Int. J. of Nuclear Governance, Economy and Ecology
2013 Vol.4, No.1, pp.59 – 75

DOI: 10.1504/IJNGEE.2013.053813

Low-dose ionizing radiation: scientific controversy, moral-ethical aspects and public choice.

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This paper is a revised and expanded version of a paper entitled "*Low doses of radiation: scientific controversy and public choice for nuclear hazards*" presented at *James H. (Jimmy) Belfer Memorial Symposium "Risk Assessment of Nuclear Accidents", Technion – Israel Institute of Technology*, *Oct 29, 2012, Haifa, Israel.*

ABSTRACT

The ethical issues of radiation protection are dealt on systematic basis. It is shown that the Linear No-Threshold model of low-dose ionizing radiation damage, being widely accepted, is still ill-founded. The paper describes scientific evidence for rather high practical threshold of adverse health effects; moreover, low levels of nuclear radiation may be even beneficial for human health.

In everyday routine, the present regulation imposes excessive cost on the society, effectively leading to loss, rather than to saving, of life. In nuclear emergency, compulsory relocation (Chernobyl, Fukushima) led to social destruction known to cause statistically significant life shortening. The present radiation regulation and the guidelines for forced evacuation should be both subjected to new scrutiny with due cost-benefit and ethical analysis.

The decision-making state officials are subjected to economical incentives, as well as to human biases and political pressures. As such, they are objectively interested in being "on the safe side" regarding the nuclear hazards, regardless of the high cost (including the human cost). While these interests cannot be eliminated in the framework of democratic society, they should be properly acknowledged and mitigated. It is also very important for the society to develop incentives for politicians and decision-makers to be properly informed themselves and to inform the general public.

Key words: LNT, threshold, hormesis, moral, human cost

INTRODUCTION

Adverse effects of high doses of ionizing radiation were discovered nearly immediately after the discovery of X-rays and radioactivity back in the 19-th century. In 1931, based on three-decades' experience, safe dose rates were recommended, and these recommendations were in effect till after the WWII. Later, it became assumed that there is no safe dose of radiation and the Linear No-Threshold (LNT) model was accepted, though the above assumption neither had a solid experimental base nor was a subject of scientific consensus.

The moral-ethical issues of the low-dose radiation protection have been already addressed in the literature (Taylor 1980; Jaworowski 1999, 2010; Calabrese 2009; Cuttler 2012). However, this article is in our opinion the first attempt of systematic approach to the problem. It combines historical review, discussion of the scientific controversy, quantitative analysis of the human costs of the present-day policy (including the recent Fukushima events), and analysis of the decision-making process on radiation-protection issues.

The article is organized as follows. First, we review the history of radiation protection policy. The relevance of this history to the moral-ethical and public-choice analysis is supported, in our opinion, by the unavoidable conclusion that the reasons for adoption of the present radiation-risk models and radiation-protection policies were not always scientific, and often dictated by interests of nuclear deterrence etc.

Then, the scientific controversy over the LNT model is discussed. Re-analysis is made for two case studies: Chernobyl accident (Chernobyl Forum 2005) and early British radiologists (Smith and Doll 1981). We will show that even largest-scale disaster like Chernobyl does not provide statistically significant data to verify LNT, while the results on early radiologists probably contradict LNT – if only economically-reasonable estimation of the involved doses is done.

In the third section, the moral and ethical issues are discussed. The radiophobia (irrational fear of radiation) and radiophobia-inspired present-day radiation regulations are analyzed quantitatively, and shown to cause loss of life rather than preserving life, even if assuming that LNT is valid.

In the fourth section, we analyze radiation-protection decision-making from the economical point of view. Human bias and political pressures on the regulators were described before, however these can in principle lead to bias on both sides (i.e., either too stringent or too permissive). We show that there are, in addition, significant economical incentives for state officials to have approach, definitely biased to "the safe side," i.e. towards too stringent regulation. Finally, the conclusions are formulated.

