

THE IMPACT OF COSMIC-ORIGIN BACKGROUND RADIATION ON HUMAN SURVIVAL IN THE CZECH REPUBLIC

Kateřina Podolská¹⁾ – Jitka Rychtařiková²⁾

Abstract

We evaluate the lifetime attributable risks induced by an increasing concentration of cosmic radiation and cosmogenic radionuclides during periods of *low solar activity* for the specific conditions in the Czech Republic. The concentration of cosmic radiation and cosmogenic radionuclides reaches its highest values during the solar minima when the Earth's magnetosphere is more penetrable. The computed estimate of lifetime attributable risks from solid neoplasms (colon, lung, and stomach) induced by doses of natural background radiation is higher for the period of low activity in solar cycle No. 24 than for the forced solar activity in the previous solar cycle Nos. 19–23. We estimated the lifetime attributable risks induced by the annual dose of natural background radiation by sex for the Czech Republic and the USA. In addition, three different scenarios based on dose radiation level were explored. The cosmogenic radionuclides in our environment may thus play a greater role than in the last decades.

Keywords: Mortality, incidence, solid cancer, lifetime attributable risk, age at exposure, solar activity, natural background radiation dose

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INTRODUCTION

Cosmic-origin background radiation has an impact on the health of human populations. The highest values of this radiation are observed during the solar minima because the penetrability of the Earth's magnetosphere is greatest at that time. It is consequently expected to have an impact on human health in the Czech Republic during the long solar minimum in 2020–2040. The average effective dose of cosmic radiation on the territory of the Czech Republic was 0.35 mSv (Table 1) in the past; however, during the solar minima it can rise to as much as 0.41 mSv (Table 2).

In the first section of the paper, four components of natural background radiation are presented: cosmic

radiation, ingestion (both of which change with solar activity), inhalation, and terrestrial radiation (which is not affected by solar activity) – see Table 1 and 2. The total annual dose of natural background radiation (the sum of the four components mentioned above) was then used to model different scenarios of the potential increase in the lifetime cancer risk.

The second section of the paper focuses on quantifications of the relationship between radiation exposure and the resulting potential risk of carcinogenesis or cancer mortality in the Czech Republic. It presents estimates of the lifetime attributable risks of incidence and of mortality for three solid tumor cancer sites (colon, lung and stomach), based on a combination

1) Department of Demography and Geodemography, Faculty of Science, Charles University, Prague, Czech Republic; Institute of Atmospheric Physics CAS, Prague, Czech Republic; contact: kapo@ufa.cas.cz.

2) Department of Demography and Geodemography, Faculty of Science, Charles University, Prague, Czech Republic; contact: rychna@natur.cuni.cz.

of the Excess Relative Risk (ERR) and the Excess Absolute Risk (EAR) models. This analysis was performed separately for men and women exposed to radiation at age 10 and age 30. Finally, the possible effects of increased radiation impacting the lifetime attributable risks were computed for three different levels of radiation (2.71; 2.85; 3.30 in mSv).

1. VARIOUS SOURCES OF NATURAL BACKGROUND RADIATION

Natural background radiation in our environment has a certain impact on the health of the human population. The human population and living organisms on Earth have inevitably always been exposed to natural background radiation. Unlike stronger radiation sources, this dose of radiation is lower; however, the human population is exposed to it long-term, and consequently there are concerns about its effects.

Natural background radiation has three sources: *cosmic radiation* (see 1.1), radiation from *cosmogenic radionuclides* (see 1.2), and *terrestrial radiation* (see 1.3). There are three sources of the cosmic radiation: *galactic radiation*, *solar radiation* and *radiation from the Van Allen Belts* of the Earth.

Natural radionuclides are distinguished by origin as *cosmogenic radionuclides* (originating from the interaction of the Earth's atmosphere with extra-terrestrial particles) and *terrestrial radionuclides* (which are the source of *terrestrial radiation*). Most frequently, natural radionuclides penetrate the human body through ingestion and inhalation of chemical substances contaminated by these radionuclides.

The amount of energy absorbed per mass is known as radiation dose D . The radiation dose is the energy (Joules) absorbed per unit mass of tissue and is measured in units of Gray ($1 \text{ Gy} = 1 \text{ J}\cdot\text{kg}^{-1}$).

Human exposure to natural background radiation has two main sources: external and internal radiation. People are exposed to internal radiation via ingestion and inhalation.

The effect of prolonged exposure to relatively low levels of ionising radiation, used for a comparison of the stochastic health effect of natural background radiation, is quantified by *dose equivalent* H . The biological effectiveness, i.e. the *relative biological effectiveness* (RBE), of each type of radiation varies depending

on the *linear energy transfer* (LET). The dose equivalent H in Sievert (Sv) is the product of the absorbed dose D in the tissue, multiplied by a radiation weighting factor often called the quality factor Q . The dose equivalent H is calculated by the body-absorbed dose D , multiplied by the quality factor Q , depending on the type of radiation and the specific biological effectiveness of different types of radiation. The *dose equivalent* H [Sv] ($1 \text{ Sievert} = 1 \text{ J}\cdot\text{kg}^{-1}$) is defined as

$$H = Q \cdot D \quad [1].$$

The magnitude of natural background radiation varies with the strength of solar activity. At times of solar activity minima, the geomagnetic field is weak and the intensity of cosmic radiation is at its maximum. Concentrations of cosmogenic radionuclides consequently increase in this period.

1.1 COSMIC RADIATION

Cosmic radiation consists of solar wind particles and of a galactic component. The *galactic component* is composed of interplanetary particles that penetrate the atmosphere to reach the Earth's surface. The effective dose from cosmic radiation depends on the specific state of the *Earth's magnetosphere* and the *Van Allen Belts*. When the solar wind is strong, the geomagnetic shield is reinforced and less cosmic radiation reaches the Earth's surface. Also when solar activity is at a maximum, the cosmic radiation dose is 10 % smaller than when solar activity is at a minimum (*UNSCEAR: Annex B*, 2000).

The intensity of cosmic rays on the Earth's surface also depends on altitude and on geographical latitude. The world average exposure to cosmic radiation increases with altitude; at sea level it is 0.32 mSv, and at middle altitude it is 0.46 mSv (*UNSCEAR: Annex B*, 2000).

The Earth's magnetic field deflects the charged particles between geographical latitudes 30° and 60° (both North and South), where the intensity of cosmic radiation is 10 % higher than at the equatorial region or around the magnetic poles.

The *adjusted dose equivalent* H'_{cr} , quantifying exposure to cosmic radiation reduced by inhabitation in buildings, is expressed as:

$$H'_{cr} = H_{cr} \cdot f_o \cdot f_s \quad [2]$$

where H_{cr} is exposure to cosmic radiation, f_o is the *occupancy factor* given by population lifestyle (0.8 for European populations), and f_s is the *shielding factor* given by the type of building (0.8 for typical buildings in Europe) (ICRP, 1991). The resulting annual exposure H_{cr}' to cosmic radiation for the population in specific conditions in the Czech Republic, which is included in the calculation of the exposure, is 0.35 mSv (UNSCEAR, 2000; Kuna et al., 2005).

1.2 COSMOGENIC RADIONUCLIDES

Cosmogenic radionuclides are produced by nuclear reactions when cosmic radiation interacts with stable elements in the outer atmosphere. In terms of radiation impact on the population, the most important radionuclides are carbon ^{14}C , tritium ^3H , beryllium ^7Be , and sodium ^{22}Na , which substantially contribute to the dose of natural background radiation. Cosmogenic radionuclides contribute 8 % to the total radiation burden (Kuna et al., 2005; ICRP, 1991; ICRP, 1996). Their effect on human health is non-threshold: that, of course, means that the risk is present even at low exposure.

