

Current radiation exposure of man - a comparison between digital imaging and environmental, workplace and accidental radiation burden

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Dedicated with great appreciation to Prof. Dr. Wolfgang Jacobi at the occasion of his 80th birthday. Neuherberg, September 10, 2008.

Abstract. X-ray imaging in diagnostic radiology is recognized worldwide as an outstanding tool for the early recognition and prevention of diseases. The reverse side is that radiography contributes essentially to the exposure of the public. Mean effective doses, averaged over patients and non-patients, are reaching or exceeding the level of natural radiation. This is particularly the case when digital imaging techniques are utilized, such as CT, coronary angiography and interventional radiology. Individual effective doses for a patient may occur between several mSv and several hundred mSv by one examination or a series of examinations, while individual organ doses of a patient may reach equivalent doses even up to several Sv, such as for the skin. The purpose of this review is to provide information on effective dose levels occurring in diagnostic radiology as compared with individual effective doses achieved from environmental radiation, radiation at workplaces and after major radiation incidents.

KEYWORDS: *Ionizing radiation, exposure, medical exposure, risk, radiology, workplace, environment, accidents.*

1. Introduction

Worldwide, about a billion of medical X-ray images are taken annually in diagnostic radiology aiming to serve for prevention and early recognition of diseases [1]. The obvious advantages of X-ray imaging are the non-invasive examination free of pain for the patient, the access to radiological facilities, mostly comfortable at least in the highly industrialised countries, and the fast and in most cases extremely reliable diagnostic procedure. Radiological examinations can help to improve health or, in acute cases, even save life. However, the ionizing radiation involved is in principle biologically negative; its application to humans may be associated with a non-negligible risk to induce cancer. Recently, X-rays have officially been classified as "carcinogen" by WHO [2] and other organizations. The carcinogenic impact has since long been evidenced at high dose levels. At low dose levels, epidemiologic evidence of the radiogenic cancer risk is lacking; in this dose region the principle of precaution is guiding us to apply the linear-no-threshold (LNT) model of the dose-risk relationship [22]. Before CT conquered medicine, the effective dose to a patient from plain-film imaging ranged between 0.01 mSv and several mSv. Nowadays single CT examinations range between a few mSv and several 10 mSv of effective dose, which figure is valid for a single examination of a patient. In course of a diagnostic procedure and follow-up control after treatment a number of such examinations may be necessary, associated with a summation of the corresponding effective doses, resulting in high cumulative effective doses for individual patients.

BEIR Report VII [3] assigns effective doses below 100 mSv to the low-dose category. Physicians administering and patients undergoing X-ray examinations may have difficulty to interpret the magnitude of exposure and the related potential risk; both need quantitative information. However, due to the so far limited achievements of epidemiological and radiobiological sciences the knowledge on dose-risk relationship for carcinogenesis at low doses (and dose rates) is still poor. Since there is

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no clear evidence available neither for biological effects nor for quantified cancer risk in humans at low doses, the present paper will relate typical current CT exposures to the exposure data achieved from natural and other man-made radiation sources which themselves are considered hazardous or carcinogenic, although preferentially at enhanced dose levels.

2. Medical radiation exposure of patients

A comparison of mean annual effective dose values to each member of the population, as originating from diagnostic X-ray imaging and averaged over the respective populations in a number of selected countries in Europe and overseas, all representing health-care level I, is given in Table 1. Within Europe, Luxembourg, Belgium and Germany have reported the highest mean annual effective doses of about 1.8 mSv to 2 mSv per head of the population. The United Kingdom, on the other end of the dose scale in Europe, has reported a mean annual effective dose of 0.4 mSv per head of its population, for about the same year [4].

Table 1 Comparison of (a) mean annual effective doses per caput and (b) collective effective doses for different countries in Europe and overseas, taken basically from UNSCEAR [5] and referring to the year of collection and the number of population. Data are actualized, respectively complemented, for Belgium [6], Germany [7, 8], Luxembourg [9], Netherlands [10], Switzerland [11], UK [4] as well as for Japan [12, 13] and the USA [14].

