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REVIEW ARTICLE

How reliable are the risk estimates for X-ray examinations in forensic age estimations? A safety update

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Abstract Possible biological side effects of exposure to X-rays are stochastic effects such as carcinogenesis and genetic alterations. In recent years, a number of new studies have been published about the special cancer risk that children may suffer from diagnostic X-rays. Children and adolescents who constitute many of the probands in forensic age-estimation proceedings are considerably more sensitive to the carcinogenic risks of ionizing radiation than adults. Established doses for X-ray examinations in forensic age estimations vary from less than 0.1 µSv (left hand X-ray) up to more than 800 µSv (computed tomography). Computed tomography in children, as a relatively high-dose procedure, is of particular interest because the doses involved are near to the lower limit of the doses observed and analyzed in A-bombing survivor studies. From these studies, direct epidemiological data exist concerning the lifetime cancer risk. Since there is no medical indication for forensic age examinations, it should be stressed that only safe methods are generally acceptable. This paper reviews current knowledge on cancer risks associated with diagnostic radiation and aims to help forensic experts, dentists, and pediatricians evaluate the risk from radiation when using X-rays in age-estimation procedures.

Keywords Forensic age estimation · Radiation risk · Radiation protection · Radiosensitivity · CT · LNT · Children · Adolescent

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Introduction

According to the United Nations Scientific Committee on the effects of atomic radiation and the International Commission on Radiological Protection (ICRP), the exposure to radiation of the populations in western countries has continually increased in the past decades [36, 87]. Due to the increasing frequency of pediatric computed tomography examinations in particular, several authors have warned against a possible rise in lifetime cancer mortality risks attributable to radiation from pediatric computed tomography (CT) [17, 20, 21, 67, 68].

Apart from their diagnostic or therapeutic use in clinical medicine, X-rays are also used on children for forensic age estimations.

According to the recently updated recommendations, the following X-ray methods are often used in the forensic age-estimation procedure [73, 77]:

- Radiographic examination of the left hand [55, 76, 78, 80, 82]
- Dental radiography [23, 50, 62–64]
- CT examination of collar bones (conventional X-ray from collar bone) [54, 59, 77, 81, 83]

The use of CT is restricted to answering the question of whether an individual has completed the 18th or 21st year of life.

CT examinations account for a disproportionately higher radiation dose than other diagnostic X-ray methods. A CT of the sternoclavicular joint produces a dose of approximately 600–800 µSv per examination [37, 38]. However, surveys have shown that the radiation exposure from CT depends heavily on the parameter settings [47].

Brenner et al. have pointed out that the lifetime cancer mortality attributable to radiation exposure from CTs is significantly higher in childhood [17, 20]. In children, the internal organs are anatomically closer together, and the distribution of red bone marrow is more dense, which leads to higher radiation exposure [24, 30, 34, 46, 85]. Zietz el al. called attention to the fact that, in children, the clavicle should be considered a bone vulnerable to ionizing radiation [92].

Risk from radiation exposure: theories

To date, many risk estimations for X-rays were based on the linear no-threshold model (LNT) [16, 21, 22, 57]. Proponents of the LNT hypothesis claim that the extrapolation of radiation-induced health risks from observed high to low doses is strongly linear and that this effect is valid even down to zero doses [22, 44, 53, 69, 70, 84].

Wall et al. reviewed the evidence for and against the LNT hypothesis and explained that, at present, the scientific community favors the LNT philosophy as the most evident risk model [90].

However, data from patients who underwent numerous X-ray examinations during their childhood because they were suffering from tuberculosis or scoliosis demonstrate a significant increase in cancer incidences in their future life [9, 11, 12, 46, 48, 72, 75].

In 2002–2003, supplementary data have been evaluated for child A-bomb survivors who were exposed to nearly the same range of effective doses as were children who were examined by CT [30, 31]. Even at this low-dose level, statistically significant increases in cancer rates have been observed [30, 32].

As a result of recent discussion, the ICRP approved new recommendations for the protection against ionizing radiation in 2007, which take into account biological and medical information [36].

The increase in reliable data is due to one decisive reason: most radiation-induced cancers have a latency period of more than 40 years between exposure and the appearance of the disease [7, 32]. Berrington de Gonzales et al. publications about the risk of cancer from diagnostic X-ray clearly underlined that, currently, existing best evidence from experimental and epidemiological data does not suggest a threshold dose below which radiation exposure is definitively harmless [8]. However, the need for the moment is to minimize all radiation as far as possible and to avoid X-rays where they are not necessary. Finestone and colleagues assessed physician's knowledge about radiation risk and concluded that the majority grossly underestimated the potential radiation risk from bone scans [25].