Carbon ^{14}C is produced in the upper atmosphere when nitrogen atoms interact with slow neutrons of cosmic radiation. Carbon radionuclide ^{14}C with a half-life of 5 730 years oxidises into CO_2 and enters the *global carbon cycle* between the atmosphere, the biosphere, and the oceans (Solanki, 2004). The spatial variation of the radiation burden caused by ^{14}C is not significant, and the effective annual dose of the radionuclide ^{14}C in human body is 0.012 mSv (Bencko aj, 2002).

The beryllium radionuclide ^7Be is formed when cosmic radiation interacts with the nuclei of nitrogen and oxygen in the atmosphere. These two radionuclides are transported through the geosphere in a very different way. Beryllium ^7Be binds to aerosols and is transported within a few years to the Earth's surface. Its half-life is 53 days and its concentrations are higher in the spring and summer months when stratospheric ^7Be penetrates the troposphere as a result of the exchange of air masses between the troposphere and stratosphere. The beryllium radionuclide ^7Be enters the human body mainly by the ingestion of leafy green vegetables, with an annual average effective

dose of 0.03 μSv (UNSCEAR, 2000; Hůlka – Malátová, 2006).

The earth's atmosphere is also the main source of natural tritium ^3H , which is produced when cosmic radiation interacts with the nuclei of nitrogen, oxygen, and lithium in the atmosphere. Tritium enters the food chain together with plain water and thereby becomes a part of human tissue, so that it is a source of external and internal irradiation of the human body.

The combined radiation burden caused by ^3H , ^7Be and ^{22}Na is much lower than for ^{14}C .

1.3 TERRESTRIAL RADIATION

Another component of the radiation burden from natural background radiation is *terrestrial radiation*. This component is very significant in the Czech Republic due to the specific geological composition of the bedrock: in 90% of sites terrestrial radiation is higher than the European average. The main source of the terrestrial radiation is radium ^{226}Ra and its daughter products such as radon ^{222}Rn and thoron ^{220}Ra . ^{222}Rn and its daughter products play a main role in radionuclides inhalation. The annual equivalent dose of terrestrial radiation in the Czech Republic is 0.81 mSv, which is five times higher than the world average as indicated in data (SÚRO, 2014; Hůlka – Malátová, 2006). This value is constant over time. However, the spatial variation in the terrestrial radiation burden is very distinctive and depends on the composition of local bedrock and materials of residential buildings.

2. THE INFLUENCE OF SOLAR ACTIVITY

The level of natural background radiation is also significantly influenced by solar activity, which varies across its 11-year cycle. Geomagnetic storms and radiation showers affecting the Earth do not occur very often, but their intensity and occurrence increases in the years around solar maxima. Some super-energetic protons pass through the Earth's magnetosphere. Conversely, energetic electron events actually culminate in the years around solar minima, sunspot number around the maxima, and geomagnetic storms around solar maxima.

An important proxy of solar activity is the sunspots number S_n , which is related to the magnetic activity

of the Sun. It is reported each day without reference to the prior daily value. Each isolated array of sunspots is termed a sunspot group. These groups may consist of one or more distinct spots whose size can range from 10 to more square degrees of the solar disc. The sunspot number S_n is defined as $S_n = 10 \cdot G + F$, where G is the number of groups of sunspots in the solar disc, and F is the number of individual sunspots. During the cycle, the sunspot number, the geomagnetic activity, and the quantity of high-energetic particle changes. In the course of the solar maximum, the activity of the Sun and its effects on the terrestrial environment are distinctly higher. The sunspot number S_n ranges between zero and roughly 300 in periods of extreme solar activity (NOAA, 2014) – see Figure 1.

The last solar cycle No. 24 and surrounding minima from the years 2009 to 2011 were long and very weak. The last solar maximum was relatively low with S_n under 150. For a comparison of recent solar cycles, see Figure 2. The maximum of cycle No. 25 for the years 2022–2023 is predicted to be also low (Kane, 2006).

A long solar minimum is predicted to last from 2020 to 2040 (Owens et al., 2012). According to the last,

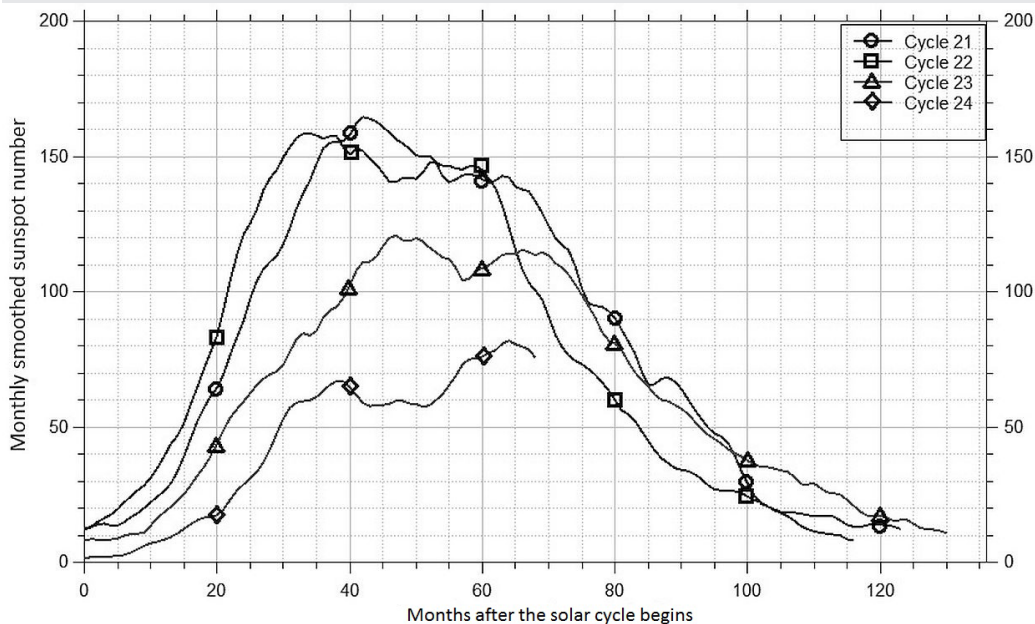
the 23rd solar cycle, the current 24th, and the predicted 25th and 26th solar cycles, solar activity will be low in further periods (Podladchikova – Van der Linden, 2011; Shepherd, 2014) – see the right side of Figure 2.

Galactic cosmic radiation originates in deep space and consists of protons (85 %), helium nuclei (11 %), heavier nuclei of practically all chemical elements (1 %), and electrons (3 %). This radiation is isotropic (in all directions with equal intensity), and the dose equivalent reaches values around 1 Sv per year. However, in the vicinity of the Earth, the variation of its composition and intensity is greater due to interaction with solar wind, the geomagnetic field, and the Earth's atmosphere.

Solar cosmic radiation, also contributing to the radiation on Earth, originates mainly from solar eruptions. It mostly consists of protons (99 %), and heavier charged particles account for only 0.1 % of the total fluence (Kuna et al., 2005; UNSCEAR: Annex B, 2000). During the solar flares and eruptions, superhot gas with charged particles is ejected toward the Earth.