1. RADIOPHOBIA EMERGES

Adverse effects of high doses of ionizing radiation were discovered nearly immediately after the discovery of X-rays and radioactivity back in the 19-th 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, Mutscheller recommended permissible dose rate for radiation workers of 0.2 roentgen (R) per day. The relation between different radiation units is given in Table 1. In this article, we prefer to use were applicable the historical units of roentgen (R), rad and rem, though modern SI units of Gray (Gy) and Sievert (Sv) are recommended by several bodies. The reason is threefold: 1) For public perception, "Roentgen" has positive connotation with health care, while "Gray" and "Sievert" sound strange and therefore frightening. 2) Units of Gy and Sv represent high values: 1 Gy ≈100 R. E.g., certainly lethal acute dose (without medical treatment) is 600 R – and correspondingly 6 Gy which seems psychologically undesirable: small number (six) as a lethal dose is more frightening. 3) The US emergency agencies (including FEMA) continue to use the units of roentgen and rem (probably by the reasons mentioned above).

1.	X-rays, gamma-rays	1 R = 1 rad = 1 rem = 0.01 Gy = 0.01 Sv
2.	Alpha-particles	1 R = 1 rad = 20 rem = 0.01 Gy = 0.2 Sv

Table 1. Radiation units and their approximate relations.

The above rate of 0.2 R/day was 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 (Inkret et al. 1995). ICRP – the International Commission on Radiological Protection, established in 1928 – accepted in 1931 this 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, which is 35 times higher than the present-day occupational (professional) exposure limit and 700 times higher than the present-day public one. Based on about 30 years of human experience, it was assumed that this dose rate could be tolerated indefinitely, i.e. no harm will be caused by radiation below this tolerance level (Calabrese 2009).

It should be stressed that nobody succeeded to disprove the assumption of tolerance level (Taylor 1980; Jaworowski 1999; Tubiana and Aurengo 2006; Feinendegen et al. 2013), while it is clear that high radiation level is harmful: acute dose of 100 R leads to radiation sickness and 200 R may already be lethal (Glasstone and Dolan 1977). For example, the studies of radium dial-painters, exposed to huge cumulative doses (mostly at low rates), revealed that no bone cancer was observed below the life-time dose of about 1000 rad (BEIR 1988). For α-particles, emitted by radium, the radiation weighting factor w_R=20, i.e. 1000 rad = 10 Gray and correspond to 20,000 rem = 200,000 mSv – about 200 times the present-day life-time occupational limit.

However, in 1927 radiation-induced mutations were discovered (Muller 1927) and many geneticists became convinced that the number of genetic mutations is linearly proportional to the radiation dose, just like the number of ionized atoms. They believed that no mechanism for gene repair existed and therefore, that mutagenic damage was cumulative. According to this point of view, no tolerant (safe) dose for radiation could ever be set, and the safety level should only be weighed against the cost to achieve it (Calabrese 2009).

After the atomic bombing of Japan and the start of the nuclear arms race, many scientists became concerned about the very survival of the civilization. Actually, before the first atomic bomb was dropped and even tested, official report suggested that "*civilization would have the means to commit suicide at will*" (Smyth 1945). Particularly, geneticists were concerned that exposure to radiation of atomic bomb fall-out would likely have devastating consequences on the gene pool of the human population. Probably not accidentally, 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 mutations was linear and that there was "*no escape from the conclusion that there is no threshold dose*" (Muller 1946). This statement may be questioned from the ethical point of view: it has been shown that Muller was already aware of evidence against the point when he delivered his lecture (Calabrese 2012).

There was great controversy and extensive arguments during the following decade. In general, it can be said that among scientists "*the data to support the linearity at low dose perspective was generally viewed as lacking but the fear that it may be true was a motivating factor*" (Calabrese 2009).

Probably, both super-powers became interested in exaggerating the radiation effects in order to promote their nuclear deterrence (Jaworowski 1999). It seems that at the onset of the nuclear age, the Western powers were interested in exaggerating the effects of nuclear weapons in order to deter the USSR from its expansionist plans (Sams 1979). The UK Home Office (1950) top secret report stated:

"The wide publicity given to the appalling destruction caused by the atomic bombs at Hiroshima and Nagasaki has possibly tended to give an exaggerated impression of their effectiveness."