Country	Year of data collection	Present number of population (in million)	Collective effective dose (person·Sv) per year	Mean annual effective dose (E), per head of the population (mSv)
EUROPE				
Belgium	1999	11	18,315	1.78
Finland		5.5	2,270	0.45
France		65	57,660	1.00
Luxembourg	2002	0.5	990	1.98
Germany	2003	80	140,000	1.8
Netherlands		16	8,000	0.51
Poland		38.5	32,200	0.80
Russia		144	128,000	0.90
Sweden		9	6,000	0.68
Switzerland	2007	7.5	9,000	1.20
United Kingdom	2000	60	19,300	0.40
OVERSEAS				
Australia		21	13,000	0.80
Canada		32	26,200	0.94
Japan	2000	127	473,000	≈ 3.7
	2006		*762,000	*≈ 6.0
USA	2006	300	+960,000	≈ 3.2

*Extrapolated by 12% per year increase of CT examinations as given in [13].

+The Chernobyl nuclear power plant accident in 1986 produced a global collective dose of 600,000 person·Sv [14].

More interesting are the newly published data for the USA (for 2006) and Japan (for 2000): The US mean annual effective dose per head of the population has significantly increased up to 3.2 mSv for the year 2006 [14] or the year 2005 [15], after an effective dose of 0.5 mSv has been reported for almost three decades since 1980 [5]. The individual effective doses of US patients range between 2 and 20 mSv, for a single CT depending on the type of examination. Furthermore, more than one CT

scan has been reported, even on the same day, at most patients undergoing abdominal or pelvic CT examinations [16]. At least three scans were administered to 30% of all CT patients, more than five scans to 7%, and nine or more scans to 4% [17].

Corresponding Japanese data on patient exposure have for long time not really shown-up in the English language literature. More recently, a mean annual per caput effective dose of 2.3 mSv has been published in an English abstract dealing solely with CT [12], which dose value has actually to be backed-up by about 1.4 mSv due to conventional radiology. In total, this will sum-up to a mean annual effective dose per caput of about 3.7 mSv valid for the year 2000, with an increase of about 12% annually in CT examinations, both figures stem from [13]. By extrapolation to the year 2006, the mean annual effective dose per caput in Japan will have reached more than 6 mSv, the exposure of nuclear medicine not yet included. It is moreover unclear whether or not angiography and interventions have been included in the Japanese CT data given in [12]. For Japan and the year 2000, the number of CT scanners has been given to be 87.8 per million populations [12], which would stand for about 11,000 CT units. It should still be noted that all data reported in Table 1 suffer from the pitfall that the exposure data reported nationally have not been evaluated according to a jointly agreed protocol [8].

As for paediatric plain-film radiology in Germany, high frequencies of X-ray examinations have recently been evaluated for new-borns and young children, resulting up to about, e.g., 80 chest examinations per child [18]. As for paediatric CT examinations, recent US estimates indicate CT studies to be between 6% and 11% on children of the total number of CT examinations, which means 3 to 7 million paediatric CT examinations in around 2006 [19]. The frequent examination practice in paediatric radiology using adult CT settings for new-borns and young children may result in large doses also to the children. A single neonatal abdominal CT scan may under these conditions expose an infant to an effective dose of up to about 20 mSv [19]. It has been observed that paediatric CT practice can differ in exposure up to a factor 10 and more between different clinics [20]. These figures appear of great concern since children should be considered more sensitive to ionizing radiation than the adults [21] and have a longer life expectancy. By contrast, for senior persons the life-time risk of developing a radiation-induced fatal cancer is lower than for mid-life grown-ups and children, as the risk decreases with age [21].