When solar particles collide with the Earth's magnetic field, they can cause geomagnetic storms and polar lights. Charged particles from the Sun hit

Figure 1 Comparison of the last few solar cycles



Source: According to <http://www.sidc.be>.

the Earth in a few days, and electromagnetic radiation in just 8 minutes. Many of the effects of charged particles hitting the Earth's magnetosphere are dangerous to human health and can, in fact, be malignant. On entering the atmosphere, cosmic radiation particles, both galactic and solar, interact with atoms and molecules in the air. While heavier nuclei penetrate only the outer layers of the atmosphere, lighter particles may reach the Earth's surface (so-called secondary cosmic radiation).

As was mentioned above, the concentration of cosmogenic radionuclides reaches its highest levels during the solar *minima* as the Earth's magnetosphere is more penetrable. The problem of cosmogenic radionuclides in our environment may have a much greater role in human health in the near future than in past last decades (Bard, 2007). Our aim here is to quantify these risks.

2.1 ANNUAL DOSE OF NATURAL BACKGROUND RADIATION

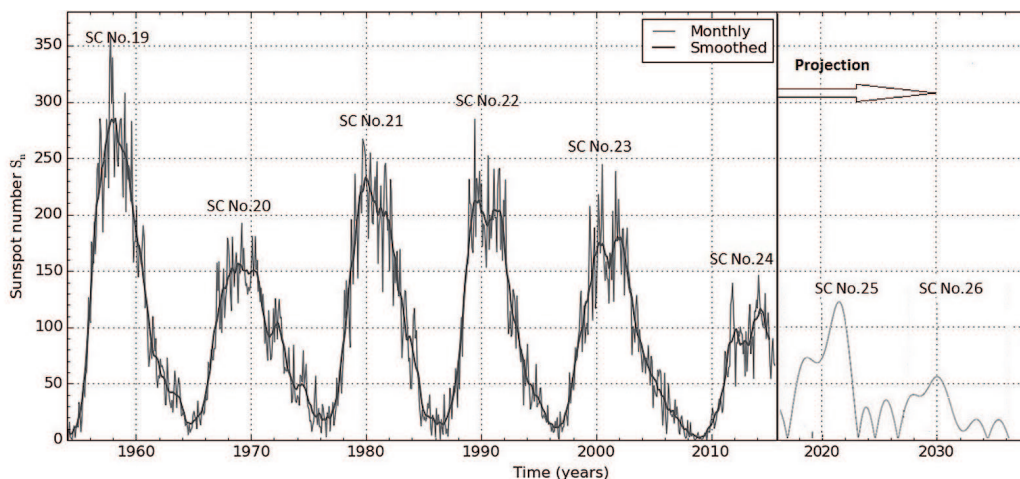
As mentioned above, the average effective dose of cosmic radiation for the Czech Republic is 0.35 mSv. In a long-term solar minimum, it can be up to 0.41 mSv, because in the period of solar minimum the penetrability of the cosmic radiation to the surface of the Earth

is 17 % higher than during solar maxima (UNSCEAR: *Annex B*, 2000; Kuna *et al.*, 2005).

Both components of the annual dose (external and internal) of natural background radiation in the Czech Republic are included in our computation. The dose equivalents of cosmic radiation H_{cr} are 0.35 mSv, terrestrial radiation H_{tr} 0.81 mSv, ingestion H_{ig} 0.30 mSv, inhalation H_{ih} 1.25 mSv, and terrestrial radiation 0.81 mSv. The ingestion dose (0.30 mSv) via incorporation contains 0.17 mSv from ^{40}K , 0.12 mSv from ^{210}Po and ^{210}Pb , and 0.01 mSv from ^{14}C . The dose equivalent of inhalation (1.25 mSv) is significantly higher in the Czech Republic than in the rest of Europe (SÚRO, 2001; Hůlka – Malátová, 2006; UNSCEAR: *Annex F*, 2000). This is mainly due to radium radionuclides ^{222}Rn and ^{220}Ra . The total average annual dose H from natural background radiation in the Czech Republic is $H = H_{cr} + H_{tr} + H_{ig} + H_{ih} = 0.35 \text{ mSv} + 0.81 \text{ mSv} + 0.30 \text{ mSv} + 1.25 \text{ mSv} = 2.71 \text{ mSv}$ (see Table 1). The assumption of a linear dependence between the effective dose and lethal effect even at low doses of radiation (NRC, 2006; FGR, 1994; FRG, 1999) was mentioned in the preceding section.

The radiation dose from cosmogenic radionuclides in a period of very low solar activity is estimated to be higher than in past decades. Higher concentrations of carbon ^{14}C will also be influenced by burning

Figure 2 Past solar cycles SC No.19 – SC No.24 and a projection for future solar cycles



Source: According to <http://www.sidc.be>; (Shepherd, 2014; Usoskin, 2003; Podladchikova – Van der Linden, 2011).

biomass. The dominant input into the atmosphere is the backflow of ^{14}C from the oceans (and to a lesser extent the backflow of terrestrial biotas) into which ^{14}C enters relatively quickly with a half-life of around 7 years. It results from the exchange between the atmosphere and the ocean surface. Although the production of cosmogenic radionuclides is the main carbon source on Earth, this production can be estimated at approximately 1.5–5.0 % of the total input of ^{14}C in the atmosphere (Světlík *et al.*, 2010).

Global carbon ^{14}C concentration may nearly double during an inversion of the geomagnetic field. The modulation potential of the Earth's electromagnetic field varies between about 300 and 1500 MV (megavolts) within a modern high solar cycle (Usoskin *et al.*, 2011), and may have been as low as about 100 MV during the long solar minima between 1638 and 1715 years (McCracken *et al.*, 2004; Usoskin *et al.*, 2007; Steinhilber *et al.*, 2008). Thus, changes in solar modulation can also lead to a factor of 2–3 variability on the global ^{14}C production rate.

For the expected increase of the dose from cosmic radiation, and consequently also the dose from ingestion, in a period of lower solar activity we can assume an annual average dose from natural background radiation, which in the Czech Republic is 2.85 mSv (SÚRO, 2014) – see Table 2.

When the Fukushima accident is taken into the account, the annual average dose of natural background radiation is at level 3.30 mSv according to the SÚRO 2011 annual report (SÚRO, 2011). The stated three values (2.71 mSv, 2.85 mSv, 3.30 mSv, respectively) are used in the computing scenarios in section 4.

Table 1 Annual dose from natural background radiation in the Czech Republic in previous solar cycles

Origin	Dose [mSv]
Cosmic radiation (H'_c)	0.35
Ingestion (^{40}K , ^{210}Po , ^{210}Pb , ^{14}C) (H_{ig})	0.30
Inhalation (^{222}Rn , ^{220}Ra) (H_{in})	1.25
Terrestrial radiation (H'_t)	0.81
Total annual dose from natural background (H)	2.71

Source: Data SÚRO, 2001.

3. RADIATION-INDUCED SITE-SPECIFIC NEOPLASM RISKS

The radiation doses of different kinds of radiation absorbed by different organs of the human body may not produce the same biological effect, depending on the particle types (e.g. neutrons, electrons, protons, alpha particles and heavy ions) (UNSCEAR, 2008).

Therefore the *effective dose* E indicator was implemented. The effective dose E is expressed in the equation:

$$E = \sum w_T H_T = \sum w_T w_R D_{TR} \quad [3]$$

where w_T is a *tissue weighting factor* which represents the dose in tissue or organ T , it is weighted to represent the relative contribution of tissue or organ to the overall health detriment resulting from uniform irradiation of the body (ICRP, 1991), which expresses different radiation sensitivity of organs and tissues from the perspective of the probability of stochastic effect origin.