Risk estimation in childhood

It has been variously recommended to multiply the published risk coefficients by a factor of 3 in assessing the risk for children and adolescents [4]. Hall cited reports of ICRP and stated that, for example, 1-year-old infants are ten to 15 times more radiosensitive than adults [30]. Richardson and colleagues examined the influence of age at exposure on the basis of radiation risk estimates and found evidence that young children were particularly more vulnerable to ionizing radiation [72]. Accordingly, the additional long-term cancer risk (mortality) due to ionizing radiation was approximately 12–15% per Sievert of radiation exposure for 5-year-old children, while it was estimated 5–9% per Sievert for 25- to 65-year-old adults and only 2-2.5% per Sievert for the elderly over 75 years of age [5, 6, 35, 36, 85].

Nevertheless, the possible cancer risks due to ionizing radiation from X-ray doses below 1 mSv are still too small to be calculated directly from epidemiological data, and this is the case for nearly all methods used in forensic age estimation [19, 37, 79]. Only the radiation doses caused by CT of sternoclavicular joints are near to the range of radiation for which direct epidemiological data exist [18, 68].

The conclusion to follow from this situation is certainly not to dispense with X-rays from forensic age-estimation procedures under all circumstances but that the time has come for a reevaluation of the harm–benefit ratio. Nobody would question the potential profit of using X-rays in medical care where there is a diagnostic or therapeutic indication, but how should the risk–benefit ratio in forensic age-estimation procedures be calculated? From the perspective of the proband, there is mostly no personal benefit from age estimation. More commonly, the interest in age estimation comes from legal authorities in criminal proceedings because of the age of criminal responsibility.

The radiation doses from commonly used radiographs and the age-related risk estimates are shown in Table 1. The conflict between necessary image quality, on the one hand, and the desired dose reduction, on the other, was covered in detail by Maher et al. [52]. Lifetime health risks per unit dose were published by the International Commission on Radiological Protection [33, 35, 36, 91]. They present data

Table 1 Effective doses of commonly used X-ray procedures and estimated long-term cancer risk due to radiation: 12–15% per Sv for 5-year-old children, 5–9% per Sv for 25- to 65-year-old adults, and 2–2.5% per Sv for elderly over 75 years of age [4, 35, 61, 79, 85]

Examination type	Dose (mSv)	Risk at age 5 years	Risk at age 25–65 years	Risk at age over 75 years
Left hand X-ray	0.0001	$1.2–1.5\times10^{-8}$	$0.5–0.9\times10^{-8}$	$0.2–0.25\times10^{-8}$
OPG	0.026	$3.1–3.9\times10^{-6}$	$1.3–2.3\times10^{-6}$	$0.5–0.6\times10^{-6}$
CT collar bone	0.6–0.8	$0.7–1.2\times10^{-4}$	$3.0–7.2\times10^{-5}$	$1.2–2.0\times10^{-5}$
CT Thorax	1.1–6.6	$1.2–9.9\times10^{-4}$	$0.5–5.9\times10^{-4}$	$0.2–1.6\times10^{-4}$

of relative health risks from X-rays, taking into consideration age at exposure, time since exposure, and sex. Schmeling et al. estimated the radiation dose received during a CT scan of the collar bone for age-estimation purposes to be 0.6 mSv and referred to a publication by Jurik et al. who compared the exposure doses for conventional tomography and spiral-CT (0.6 mSv) of sternoclavicular joints (0.8 mSv) [38, 79].

The assessment of risk

More recent data are also available that compare radiation exposure from medical X-rays with natural background radiation and other life risks. These data allow a comparison between potential negative effects from radiographs with the hazards of everyday living. For example, the radiation exposure during an intercontinental flight is approximately 50 μSv or 5–8 μSv/hour of flight (flight height 9–12 km) for the middle geographical latitudes [13–15, 49, 79]. Hence, the exposure dose of a 7-h intercontinental flight (40–56 μSv) would be comparable to the radiation dose obtained by two orthopantograms (OPG; 52 μSv) [1, 26, 28, 51].

Studies by Frederiksen et al. estimate the stochastic effects at $1.0–1.9\times10^{-6}$, depending on the radiological method employed for dental examinations [26, 27]. Considered theoretically, the health risks that could ensue from an OPG examination ($1.0–1.9\times10^{-6}$) due to the emitted radiation dose [26, 27, 45, 61, 79] are thus 100 times smaller than other everyday risks, such as the use of a car or public transportation (1×10^{-4}). These data that relate radiation doses from dental examination to normal background exposure levels allow an informed assessment of risk [1]. Jung estimated that, on the basis of the exposure dose incurred by a single OPG picture, a 2.5-h long participation in traffic would bear an equivalent risk of having a fatal accident [37]. Based on these facts, the resulting risk from using X-rays in age-determination procedures (with the exception of CTs on sternoclavicular joints) is very low in comparison to other life risks (Table 2). [2, 86].