After the Soviet nuclear weapons turned to be a credible threat, it was the turn of the USSR to be interested in exaggerating the nuclear effects. As described by Pipes (2003), the USSR was interested to jeopardize the Western nuclear deterrence by creating atmosphere that in nuclear war there would be no winners. Western anti-nuclear movements objectively served this aim and were indirectly supported by the Soviets (Staar 1991). By the way, the Soviets themselves did not consider a nuclear war as "assured destruction" and had even prepared plans to win a nuclear war if such would take place (Pipes 2003).

Ultimately, all kinds of ionizing radiation became connected in public perception with nuclear apocalypse – though before the nuclear age, the extent of public confidence in the usefulness and safety of ionizing radiation can be illustrated by the fact that until after the Second World War, X-ray machines were typical equipment of shoe shops, as mentioned in passing in the book of Peierls (1956). 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 (Preston et al. 2003) was taken as the basis for extrapolation to low doses of radiation. The ICRP tightened its recommendations for occupational and public exposures to 50 and 5 mSv/year in 1958 (ICRP 1958) and further to 20 and 1 mSv/year in 1990 (ICRP 1990). National regulators usually followed this trend. Probably even more important, these stringent norms were (and, unfortunately, are still being to a large extent) considered unsafe by the general public.

2. SCIENTIFIC CONTROVERSY OVER LNT

2.1 Arguments pro and contra

The Linear No-Threshold (LNT) model is presently a commonplace for the risk assessment by official and other public bodies, and as such it is the basis for nuclear and radiation regulation. LNT is also widely accepted by the general public. However, the scientific grounds of this model have never been a subject of consensus. The absence of scientific consensus has been always officially acknowledged, including by the US Congress Office of Technology Assessment (OTA 1979). The US National Council on Radiation Protection and Measurements put it pretty clear (NCRP 1995):

"*…essentially no human data can be said to prove or even to provide direct support for the concept of collective dose with its implicit uncertainties of nonthreshold, linearity and dose-rate independence with respect to risk. The best that can be said is that most studies do not provide quantitative data that, with statistical significance, contradict the concept of collective dose.*

Ultimately, confidence in the linear no threshold dose-response relationship at low doses is based on our understanding of the basic mechanisms involved…"

However, speaking about the mechanisms involved, the concept of cumulative no-threshold damage to living organism by any possible factor "*is contradicted by everything we know of human physiology and therapy*" (Pollycove 1997). E.g., for paracetamol – a widely used non-prescription FDA-approved medicine (pain reliever and fever reducer) – the lethal dose LD_{50} (at which 50% will die) 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.

More particularly, LNT is implicitly based on two assumptions: that the probability of mutation (per unit dose) is constant whatever the dose or dose rate, and that the carcinogenic process evolves similarly. A vast amount of research was carried on genetics and on the effects of radiation on DNA throughout the 20-th century. As a result, towards the end of the Cold War the second assumption (and the LNT model itself) becomes more and more challenged. As stated by the joint report of the French Academies (Tubiana and Aurengo 2006),

"*... progress in radiobiology has shown that a cell is not passively affected by the accumulation of lesions induced by ionizing radiation. It reacts through at least three mechanisms: a) by fighting against reactive oxygen species generated by ionizing radiation and by any oxidative stress, b) by eliminating injured cells (mutated or unstable), ... c) by stimulating or activating DNA repair systems...*"

Quantitatively, the spontaneous DNA damage occurs at a rate of about 10,000 natural events (lesions) per cell per hour (Billen 1990). Let us compare this with the damage caused by ionizing radiation. It is estimated to be below 100 DNA damaged sites per cell per roentgen (Billen 1990). 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.

Later, it has been asserted that the DNA damage caused by radiation is qualitatively different from that caused by oxygen metabolism, so the two are not comparable (Ward 1994; Sutherland et al. 2002). While the quantitative analysis made above may be not applicable therefore, carcinogenic process is still counteracted by effective defense mechanisms in the cell, tissue and the organism (Tubiana and Aurengo 2006).