Tissue weighting factor w_T has the following values: 0.20 for gonads; 0.12 for colon, lung, red marrow and stomach; 0.05 for bladder, breast, liver, esophagus, thyroid and other organs; 0.01 for bones surface and skin (ICRP, 2012). Higher value of w_T signifies higher radiosensitivity from the perspective of the stochastic effect. The sum of individual organs and tissue weights w_T is 1.0.

The tissue-specific *equivalent dose* $H_T = \sum w_R D_{TR}$ is the time integral of the equivalent dose rate type R in a particular tissue or organ T that will be received by a reference person. The value of radiation weighting factor w_R for photons and electrons is 1, for neutrons 5–20 depending on their energy, for protons 5, for alpha particles and for heavy nuclei and fission

Table 2 Annual average dose from natural background radiation in the Czech Republic during a long solar minimum

Origin	Dose in long-term solar minimum [mSv]
Cosmic radiation (H'_c)	0.41
Ingestion (^{40}K , ^{210}Po , ^{210}Pb , ^{14}C) (H_{ig})	0.38
Inhalation (^{222}Rn , ^{220}Ra) (H_{in})	1.25
Terrestrial radiation (H'_t)	0.81
Total (H)	2.85

Source: Data SÚRO, 2014.

fragments it is 20. Both the radiation- and the tissue-weighting factors w_R and w_T are given in the Publication 60 recommendations (ICRP, 2012; UNSCEAR: Annex B, 2000).

As is apparent from the data mentioned above, for a dose of 2.5 mSv every cell of the human body is on average affected by one DNA damage for each year, which suggests the probability of a certain mutation. For fatal neoplasms, it depends on the life expectancy of the study population – a neoplasm takes time to develop. For the overall population, it is possible to quantify the total risk increase by the method (ICRP, 1991) and (FGR, 1994) described in the following section.

4. CANCER RISK ESTIMATE FOR LOW DOSES

The aim of this section is to quantify the relationship between a low radiation exposure and the resulting potential human damage (i.e. risk of carcinogenesis or cancer mortality). We present models that can be used to estimate the lifetime risk of three selected types of cancer (colon, lung, and stomach), which may have been influenced by low doses of ionising radiation during the period of 2009–2011 in the Czech Republic. The solid cancer³⁾ specific sites are selected because of their frequencies and verified modelling approaches. The time period corresponds to one of increased cosmic radiation due to low solar activity on the territory of the Czech Republic. The Czech results are also compared with the US risks of the same sites of cancer incidence and mortality during the same time period. Our modelling of lifetime attributable risks (LAR) of cancer incidence and mortality due to the exposure to low Linear Energy Transfer (LET) radiation takes into account sex, age at exposure, attained age, and dose rate. Of course, the cancer risk may also depend on the exposure to other carcinogens, such as tobacco, or other characteristics of the exposed individual. However, our data (on the national level) are not adequate to quantify these dependencies precisely.

There are many epidemiological studies focusing on the relationship between radiation exposure and health or mortality (Gonzales *et al.*, 2012; Kellerer *et al.*, 2001; Peterson, 2015; Preston *et al.*, 2003, 2004; Sasieni *et al.*, 2011). The most important source of epidemiological data is the Life Span Study (LSS) of the Japanese atomic bomb survivors from Hiroshima and Nagasaki, who received an acute dose of ionising radiation. Such data are suitable because they include a large sample of people of both sexes and all ages. The individuals were exposed to a wide range of doses and were scientifically followed long term, thus offering us high-quality cancer mortality and incidence information. This justifies the use of LSS as an important and unique source for cancer risk research. There are several institutions that have developed risk models for cancer incidence and mortality related to radiation effects (NCRP – National Council on Radiation Protection and Measurements, ICRP – International Commission on Radiological Protection, UNSCEAR – United Nations Scientific Committee on the Effects of Atomic Radiation). Our study uses the modelling of health effects from exposure to low LET radiation proposed in the *BEIR VII* report.⁴⁾ The models are based on a follow-up study of the LSS cohort (the initial number of subjects was 86 572, 48 % of whom were alive on 1 January 1998; Preston, 2003) and include the number of incidences of site-specific cancers in the period 1958–1998 (number of cases: colon 1 165; lung 1 344; stomach 3 602) and the number of deaths in the period 1950–1997 (colon 478; lung 1 264; stomach 2 867) (*BEIR VII*, p. 298). Models are provided for estimating risk as a function of age at exposure, age at risk, sex, and cancer site focusing on the risk from low-LET radiation.

Lifetime risks generated from the LSS study are not directly applicable to modelling low radiation risks because the LSS population was primarily exposed to a high dose rate. Therefore, we introduced a reduction factor called the Dose and Dose-Rate Effectiveness Factor (DDREF). A plausible range of DDREF values for adjusting linear risk estimates based

3) Solid cancers is a malignancy that forms a discrete tumor mass.

4) Report on Health Risks from Exposure to Low Levels of Ionizing Radiation, released by the National Research Council of the National Academy of Sciences (NAS).

on the LSS cohort is 1.1 – 2.3. A single value of 1.5 was used as the median of the Bayesian posterior probability distribution for solid tumors (*BEIR VII*, p. 309). As a result, our estimates are reduced by a DDREF of 1.5 (*BEIR VII*, p. 274).

Cancer risk models may be expressed as either the Excess Relative Risk (ERR⁵⁾) or the Excess Absolute Risk (EAR⁶⁾). The ERR measures the proportional increase in risk over the background absolute risk (in the absence of exposure). The EAR is the additional risk beyond the background absolute risk. Cancer-specific risk models incorporate intrinsic factors that significantly modify the radiation-related excess risk. Risk modifying factors (in our modelling) are sex,

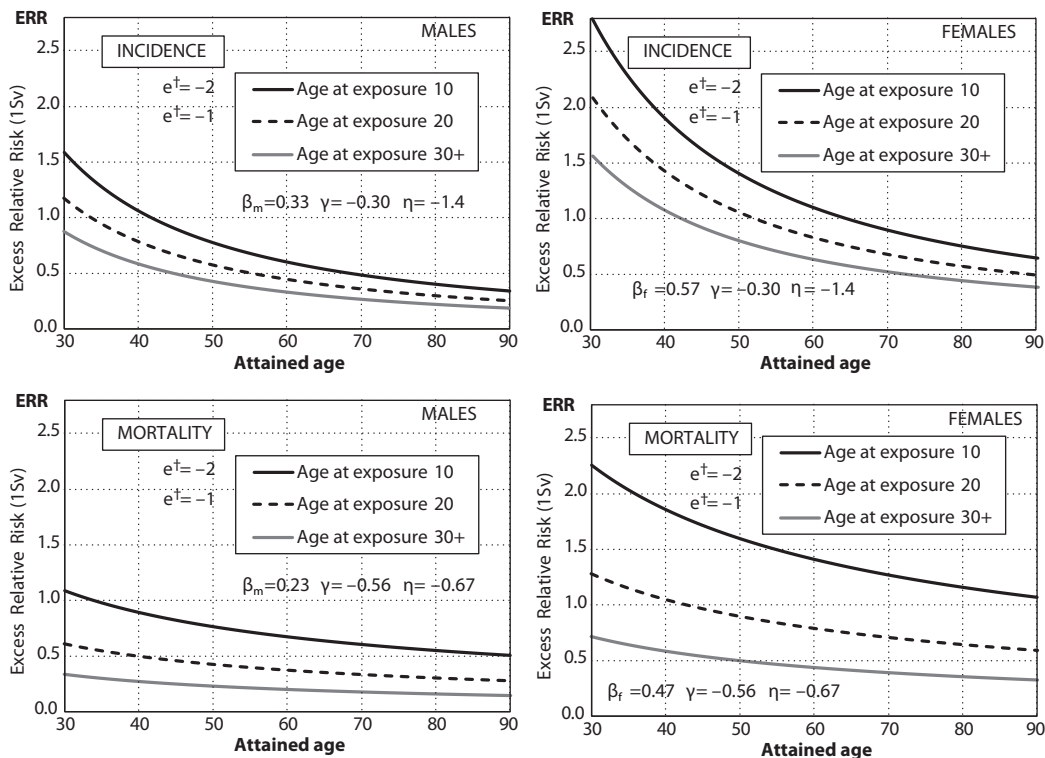
age at exposure, attained age (or age at risk). The rates of incidence or mortality specific to age at exposure to radiation, attained age, sex and other explanatory variables, are represented by two types of models (*BEIR VII*, p. 269):

