CHANGING ATTITUDE TO RADIATION HAZARDS AND CONSEQUENT OPPORTUNITIES FOR LINAC APPLICATIONS

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Abstract

High-energy LINACs unavoidably yield ionizing radiation. This fact makes them subject to strict regulations and considerably limits their possible applications. During the last two decades the attitude to ionizing radiation hazards seems to become more balanced, as opposed to "radiophobia" of the Cold-War era. Scientifically, the Linear No-Threshold (LNT) model of radiation damage is more frequently questioned. Moreover, the hypothesis of radiation hormesis – beneficial effect of low-dose radiation – is studied. While this scientific debate has not yet given fruit in terms of changes in radiation regulation policy, we may expect this to happen in the near to middle term. Namely, the ALARA (as low as reasonably achievable) demand is anticipated to be substituted by some tolerance level, which in turn is anticipated to be very high according to the present standards. The presentation will review the present status of the radiation-hazard debate, and outline anticipated opportunities for LINAC applications, like compact designs and wider industrial outreach.

TOLERANCE LEVEL VS. LINEAR NO-THRESHOLD

High-energy LINACs unavoidably yield ionizing radiation. Adverse effects of high doses of ionizing radiation were discovered nearly immediately after the discovery of X-rays and radioactivity back in the XIX century. However, it took about two decades before early medical practitioners began to control their exposures to ionizing radiation. For example, the British X-ray and Radium Protection Committee was formed in 1921. In 1924, at a meeting of the American Roentgen Ray Society, Arthur Mutscheller recommended "tolerance" (permissible) dose rate for radiation workers, a dose rate that could be tolerated indefinitely. This rate was 0.2 roentgen per day (R/day), based on applying a factor of 1/100 to the commonly accepted average erythema dose of 600 R (not accidentally – lethal dose in case of acute whole-body irradiation), spread over 30 days [1]. The International Commission on Radiological Protection (ICRP), established in 1928, accepted in 1931 this tolerance dose rate as a universal recommendation that was in effect for more than quarter of a century. This level corresponds to 70 R/year or about 700 mSv/year – 35 times higher than the present-day occupational (professional) exposure limit, and 700 times higher than the present-day public one. It was assumed that no harm will be caused by radiation below this tolerance level. To illustrate the extent of public confidence in the usefulness and safety of ionizing radiation we will remind that until after the Second World War X-ray machines were typical equipment of shoe shops (this fact was mentioned in passing in Rudolf Peierls' book from 1956 [2]).

It should be stressed that until now nobody succeeded to disprove the assumption of tolerance level (while it is clear that high dose is harmful: acute dose of 100 R leads to radiation sickness and 200 R may be already lethal). For example, a study of British radiological society members [3] reveals that while the pre-1921 radiologists (who had not controlled their exposure and therefore received high doses of ionizing radiation) had a 75% (4σ of the expected value) higher cancer mortality than other medical practitioners, the post-1920 radiologists had an insignificant 5% (0.4σ) excess. Furthermore, the studies of radium dial-painters, exposed to huge cumulative doses (mostly at low rates), revealed that no cancer excess was observed below the life-time dose of about 1000 rad [4]. For α-particles, emitted by radium, the radiation weighting factor w_R=20, i.e. 1000 rad = 10 Gray correspond to 200,000 mSv!

However, geneticists strongly believed the theory that the number of genetic mutations is linearly proportional to radiation dose just like the number of ionized atoms, that mutagenic damage was cumulative and therefore no tolerant (safe) dose for radiation could be set. According to this view, there is no absolute radiation safety, so that the safety level should only be weighed against the cost to achieve it [1].

After the bombing of Hiroshima and the start of the nuclear arms race, geneticists greatly amplified their concerns that exposure to radiation of atomic bomb fall-out would likely have devastating consequences on the gene pool of the human population. Hermann Muller was awarded the Nobel Prize in 1946 for his discovery of radiation-induced mutations. In his Nobel Prize Lecture, he argued that the dose-response for radiation-induced germ cell mutations was linear and that there was "no escape from the conclusion that there is no threshold" [5].