3. Medical versus occupational, public and incidental exposure

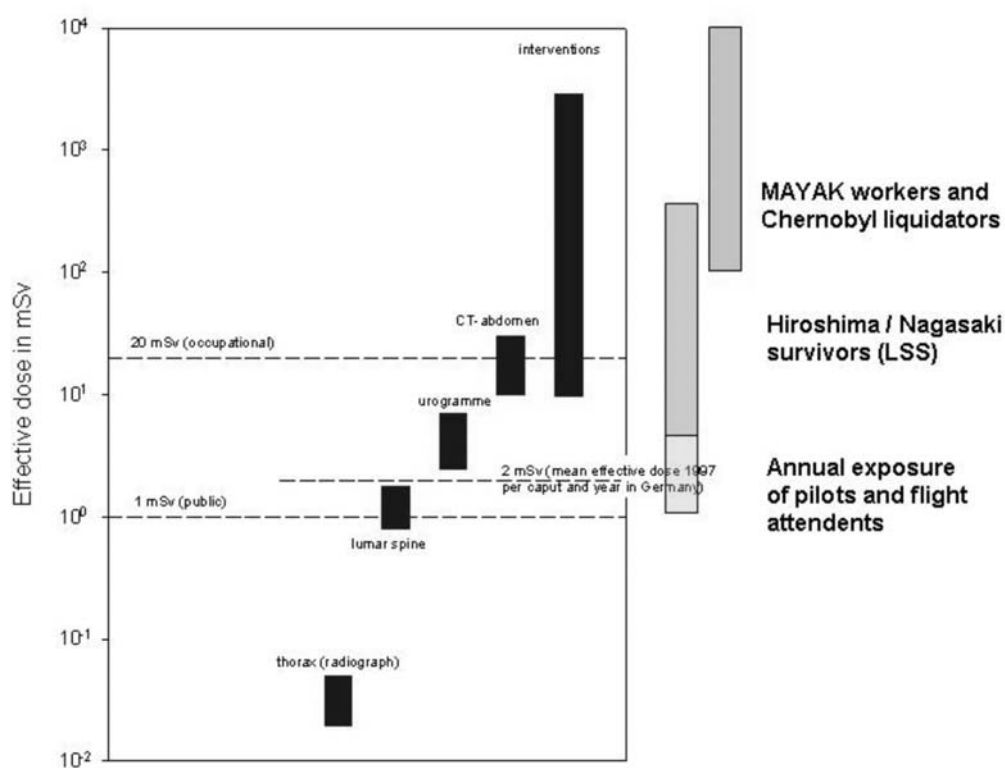
Figure 1 compares the variation width of effective doses per patient and X-ray examination with annual dose limits valid for (a) occupationally exposed persons and (b) members of the public, as given by ICRP recommendations [22] and national legislation: Radiation workers are under permanent control, well kept individually below an effective dose limit of 20 mSv per year. Another dose limit is recommended by ICRP for members of the public to be 1 mSv per year at work places, applying to the sum of the relevant effective doses from external exposures in the specified time period and the committed effective dose from intakes of radio nuclides in the same period [22]. The observance of the limits should prevent harm from man's health caused by ionizing radiation.

By contrast, ionizing radiation in medicine is intentionally administered for the health benefit of the patient. No dose limits exist for patients in radiology. Instead, radiation administration in medicine is governed by principles, i.e. the ethical justification of an examination, the optimization of equipment and procedures, and the ALARA principle [22]. These principles are expected to be adhered strictly by each radiologist, for each patient and for each X-ray examination, although the principles are neither quantifiable nor are they regulated or controlled. It is worth pointing out from figure 1, that the effective dose of one adult chest CT of 10 mSv correlates to 500 to 1,000 conventional plain-film chest examinations to the same patient.

The following effective dose figures hold for occupationally exposed persons, and are presented here for comparison [23]. The German Radiation Protection Register reports a mean annual effective dose for about 315,000 radiation workers (at a terrestrial working environment) to be 0.13 mSv per person

as monitored in 2006 (max 30 mSv) [24]. In contrast, pilots and flight attendants are expected to reach higher effective doses annually originating from cosmic radiation at flight altitudes. Again the German Radiation Protection Register reports a mean annual effective dose of 2.2 mSv per crew member in 2006 (min 0.5 mSv; max 8 mSv) determined for a cohort of roughly 35,000 persons monitored (data base with 45 airlines) [24]. Having this mean effective dose of 2.2 mSv in mind, a single CT examination of the head will refer to more than two years flight time exposure, an abdominal CT up to roughly 10 years flight time exposure.

Figure 1: Comparison of exposure data of individual patients from medical X-rays versus exposure data of pilots and flight attendants, atomic bomb survivors, Chernobyl liquidators and PO MAYAK workers. The dose limits marked in the figure, due to ICRP recommendations [22] and national ordinances, are given for members of the public and radiation workers, hence not for patients. The doses should be compared with the mean annual effective dose per caput from background radiation of about 2 - 3 mSv [7, 16]; maximum effective doses from background are reported to be up to 10 mSv by terrestrial radiation [3], and more by radon [11].