$$\lambda(s, a, b, d) = \lambda(s, a, b) * [1 + \beta_s * ERR(e, a) * d] \quad [4]$$

$$\lambda(s, a, b, d) = \lambda(s, a, b) + \beta_s * EAR(e, a) * d \quad [5]$$

where $\lambda(s, a, b)$ denotes the background rate at zero dose and depends on sex (s), attained age (a), and birth cohort (b). The $\beta_s * ERR(e, a)$ or the $\beta_s * EAR(e, a)$ are respectively the *ERR* and the *EAR* per unit of dose expressed in Sievert⁷⁾ with e as age at exposure. Generalised models of Poisson rates were fitted in order to obtain dose-dependent excess absolute risk (*EAR*) and

Figure 3 Age-time patterns in radiation-associated risks ($d=1\text{ Sv}$) for solid cancer incidence and mortality excluding thyroid and nonmelanoma skin cancers based on the ERR model



5) ERR is the rate of disease in an exposed population divided by the rate of disease in an unexposed population minus 1 (equation 4).

6) EAR is the rate of disease in an exposed population minus the rate of disease in an unexposed population (equation 5).

7) Sievert (Sv): Unit of dose equivalent. In the BEIR VII analysis of the A-bomb survivor data, the dose equivalent was calculated from the absorbed γ -ray and neutron doses, assuming a radiation-weighting factor of 10 for neutrons.

$$ERR \text{ or } EAR = \beta s * d * e^{(\gamma * e^{\eta})} * (a/60)^{\eta}$$

or

$$ERR \text{ or } EAR = \beta s * d * e^{[\gamma * e^{\eta} + \eta * \ln(a/60)]}$$

[6]

where d is the dose (in Sv), e is age at exposure (years), e^{η} is the effect modifier for age at exposure which is $(e-30)/10$ for $e < 30$ and zero for $e = 30+$ (i.e. the effect of exposure at ages over 30 is constant), a is attained age and $\ln(a/60)$ is the effect modifier for attained age a . ERR is expressed per Sievert and EAR per 10^4 person-years (PY) per Sievert. The models were developed from LSS incidence and mortality data.

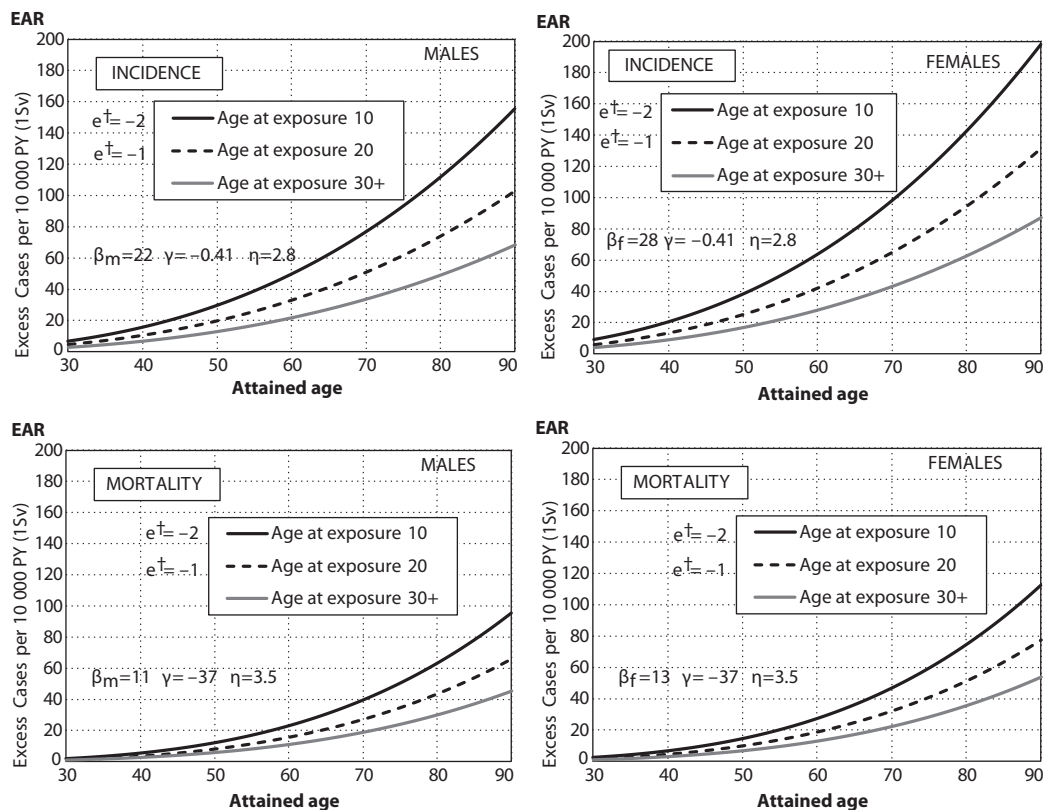
Figure 3 shows ERR plots for the incidence and mortality of all solid cancers by sex as a function of exposure age (e) and attained age (a) using equation 6 (the values of the model parameters are included inside the graphs, source *BEIR VII*, p. 271). The ERR distribution shows a decrease with attained age. Cancer risks increase strongly as age at exposure lowers.

The ERR tends to be larger for females than males (β coefficients). $\gamma = -0.3$ suggests that the radiogenic risk of cancer at age e falls by about 26% ($1 - \exp(\gamma)$) for every decade of increase in age at exposure, and $\eta = -1.4$ suggests that the ERR is almost 20 % smaller at attained age 70 than at age 60 ($1 - (70/60)^{-1.4}$).

The EAR decreases with age at exposure, but increases with attained age. Therefore, unlike the ERR model, the EAR shows a strong increase with attained age (Figure 4) since the EAR model expresses the excess risk as the difference between the exposed and the unexposed population, while the ERR model represents a ratio. Women are more affected than men and incidence risks are higher when compared to mortality patterns.