There was great controversy and extensive arguments during the following decade. Probably, both super-powers became interested in exaggerating the nuclear fall-out hazard. Ultimately all kinds of ionizing radiation became connected in public perception with nuclear apocalypse. As a result of (or at least in the wake of) this change in public perception, the ICRP and the national regulators changed their radiation protection policies in the mid-1950s. They rejected the tolerance dose concept and adopted the ALARA (as low as reasonably achievable) policy, i.e., to keep the radiation exposure ALARA. The accepted model for low-dose radiation-induced health damage became the so-called Linear No-Threshold (LNT) model. In LNT, the acute exposure, high-dose cancer mortality data from the study on Hiroshima-Nagasaki survivors [6] was taken as the basis for extrapolation to low doses of radiation. (We should also mention in brackets, that the Life Span Study of the survivors, though dealing with vast amount of data, is performed by single organization that grants only a very limited access to its raw data for the scientific community). The ICRP has been progressively tightening its recommendations for occupational and public exposures, from 50 and 5 mSv/year in 1958 [7] to 20 and 1 mSv/year in 1990 [8], and national regulators usually followed. And probably even more importantly, these stringent norms were (and to a large extent are still being) considered unsafe by the general public.

NEW TRENDS

While the Linear No-Threshold (LNT) view is commonplace for the present regulation and for the public perception, it has never been a subject to scientific consensus. The absence of consensus has been always officially acknowledged – see e.g. the 1979 report of the US Congress Office of Technology Assessment [9]. Towards the end of the Cold War, the LNT model becomes more and more challenged.

In simple terms, the concept of a cumulative no-threshold damage to living organism by *any* possible factor contradicts most of the existing scientific evidence. E.g., for paracetamol – a widely used non-prescription medicine – the lethal dose LD_{50} is about 2 g/kg, i.e. below 200 g for a normal person (few weigh above 100 kg). Following the LNT logic, each caplet of paracetamol (0.5 g) has lethal probability of 50%×0.5/200=0.125% – i.e. a caplet should kill on average 1 out of 800 patients! Clearly, the LNT logic is completely inapplicable here, which is typical for biology. In more professional terms, an enormous amount of research has been underway on genetics and on the effects of radiation on DNA throughout the XX century. A very important review of this subject, as pointed by Jerry Cuttler [1], was published in 1990 by Daniel Billen in the Radiation Research Journal [10].

The above review points out that "DNA is not as structurally stable as once thought. On the contrary, there appears to be a natural background of chemical and physical lesions introduced into cellular DNA by thermal as well as oxidative insult. In addition, in the course of evolution, many cells have evolved biochemical mechanisms for repair or bypass of these lesions."

Billen points that spontaneous DNA damage occurs at a rate of about 10,000 natural events per cell per hour. Let us compare this with the damage caused by ionizing radiation. The number of DNA damaged sites per cell per roentgen (R) is estimated to be below 100 [10]. A radiation level of 0.2 R (or 2 mSv) per day (ICRP 1931 recommendation) would cause on average less than 20 events per cell per day, or below 1 event/cell per hour. This is 10,000 times lower (!) than the natural rate of DNA damage that occurs in every person. The above numbers have been known for more than 20 years, verified by numerous investigations and considered to be a solid scientific evidence.

Moreover, one can even suggest that low doses of X-rays and nuclear radiation are beneficial to human health ("hormesis" hypothesis) – just as the ultraviolet radiation (also a form of ionizing radiation) is clearly beneficial in low doses (sun tanning) while high doses are certainly harmful (sunburns and skin cancer). In that context it is worth mentioning that the healing properties of radon spas have been utilized for centuries before people heard the word "radiation", and that radon treatment is definitely not considered to be an "alternative therapy" by the mainstream medicine in Europe (as opposed to the US) [11]. Another fact worth mentioning is that in most of the nuclear industry workers studies, the rate of cancer mortality (as well as overall mortality) among the radiation workers is substantially lower than in the reference population [12]. These little-spoken facts and many others [11,13] comprise emerging (though not yet conclusive) scientific support for the hormesis hypothesis. The very idea of radiation hormesis and the term itself appeared back in 1920-s, but since 1950-s were missing in the scientific literature for decades till re-appearance in 1982. Since then, the scientific interest to hormesis steadily grows, as shown in Fig. 1.