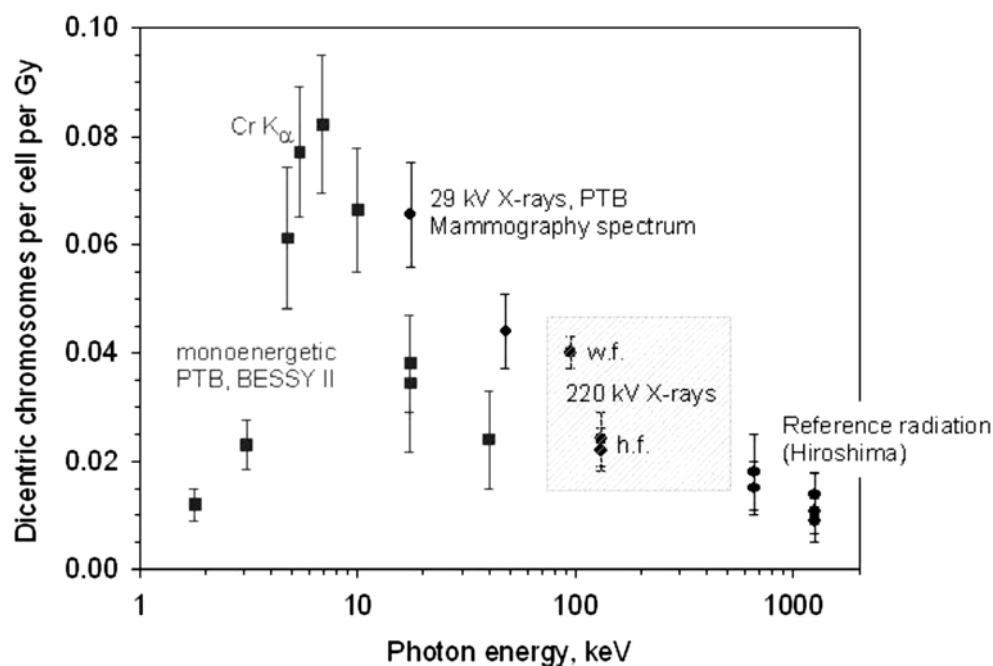


The effective doses to atomic bomb survivors, for comparison, cover a range between several mSv and several hundred mSv [25], which dose range matches some of the nowadays accepted effective doses to patients from diagnostic procedures. Reporting on the doses of the exposed atomic bomb survivor, Brenner and Hall [25] point out that a substantial proportion of the 25,000 survivors received effective doses of less than 50 mSv, which is the equivalent of about three abdominal or cardiac CT scans. They report that a significant increase in the overall risk of cancer was recorded for the subgroup of atom bomb survivors who received low doses in the 5 to 50 mSv range. "There is direct evidence from epidemiologic studies that the organ doses corresponding to an extended CT study (two or three scans) result in an increased risk of cancer" and "the evidence is reasonably convincing for adults and more convincing for children" [25]. Hence, repeated CT examinations, angiography and interventional radiology are dealing with doses for which carcinogenic risk can not be excluded and may be quantifiable.

4. Relative biological efficiency (RBE) of X-rays

Atomic bomb survivors experienced high energy photon spectra around 1 MeV and more, the spectra of cosmic rays at flight levels show maxima around 1 MeV and 100 MeV, while diagnostic X-ray spectra have maxima at about 15 keV (mammography), 50 keV (dental radiology) and around 80 keV (2- and 3-dimensional organ radiography, among CT). The biological endpoint of exchange-type chromosome aberrations in human lymphocytes may be considered as a typical example of the RBE values to be therefore expected. In vitro studies have resulted in significant RBE differences between various energies of these sparsely ionizing radiations, and RBE changes up to about a factor of 8 between ^{60}Co γ -rays and soft X-rays, depending on radiation quality (Fig. 2) [8, 26-28] and receptor size [29, 30] have been observed. Although dicentric chromosomes, as cytotoxic chromosome aberrations, are not directly relevant for cancer induction, the related RBEs may be taken as a model for the RBEs of chromosome exchanges and deletions which have a more direct bearing on cancer-prone somatic mutations. ICRU and ICRP recommend constant weighting factors $Q = 1$ and $w_R = 1$ for all weakly ionising radiations, irrespective of radiation quality [22]. This recommendation appears justified for reasons of the desirable simplification in practical radiation protection and by the missing evidence of RBE variations within the presently available epidemiologic risk coefficients for weakly ionizing radiations. However, ICRP [22] has also expressed that in specific risk estimates, RBE differences should be considered [8, 31] (see Fig. 2).

Figure 2: Yield of dicentric chromosome aberrations plotted versus the energy of different monoenergetic synchrotron X-rays (PTB/BESSY II, Berlin) [28] (filled squares) and chromium K_α fluorescence X-rays, as well as versus the mean energies of different X-ray spectra, respectively the one of ^{60}Co γ -radiation (approximately serving as reference radiation for the Hiroshima/Nagasaki photon spectra) (filled circles) [26, 27]. (Note, w.f. stands for weakly filtered, h.f. for heavily filtered X-ray spectra).