Baseline risks for many site-specific cancers are different in the Czech Republic or other countries compared to Japan. The EAR and ERR values from the atomic-bomb population need to be ‘transported’

Figure 4 Age-time patterns in radiation-associated risks ($d=1$ Sv) for solid cancer incidence and mortality excluding thyroid and nonmelanoma skin cancers based on the EAR model



to the target population. Two approaches are used. The first approach assumes that the cancer risk induced by radiation exposure is proportional to the baseline risks of a given country and is represented by the excess relative risk (ERR), whereas the second approach assumes that the excess absolute risk (EAR) is the same for any country and Japan. The results from these two approaches can be very different (see Table 4a, b). Based on the *BEIR VII* (p. 275) methodology, the calculation of the lifetime attributable risk (LAR) focuses on the combination of both results (based on ERR and EAR). The fitted sex-specific LAR for cancer incidence or mortality based on LSS survivors are the weighted averages of the two estimates (*LAR_ERR* with a weight of 0.7 and *LAR_EAR* with a weight of 0.3) on a logarithmic scale. For lung cancer, the weighting scheme is reversed (equation 7).

$$LAR = \exp[0.7 \cdot \ln(LAR_ERR) + 0.3 \cdot \ln(LAR_EAR)] / DDREF \quad [7]$$

The lifetime attributable risk (LAR) is a primary risk measure. The LAR estimates the probability of a premature cancer death from radiation. It shows the probability that an individual will die (or develop) cancer associated with exposure. The lifetime attributable risk (LAR) was quantified by applying the risk of specific exposure to radiation at each age to the total force of mortality experienced over a lifetime. The LAR for a person exposed to dose *d* at age *e* is calculated as follows (*BEIR VII*, p. 277):

$$LAR(e,d) = \sum M(d,e,a) \cdot S(a)/S(e) \quad [8]$$

where the summation is from $a=e + L$ to ω (upper age), where *a* denotes attained age (years), and *L* is the risk-free latent period ($L=5$ for solid cancers). $S(a)/S(e)$ is the probability of surviving to age *a* conditional on survival to age *e*. The quantities of $S(a)$ were obtained from a 2010 unabridged life table (units

of age; life tables published by the Czech Statistical Office) for the Czech Republic. The $M(d,e,a)$ is the excess absolute risk at attained age *a* from an exposure at age *e* (i.e. *EAR*). Therefore, the LAR can be thought of as weighted sums (over attained ages *a* up to ω) of the age-specific excess probabilities of radiation-induced cancer incidence or death. The quantities $M(d,e,a)$ were obtained using either the *EAR* or the *ERR* model. In *BEIR VII*, it was assumed that the age-specific *ERR* and *EAR* are the same for both incidence and mortality (see Table 3 and equation 6). Both the *ERR* and the *EAR* models have advantages and disadvantages in terms of closeness of fit to epidemiological data and transferability of risks between populations. Because of that, the calculation of the final LAR combines both models (equation 7).

For cancer incidence, $M(d,e,a)$ is calculated using either:

$$M(d,e,a) = EAR(d,e,a) \quad \text{when using EAR model}$$

$$M(d,e,a) = ERR(d,e,a) \cdot \lambda_i(a) \quad \text{when using ERR model}$$

where $\lambda_i(a)$ is the Czech baseline cancer incidence rate at age *a*, by sex (cause, units of age, period 2009–2011).

For mortality, the approach is very similar, but for estimating site-specific cancer mortality, it was necessary to adjust the *EAR* by the ratio of the sex and age-specific mortality and incidence rates for the Czech population.

$$M(d,e,a) = EAR(d,e,a) \cdot \lambda_m(a) / \lambda_i(a) \quad \text{when using EAR model}$$

$$M(d,e,a) = ERR(d,e,a) \cdot \lambda_m(a) \quad \text{when using ERR model}$$

where $\lambda_m(a)$ is the Czech baseline cancer mortality rate at age *a*, by sex (cause, units of age, period 2009–2011).

Table 3 Parameters of the ERR and the EAR models for site-specific cancer incidence and mortality

Cancer site	ERR models				EAR models			
	β_m	β_f	γ	η	β_m	β_f	γ	η
Colon (C18)	0.63	0.43	-0.30	-1.40	3.20	1.60	-0.41	2.80
Lung (C34)	0.32	1.40	-0.30	-1.40	2.30	3.40	-0.41	5.20
Stomach (C16)	0.21	0.48	-0.30	-1.40	4.90	4.90	-0.41	2.80

Source: BEIR VII report, p. 272; parameters for 100 000 patient-years and dose=100 mSv.⁸⁾

8) The epidemiological data suggest increased cancer risk in the 10 mSv to 100 mSv range.

Based on SVOD data (<http://www.svod.cz/>), five-year age-specific incidence and mortality rates (data on deaths from the Czech Statistical Office) were computed for the period 2009–2011 by sex for each cause (colon, lung, and stomach). The numerator included the sum of incidences or deaths during three years (2009–2011) by age, sex, and cause. The sum of midyear male or female populations during 2009–2011 within 5-year age groups was reported in the denominator. These rates, available for each 5-year age group (centred at ages 2.5; 7.5; ... 87.5), were linearly interpolated (using SAS 9.4 procedure expand) as having single years of age for incidence and mortality rate estimates.

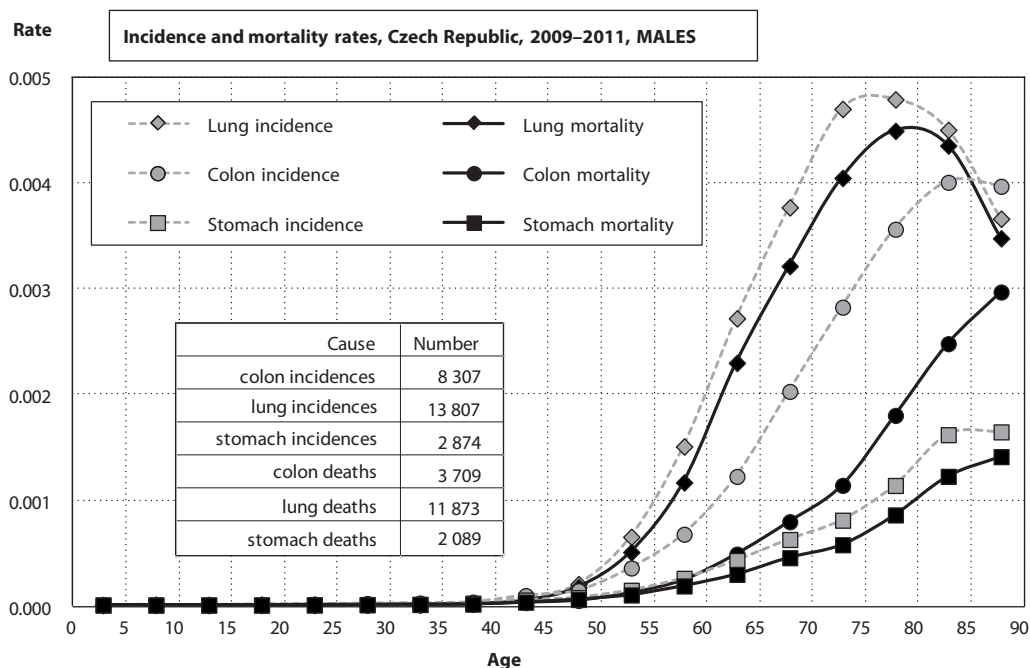
The estimates of site-specific cancer parameters (based on Poisson regression modelling) are published in *BEIR VII* (p. 272) and are shown in Table 3 above. These parameters are then used for the sex-specific estimates of LAR for incidence and mortality, employing both the *ERR* and the *EAR* approaches and finally combining them together (equations 6, 8, 7).

The values of LAR are provided in Table 4a (for age at exposure at 10) and in Table 4b (for age at exposure at 30) for the Czech Republic and for the United States during the same time period of 2009–2011.⁹⁾ The US values are included in order to provide some reference information verifying the integrity of the Czech results. Since the contribution focuses on ionising radiation in the Czech Republic (which is different than in the USA), it is not our aim to examine the differences in sex-, age-, and cause-specific incidence and death rates between the Czech Republic and United States.