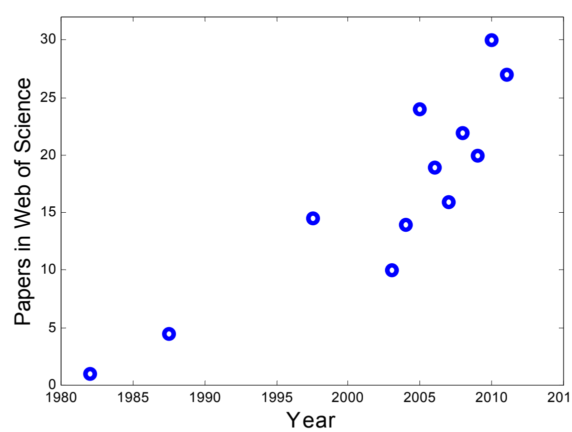

Figure 1: Growing number of scientific papers dealing with *radiation hormesis* (beneficial effects of low-dose ionizing radiation). The term "hormesis" appeared in 1920-s, but since 1950-s was missing in the scientific literature for decades till re-appearance in 1982. Source: Science Citation Index Expanded [14].

While this scientific debate has not yet given fruit in terms of changes in radiation regulation policy, we may expect this to happen in the near to middle term. For example, after the Fukushima accident it was publicly announced – probably for the first time after 1950-s – that no positive scientific evidence (besides extrapolation from high acute dose) supports carcinogenic or other harmful effect of radiation dose below 10 R (100 mSv). While the above understanding did not prevent the Japanese authorities from performing large-scale (and in our opinion unjustified) evacuation [1], it was still

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essential in *ad hoc* setting higher radiation limits for the radiation workers, which led to ultimate solving of the damaged reactors' issues.

Instead of the ALARA (as low as reasonably achievable) demand, "as high as reasonably safe" AHARS approach was suggested [15]. Reasonably safe tolerance level is anticipated to be very high according to the present standards, probably orders of magnitude higher than the present limits, as discussed in the first part of this paper.

APPLICATIONS

Below we discuss how different applications of LINACs may benefit from the more realistic attitude to radiation hazards.

Food industry

Electron LINACs may be used for food sterilization, leading to the reduction in supply-chain losses and to extended shelf life. Since the irradiated food does not become radioactive, the main obstacle to the spread of this technology seems to be related to the public perception of radiation hazards. With more realistic attitude to radiation hazards, the market for LINAC-irradiated food is anticipated to considerably grow.

Manufacturing of plastics

Irradiation leads to intensification of important chemical processes, such as polymerization or curing in composites. In high-volume production, the radiation doses for the workers are relatively high. Since the plastics industry is generally regarded as low-tech with relatively cheap labour, upgrading the employees officially to a status of "radiation workers" does not seem to be a viable option in the present situation. However, the situation will change dramatically with easing of the radiation regulations and changing of the public perception of radiation hazards.

Other applications

All LINAC applications, especially compact Free-Electron Lasers still to be designed, will benefit from easing the radiation regulation and elimination of radiophobia. However, other applications seem to be less affected. For example, in medical applications (radiotherapy and end-point sterilization of equipment) there seems to be virtually no radiophobia whatsoever. It is as if these were different types of X-rays, electrons and isotopes being used for the different applications – harmless in medicine, yet extremely dangerous in all other fields of human endeavour. This topic by itself is worth of serious research, however more in relation to psychology and sociology than to physics.

CONCLUSIONS

During the last two decades the attitude to ionizing radiation hazards seems to become more balanced, as opposed to "radiophobia" of the Cold-War era. We may expect in the near or the middle term future a decline of radiophobia and easing of the radiation regulations. The ALARA (as low as reasonably achievable) demand is anticipated to be substituted by some tolerance level, which in turn is anticipated to be very high according to the present standards. The main anticipated opportunities for LINAC applications belong in our opinion to the food industry and plastic production technologies.

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