5. Discussion

Elias Zerhouni, NIH, in his Mansfield Lecture at the 2006 International Society for Magnetic Resonance in Medicine meeting in Seattle, predicted a central role for medical imaging in the 21st century medical research and practice [32]. He predicted radiology move to the forefront of medicine, a trend he expects to continue. His visions may be expected to apply particularly for CT in the near future focussing on wide-band applications in emergency medicine, for whole body scans and new screening programs. Screening is an important motivation for increased CT use in asymptomatic

adults, its utilization growth will arise from virtual CT colonoscopy, CT lung cancer screening, cardiac screening, and whole-body screening. But it should also be noted that a single whole-body CT scan may give rise to an effective dose of several ten mSv up to 100 mSv. Noteworthy, the effective dose of 100 mSv to a patient due to an extended CT examination corresponds to the effective dose of five thousand conventional chest X-ray examinations taken with screen-film technique [1]. No doubt, CT and other high-dose digital imaging techniques are of greatest benefit for the patient, provided they are justified and properly executed. But the prize for this high diagnostic quality is a high radiation dose to the respective patient. The number of CT units and hence CT examinations will continue to rise for the next future. "Medical imaging has become the largest controllable source of radiation exposure, although it remains unregulated", says Fred Mettler [14, 16].

As for the resulting radiation risk, our knowledge, still today, refers mainly to the consequences of nuclear impact, such as the long-term observation of atomic bomb survivors in Japan (dealing with some five hundred cases of leukaemia and solid cancer, in total), but also of some hundred thousand radiation workers in nuclear industry [33], and more recently, late effect studies on some 10 thousand radiation workers of the early USSR nuclear facilities like MAYAK (formerly, Chelyabinsk-65, USSR [34-36]. However, our knowledge is definitely limited, as far as risk of low doses and low dose rates and of X-rays is concerned, such as in diagnostic radiology.

Unlike the nuclear cohorts, diagnostic radiology deals with about a billion X-ray patients and examinations world-wide each year, among them a high percentage of high-dose CTs, e.g., 10 million CT examinations a year in Germany and more than 60 million a year in the USA. These figures are presently rising by roughly 10 % a year, as evaluated from the past years, and will probably continue to rise in the near future. As a consequence, corresponding data on individual patients and related X-ray examinations pile-up in clinical departments. The individual or reference dose information and available technical data of the X-ray equipment could be utilized for dose assessment and, together with the hospital records, serve for subsequent epidemiological risk estimates, directly in the domain of diagnostic X-ray qualities. These data are awaiting epidemiologic evaluation of the dose-risk relationship. But even after a successful epidemiological evaluation of X-ray risk, the underlying biological mechanisms for radiation induced cancer in humans would continue to be an open issue searching for answers. The problem with these studies, however, is that the patients are typically ill and might have a higher potential risk of similar cancers or diseases as those expected from the radiation effect. The age distribution of the patients has been another argument for not using such data, but today the age distributions especially for CT have another peak for younger patients.

6. Reduction of patient exposure

The patients' exposure can be lowered conventionally by, e.g., compliance with the so-called indication catalogue [37], alternative use of ultrasound and MRI techniques, highly ethical indication of the X-ray examination, optimization of techniques and procedures as well as education and training of physicians including careful observance of the so-called diagnostic reference levels. In US, one third of all CT scans are argued not to be justified by a medical need [19]. Many radiologists agree that inappropriate CT scans are performed because of medico-legal concerns and exploitation by profit-driven physicians and commercial imaging providers, said Dr. Michael Brant-Zawadzki, a member of the RSNA's public information advisor's network [38].

