukemia and brain, thyroid, skin, and breast cancer[2]. In other types of cancer, children seem to be equally or even less sensitive than adults[2]. The included mechanisms of damage are complex and poorly understood, they might even be different from those in adults[2]. Therefore, according to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)[2], general conclusions on the risks of the effects of ionizing radiation in children cannot be drawn at present.

As already discussed in Chapter 1, no studies investigating the cancer risk due to cosmic radiation from flight travels are found for the general population and children, probably due to the relatively small contribution. Even for aircrew, findings are inconclusive and the excess risk, if it exists, is assumed very small.[7,9–13] Typical annual doses of aircrew are 1 - 5 mSv[6,23]. For pregnant aircrew, the International Commission on Radiological Protection (ICRP) recommends a maximal cosmic radiation dose of 1 mSv[24], which is equivalent to the recommendation of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) for the general population[23].

The 0.0173 mSv/y observed as the mean value in this thesis are small compared to the recommendations for pregnant aircrew and the general population, as well as compared to the mean annual cosmic radiation dose of the general population in Switzerland. For excessively flying children, however, this might be different. As discussed in Section 4.5, their cosmic radiation dose from flight travels alone is in the range of the values observed in the general population.

Epidemiological studies that assess the association between background radiation and childhood cancer[5,25] do not account for exposure from flight travels. Based on our findings, it is not expected that neglecting flight travels introduces a large bias to these studies due to the flight travel's small contribution. However, we see important differences in some groups, particularly children with a high socioeconomic status are increasingly exposed.

For the above reasons, no conclusive statement about the effect of cosmic radiation from flight travels in children can be made. Further research is required to better understand and quantify the consequences for the children's cancer risk.

4.8 Strengths and limitations

The study is based on a large sample size of 2841 questionnaires. Despite some missing data, the results of the sensitivity analysis in Table 6 show that the key findings of the study are very robust estimates.

As a drawback, a flight profile model is used instead of real flight data. The model only represents flight characteristics of typical airplanes and may not be a good approximation in all cases. Other effects, such as wind, weather, and air traffic conditions are not taken into account at all. Moreover, there might be a recall bias from people having to remember the number of flights and the flight details for the survey.

4.9 Conclusion

This work combines flight-related data from the CALIRIS study with a flight profile model and subsequent dose calculations to obtain estimates for the total number of flights and the total annual cosmic radiation dose for children in Switzerland. The study data and models are considered of good quality.

We find that the number of flights in children is comparable to the general population in Switzerland. The distances traveled, though, tend to be shorter. Furthermore, it is shown that flight behavior is strongly affected by socioeconomic factors. Compared to the total annual cosmic radiation dose of the general population, the dose from flight travels in children is rather small and it is not expected that it greatly affects the cancer risk of most children. For some individuals with extreme numbers of flight travels, however, this contribution might become more important be the case.

5 Literature

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A Flight-related questions in survey

IV. FLIGHT TRAVELS

Q12 How many flight travels has your child had during the **last 12 months**? Each round trip counts as one flight.

Number of Flights: _____

→ **If ZERO, continue to next section "DWELLING".**

Q13 For each flight that your child took during the **last 12 months**, please indicate the following details as shown in the example (note that each round trip counts as one flight):

		Flight 1	Flight 2	Flight 3	Flight 4
Outbound	*Example*				
Departure airport	Geneva				
Date (dd.mm.yy)	13.04.18				
Destination airport	John F. Kennedy, NY				
Stop airports	Frankfurt				
Company	SWISS/Lufthansa				
Return					
Departure airport	John F. Kennedy, NY				
Date (dd.mm.yy)	02.05.18				
Destination airport	Geneva				
Stop airport	Frankfurt				
Company	Lufthansa				

➔ *If more space required, please continue in a separate paper sheet and attach it to the questionnaire.*