Before proceeding to a discussion of the LARs, we provide a brief review of the Czech age- and sex-specific incidence and mortality rates according to the three selected cancer sites (Figures 5a, b).

Age- and sex-specific cancer mortality rates, like incidence rates, continue to rise with advancing age group (Figures 5a, b). Dose-duration effects of carcinogenic exposures likely increase cancer risk with age, regardless of any effects of ageing. However, lung in-

Figure 5a Age-specific incidence and mortality rates of three cancer sites for males, Czech Republic



9) The US data are drawn from <http://seer.cancer.gov> and https://www.cdc.gov/nchs/products/life_tables.htm.

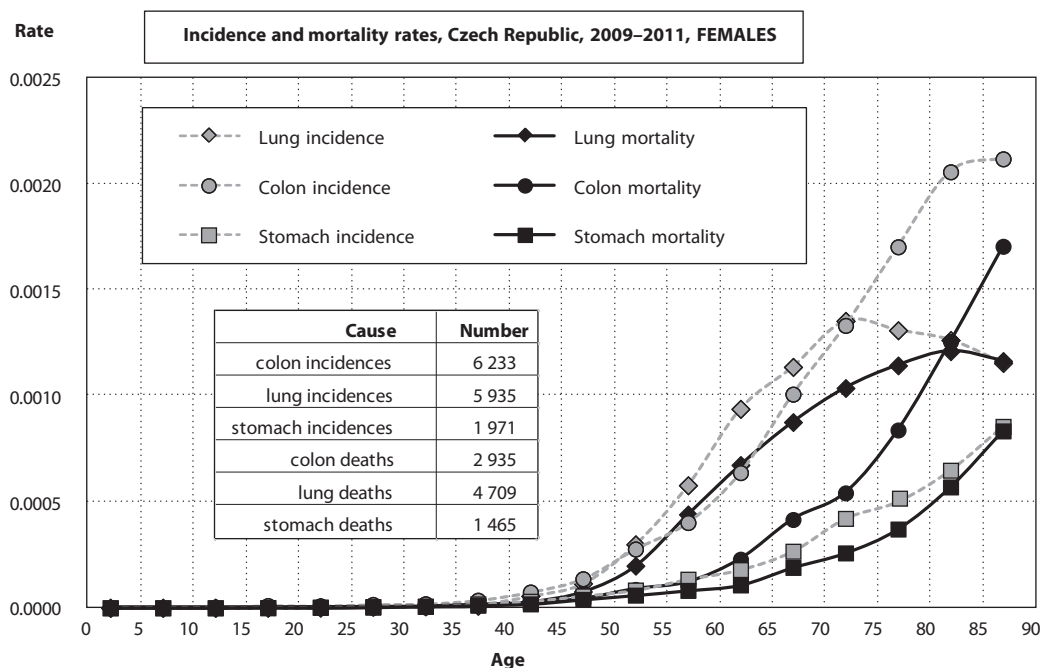
cidence or mortality rates do not peak at the highest age but rather earlier in both sexes. Men have two times higher incidence and mortality rates (see Y-axis) than women. Men experience the highest incidence and mortality rates for lung cancer, while older women experience the highest incidence and mortality rates for colon cancer. Cancer of the stomach shows the lowest values.

A rather different pattern of risks is observed in the LAR estimates (Tables 4a and 4b) for cancer incidence and mortality (based on equations 7, 8). The values of the LARs are provided for the Czech Republic and the USA. The estimates of the combined/weighted LARs (shown in bold, in the columns named: Combined and adjusted by DDREF for the Czech Republic and the USA 2009–2011) are specified for colon (C18), lung (C34), and stomach (C10) cancers.

The highest lifetime attributable incidence risk for men was colon cancer and for women lung cancer, while the incidence and mortality risk of stomach cancer was the lowest for both sexes. Regarding lifetime attributable mortality risk, men and women, show

the highest values for lung cancer, while the colon cancer attributable mortality risk is the second highest. This pattern is also confirmed in US data (Tables 4a, b). Lung cancer is an important cause of cancer morbidity and mortality among men (Figure 5a). Cigarette smoking is known as a major factor of such cancer (Chyou PH et al., 1992). However, the BEIR VII report assumes that the lung cancer risk is also directly proportional to the radiation dose. Unlike age-specific morbidity and mortality rates (Figure 5b) females have a higher lifetime lung cancer risk from radiation compared to males when looking at the LARs (Table 4a, b) for both exposure ages (10 or 30). This pattern is confirmed by both Czech and US data. Sex-dependent variations in lung cancer incidence risk estimates can be due to the differences in additional cancer risks similar to the breast and ovaries. This fact contributes to the increased risk for lung cancer from radiation in females. Similarly, atomic bomb survivor data suggest that this difference is due to the changes in inherent risk rather than disease latency. Age-related risks in younger populations are domi-

Figure 5b Age-specific incidence and mortality rates of three cancer sites for females, Czech Republic



nated by initiation processes, while at later ages radiation-induced cancers may also result from the growth of preexisting malignant cells (Huff *et al.*, 2016).

Results from the Japanese atomic bomb survivors provide strong evidence for cancer morbidity and mor-

tality risks not only for lung but also for colon cancers. Colon cancer is more frequent among women at older ages compared to men in the Czech Republic (Figures 5a, b). Dietary habits are considered important determinants of colon cancer risk (Health Protection Agency,

Table 4a Lifetime attributable risk for people exposed to LET at age 10 in the Czech Republic

Lifetime Attributable Risk of Solid Cancer Incidence when age at exposure is 10 in 2009–2011								
Cancer site	MALES				FEMALES			
	LAR based on EAR	LAR based on ERR	Combined and adjusted by DDREF	USA 2009–2011	LAR based on EAR	LAR based on ERR	Combined and adjusted by DDREF	USA 2009–2011
Colon (C18)	287	434	256	277	178	209	133	162
Lung (C34)	255	360	189	210	378	536	280	463
Stomach (C16)	439	50	64	46	439	58	71	58

Lifetime Attributable Risk of Solid Cancer Mortality when age at exposure is 10 in 2009–2011								
Cancer site	MALES				FEMALES			
	LAR based on EAR	LAR based on ERR	Combined and adjusted by DDREF	USA 2009–2011	LAR based on EAR	LAR based on ERR	Combined and adjusted by DDREF	USA 2009–2011
Colon (C18)	117	188	109	100	77	91	57	54
Lung (C34)	225	308	165	164	309	408	224	334
Stomach (C16)	312	36	46	22	309	41	50	29

Note: Number of cases per 100 000 persons exposed to a single dose of 100 mSv. All results in the table refer to the Czech Republic, only the column named USA 2009–2011 shows the LAR values for the USA.

Source: Own calculation.