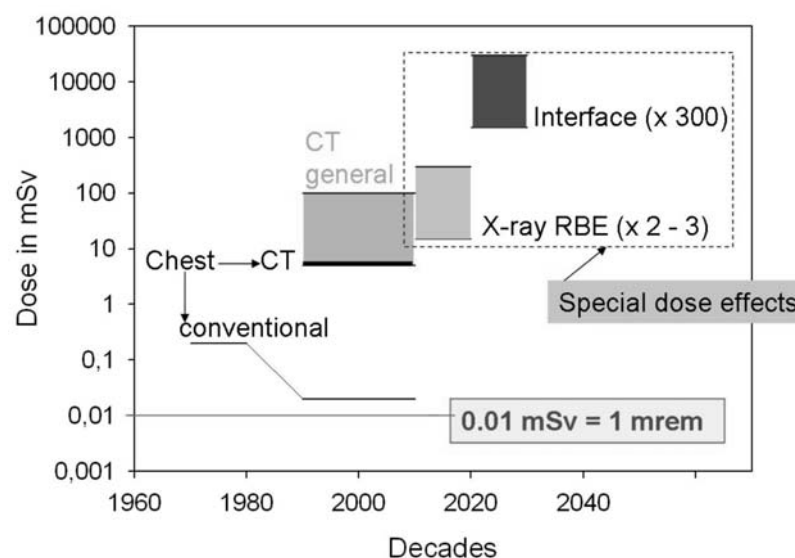
With all this in mind, there is the strong need for novel dose-saving CT technology. For the patients' protection, industry has to continue reducing patient doses effectively. There should be a clear strategy to lower radiation exposure by a factor 5 to 10. In digital projection imaging, the use of digital detectors itself did not result in lower doses per examination since the detective quantum efficiency is not significantly higher for most digital detectors than that of screen-film systems. Due to the effect that images with higher doses yield less noisy images, even higher doses to the patient are resulting. There is a better chance to optimise image quality in terms of needed information accuracy using image processing to reduce the necessary dose in digital radiography. In particular physically

based noise reduction methods might help to reduce required doses in medical radiography. One way for performing this task is to build correlations between two images and use this additional information in DR [39, 40]. This method can also be used in CT imaging. Here is the additional potential to use optimised reconstruction algorithms like algebraic methods [41] or new algorithms like SVD [42] or OPED [43]. Further, already clinically used methods allow smaller dose reductions (up to 50% instead of factors). These are more efficient detectors, bowtie-shaped filters, automatic exposure control in z-direction or in the xy-plane [44], intelligent adaptive shuttering for multi-slice CT-scanners or specific data acquisition modes for certain investigations like heart investigations [45-47].

7. Conclusions

According to most recent reports, CT frequencies and radiation exposures in diagnostic radiology are highest in Japan and USA who have thus taken over the world-leadership in medical radiation administration, among the health-care level I countries. Individual patient exposures have been reported that have reached, on an average, 10 mSv (i.e., 1000 mrem in terms of the previous units). The question whether or not there is a cancer risk at this dose level will continue to be subject of controversial issues. But a number of patients get multiple X-ray examinations. For them, total exposures may accumulate exceeding 50 mSv or even 100 mSv in the course of a diagnostic or therapeutic follow-up. Also for an angiographic examination or an interventional measure, the effective dose may reach or exceed even 100 mSv. The evaluation of the atomic bomb survivors has shown a statistically significant increase in cancer at dose estimates above 50 mSv [48]. Of course, the instantaneous diagnostic benefit of these new imaging technologies is immense and highly appreciated by the radiologists and patients. But reviewing our enormous efforts in medical radiation protection in course of the seventieth and eighties to reduce patient exposure from, e.g., 0.2 to 0.02 mSv per chest examination, the today acceptance of radiation exposures boosting by a factor of thousand up to ten's of mSv appears surprising for experts in radiation protection (Fig. 3).

Figure 3: Time-based development of effective dose to patients per X-ray examination between the years of about 1975 and presence, originating from plain-film radiographs and CT. The special dose effects refer to (a) potentially higher relative biological effectiveness (RBE) [26-28] and (b) dose enhancement effects as observed, *in vitro*, in tissue adjacent to metallic surfaces (e.g., contrast media, implants, prosthesis, etc.) [50].



Today, patients and radiologists accept CT examinations even repeatedly. Media-advertised whole body CTs are accepted for preventive medical check-up not caring particularly about ethical indication. Radiation has obviously lost its frightening for the public, for radiologists and even for the

members of the radiation protection community, at least as far as medicine is concerned. This new tolerance is not valid for even much lower exposures of the same public if the radiation would originate from other man-made sources: "The public is concerned about nuclear industry and waste problems They seem less concerned about increasing radiation doses due to new technologies in medical radiology" [49]. Does the new tolerance also mean that current radiation exposures in medicine are negligible from the risk point of view? Not really, since we must be aware that radiation-induced cancers do typically show-up not before long time after exposure [1, 15]. Of course, it is first the *acute health benefit* of, for instance, an emergency patient that deserves highest priority.

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