Table 2 Comparison of different life risks and the likelihood of fatal event [2, 86]

Life risks	Likelihood of fatal event
Lifetime cancer risk (average) from single OPG	$1.0–1.9\times10^{-6}$
Lifetime cancer risk (average) from CT of collar bone	$3.0–4.0\times10^{-5}$
Lifetime risk for drowning	3.5×10^{-4}
Probability of dying from homicide	1.9×10^{-3}
Lifetime risk to have fatal accident	4.5×10^{-3}
Probability of dying from criminal assault	4.7×10^{-3}
Lifetime risk of fatal downfall	7.0×10^{-3}
Lifetime mortality risk from myocardial infarction	5.2×10^{-2}
Lifetime mortality risk from malignant tumor	1.5×10^{-1}

Discussion

We are convinced that the comparison of stochastic life risks is admissible and that it facilitates a pragmatic evaluation of risks. Since a complete elimination of all risks is impossible, the question arises what type and degree of risk the society is willing to bear.

Hall has claimed that a risk of harm of one in a million should be generally ignored [29, 30]. On the basis of general and unrestricted life risks (i.e., pregnant women use aircrafts as a means of transportation), procedures applied that can pose comparable risks, for example, through the X-ray exposure of hands and teeth, should be considered justifiable.

In view of the significantly higher radiation doses through the use of CTs, it is particularly advisable and, indeed, necessary to adhere to the diagnostic reference values (DRV). Furthermore, the potential for reducing

Table 3 List of health conditions associated with high sensitivity to radiation [3, 10, 12]

Ataxia teleangiectasia
Fanconi's anemia
Xeroderma pigmentosum
Gravidity

radiation doses by using modern devices and optimizing the setting parameters should be realized as well as possible. Because of the 100 times higher exposure dose, CT of the inner clavicle joints should be restricted to the few cases in which the person to be examined is probably 18 years old or older, and in which the additional examination is essential in answering the question of whether the age limit of 18 or 21 has been reached.

As long as the discussion on the biological effects of low-dose radiation has not been resolved, the so-called minimization principle applies without restriction. This calls for necessary examinations to be conducted with *as low a dose as possible*. In addition, exposures that are not strictly necessary as well as unsuitable examinations should be dispensed with [25, 58, 75, 85, 89]. It is, furthermore, essential to pay attention to country-specific laws and regulations before applying X-rays in forensic age-estimation procedures [4, 60, 71, 74, 85, 88].

Departments performing the X-rays should, in addition, be required to have written instructions in line with the DRV at their disposal for taking X-rays in age estimations. In cases of age estimation on children, the radiologist should also have experience in pediatric radiology.

It is necessary to exclude all contraindications. Table 3 shows examples of diseases and conditions which are associated with higher sensitivity to radiation [3, 10, 56, 58] and underline the necessity of a clinical examination prior to use of X-rays as a fundamental part of any age estimation.

Conclusions

The aim of this publication is to help forensic experts and pediatricians evaluate risks from radiation when performing X-ray examinations in age-estimation procedures.

The data on the health risks of radiation exposure, especially in children and in particular from CT examinations, show that a great effort should be made in order to reduce radiation doses.

The comparison between risks associated with radiation and other common risks from daily hazards demonstrates that, despite the higher sensibility of children to radiation, hand radiographs and OPG are relatively harmless. The responsible use of X-rays in forensic age estimations, however, demands a critical selection of methods that are suitable for the specific age range. Thus, no X-rays should be made beyond the examination range recommend in scientific recommendations [77].

The use of collar bone CT is not appropriate for the age estimation of children under the age of 18 and is only indicated as a method for answering the age over 18 years issue or the age limit of 21 years.

Despite the continued discussion about all the difficulties in the current assessment of risk, the data show that it is indispensable to not only use dose-lowering techniques but also to take the age of the person being examined into greater account than previously [39–43, 52, 65, 66, 89].

The following list summarizes the requirements for optimizing the procedures used and thereby minimizing the risk from X-rays in forensic Age-estimation procedures:

- Strict, standardized indication
- Application only by trained radiologists with experience in forensic age estimation
- No X-rays beyond the accepted recommendations or scientific guidelines
    - CT restricted to age over 18
    - No radioscopies
- Reuse of preexisting X-rays if useful
- Application of modern X-ray devices
    - Short exposition time
    - Lowering tube voltage below 60 kV at least
    - Reduction of the effective tube current time (mAs)
    - Reduction (mean) effective tube current time (mAs)
    - Secondary filter 0.1–0.2 Cu
    - Use of raster if the proband is older than 10 years; optimized collimation
    - Last image hold
- Precise documentation of dose-area product and exposure time
- Exact knowledge of the radiation dose to justify such exposures; dose was calculated from quality control measurements and highly sensitive, calibrated dosimeters
- Use of certified protection clothing

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