Table 4b Lifetime attributable risk for people exposed to LET at age 30 in the Czech Republic

Lifetime Attributable Risk of Solid Cancer Incidence when age at exposure is 30 in 2009–2011								
Cancer site	MALES				FEMALES			
	LAR based on EAR	LAR based on ERR	Combined and adjusted by DDREF	USA 2009–2011	LAR based on EAR	LAR based on ERR	Combined and adjusted by DDREF	USA 2009–2011
Colon (C18)	125	238	131	142	77	112	67	82
Lung (C34)	114	199	90	101	168	295	132	219
Stomach (C16)	191	28	33	24	191	32	36	29

Lifetime Attributable Risk of Solid Cancer Mortality when age at exposure is 30 in 2009–2011								
Cancer site	MALES				FEMALES			
	LAR based on EAR	LAR based on ERR	Combined and adjusted by DDREF	USA 2009–2011	LAR based on EAR	LAR based on ERR	Combined and adjusted by DDREF	USA 2009–2011
Colon (C18)	52	104	56	52	34	50	30	28
Lung (C34)	100	171	78	78	137	226	106	158
Stomach (C16)	136	20	24	11	135	22	26	15

Note: Number of cases per 100 000 persons exposed to a single dose of 100 mSv. All results in the table refer to the Czech Republic, only the column named USA 2009–2011 shows the LAR values for the USA.

Source: Own calculation.

2011). Colon cancer incidence and the lifetime mortality attributable risks due to radiation are more significant for males than females (Tables 4a, b) in the Czech Republic and in the USA. The LAR of colon cancer is the highest among males when incidence is considered, while among females it is the second highest. However, the mortality pattern is different, as the LAR of colon cancer is then the second highest for both sexes, both ages at exposure (10, 30), and in both countries (Czech Republic, USA).

Stomach cancer incidence and mortality rates are lower than lung and colon cancers for males as well as for females. Stomach cancer is more common in men

than in women. However, the LAR incidence and mortality of stomach cancer is higher for women than men (Tables 4a, b) for both exposure ages (10, 30) and in both countries (Czech Republic, USA).

We can conclude that the patterns of age-specific incidence and death rates for three selected cancer sites (colon, lung and stomach; Figures 5a, b) are not the same as the figures for the lifetime attributable risks due to radiation (Tables 4a, b). The main contrast between the rates (incidence and death) and the LAR is seen when males and females are compared. Females are more susceptible to radiation in terms of the incidence risk of lung cancer and the incidence

Table 5a Lifetime attributable risk of cancer for three scenarios of radiation doses when age at exposure is 10

Dose mSv	2.71	2.85	3.30	2.71	2.85	3.30
Estimate of LAR incidence when age at exposure is 10						
Cancer site	MALES			FEMALES		
Colon (C18)	6.93	7.28	8.43	3.60	3.79	4.39
Lung (C34)	5.11	5.38	6.23	7.58	7.97	9.23
Stomach (C16)	1.73	1.82	2.11	1.93	2.03	2.35
Estimate of LAR mortality when age at exposure is 10						
Cancer site	MALES			FEMALES		
Colon (C18)	2.95	3.10	3.59	1.56	1.64	1.90
Lung (C34)	4.47	4.70	5.44	6.06	6.38	7.38
Stomach (C16)	1.24	1.31	1.52	1.36	1.43	1.66

Note: Number of cases per 100 000 persons exposed to doses in mSv.

Source: Own calculation.

Table 5b Lifetime attributable risk of cancer for three scenarios of radiation doses when age at exposure is 30

Dose mSv	2.71	2.85	3.30	2.71	2.85	3.30
Estimate of LAR incidence when age at exposure is 30						
Cancer site	MALES			FEMALES		
Colon (C18)	3.54	3.72	4.31	1.81	1.91	2.21
Lung (C34)	2.43	2.55	2.96	3.59	3.78	4.37
Stomach (C16)	0.89	0.94	1.08	0.98	1.03	1.19
Estimate of LAR mortality when age at exposure is 30						
Cancer site	MALES			FEMALES		
Colon (C18)	1.53	1.61	1.86	0.80	0.84	0.97
Lung (C34)	2.13	2.23	2.59	2.88	3.03	3.51
Stomach (C16)	0.64	0.67	0.78	0.69	0.73	0.84

Note: Number of cases per 100 000 persons exposed to doses in mSv.

Source: Own calculation.

and mortality risk of stomach cancer. The same patterns are observed in the US results.

In order to quantify the possible effects of increased radiation, the life attributable risks are computed for three different levels of radiation (2.71; 2.85; 3.30 in mSv) and included in Tables 5a, b.

The levels of average annual dose of natural background radiation in the Czech Republic were selected according to the conditions provided in Table 1 (annual dose of natural background radiation in the Czech Republic in previous solar cycles; level=2.71 mSv) and Table 2 (annual average dose of natural background radiation in the Czech Republic during a long-term solar minimum, level=2.85 mSv). The third value of 3.30 mSv reflects the higher dose observed after the Fukushima nuclear disaster in 2011. The results provided in Tables 5a, b are based on equation 7, where the resulting value of the LAR is multiplied by the corresponding level (dose in mSv). Therefore, the cancer morbidity/mortality risk patterns fitted for LAR are repeated, with clearly increased risks at higher doses.

5. CONCLUSION AND DISCUSSION

The increasing concentration of cosmic radiation and cosmogenic radionuclides during periods of low solar activity for the specific conditions in the Czech Republic augments the lifetime attributable incidence or death risks of solid cancers (colon, lung and stomach) for males and females. The adverse conditions

are present when the cosmic radiation increases by about 16 % during periods of very low solar activity. The estimated lifetime risks induced by the annual dose of natural background radiation are and will be significantly higher for the present and near future (years 2008–2040) during solar cycles Nos. 24 – 26, which will experience lower solar activity than in previous periods. While medical sources of radiation are much higher than natural background radiation, they are only applied to a part of any given population. In contrast, doses of natural background radiation affect the entire population without exception, and in the long-term. In particular, the estimate of the annual dose of radiation from medical sources for the Czech Republic is around 0.3 mSv per year. Moreover, this value was reported in 1996, when modern diagnostic techniques, such as CT multidetectors etc., were still not widely available. At the same time, the US reported its dose from medical sources of radiation to be 5 mSv per year (Cohen, 2012). In comparison, the typical dose received during a transatlantic flight (Europe – North America) from galactic cosmic rays is 0.05 mSv (FGR, 1994). It can be significantly amplified by a solar energetic particle event. Enhancements of up to a factor of 10 have been estimated in cases of maximum exposure to an event. Nevertheless, the upcoming long period of solar minimum predicted for the years 2020–2040 will mean that cosmogenic radionuclides in our environment will play a much greater role in human health than previously.

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KATEŘINA PODOLSKÁ

graduated in the master study program in Demography at the Faculty of Science of the Charles University. She currently studies the doctoral program in Demography *ibidem*.

She works in the Institute of Atmospheric Physics CAS in Prague. Her research focuses on thermal plasma modeling, statistical analysis of satellite measurements, and associations of solar activity and cosmic radiation and mortality by cause.

JITKA RYCHTAŘIKOVÁ

is a professor at the Department of Demography and Geodemography, Faculty of Science, Charles University, Prague. She is interested in demographic analysis of population trends (including regional and social aspects) in developed countries. She graduated from Charles University in 1973 with a Master's Degree in Geography and French, completed her PhD in 1982, received a degree of Associate Professor in 1993, and was nominated Professor in Demography in 2005. She was awarded a *Démographie générale* degree from l'Université de Paris I Panthéon Sorbonne in 1976. Currently, she lectures Demographic analysis, Population development in Czechia, Population ageing, and SAS software at Charles University and also acts as a visiting professor at the University Paris I Panthéon Sorbonne. She published about 180 contributions and participated or was principal investigator in 11 national and 11 international research projects

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27. ROČNÍK, 1/2017

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Pavol Ďurček | Údaje o bilancii pohybu obyvateľstva v obciach v roku 1972 a ich úprava na úroveň obcí v roku 2011

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