Solid evidence for existence of radiation-damage-repair mechanisms in humans is provided by the following fact: radiation-induced mutations (as well as any other clinical or sub-clinical effects) have "*not yet*" been observed in the offspring of the cohort (numbering about 100,000) of Hiroshima and Nagasaki survivors, unlike carcinogenic and other effects in the survivors themselves (RERF 2008). The same is correct regarding the offspring of the population of Techa region in the USSR ('Mayak', 'Kyshtym') who received high doses in 1950s-1960s (Burmistrov et al. 2000). It can be concluded that the theory of cumulative no-threshold genetic damage is no longer convincing.

Moreover, one can even suggest that low doses of X-rays and nuclear radiation as applied in medicine, are beneficial to human health ("hormesis" hypothesis) – similar to the ultraviolet radiation (part of the UV spectrum is also ionizing). UV is beneficial in low doses being essential in the production of vitamin D (underexposure leads to skeletal disease) while high doses are harmful, leading to sunburns, skin cancers and eye disease (WHO 2012). It is interesting that vitamin D itself may offer protection against a variety of radiation- and otherwise-induced damages (Hayes 2008). Speaking about evidence for ionizing-radiation hormesis, we would mention 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 (Erickson 2007). Additional fact worth mentioning is that in most of the nuclear industry workers studies done, the rate of cancer mortality (as well as overall mortality) among the radiation workers is substantially lower than in the reference population (BEIR 2006, p. 194). This effect is usually explained by the well-known "healthy worker effect" (HWE) – worker populations tend to healthier than the general population because workers must be healthy to be hired and to continue their employment. However, HWE for radiation workers is usually stated without quantitative analysis, as by BEIR (2006). When quantitative analysis was applied, HWE was often found not to be consistent with the data (UNSCEAR 1994; Fornalski and Dobrzynski 2009). The above facts and many others (Hosoi and Sakamoto 1993; Hattori 2005; Tubiana and Aurengo 2006; Cuttler and Pollycove 2009; Feinendegen et al. 2013) 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, until its re-appearance in 1982. Since then, there is steadily increasing amount of scientific research related to hormesis. According to the Science Citation Index (SCI 2012), radiation hormesis study comprises more or less constant fraction (though still of about 5%) of efforts in the field of radiation effects, as shown in Fig. 1.

To summarize this section we mention that in 2005-2008, four scientific bodies published their reviews of the current status of the knowledge regarding the low-dose radiation effects. While three of them (BEIR 2006; ICRP 2007; UNSCEAR 2008) consider that there is not yet enough evidence to dismiss the LNT model, the French Academies (Tubiana and Aurengo 2006) conclude that the use of LNT is no longer justified. Moreover, the hormesis theory is represented in a recent mainstream book on therapeutic nuclear medicine (Feinendegen et al. 2013). In the authors' opinion, the general attitude to the LNT model is beginning to change.

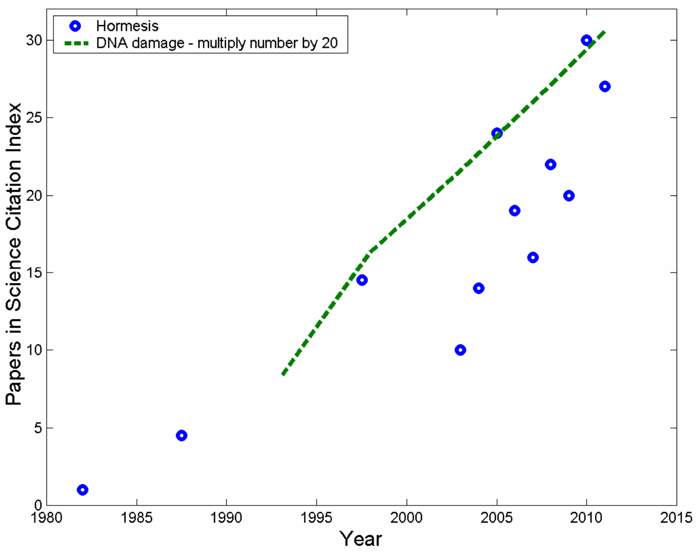

Fig. 1: Number of scientific papers dealing with *radiation hormesis* – beneficial effects of low-dose ionizing radiation. The term "hormesis" appeared in 1920-s, but since 1950-s was missing in the scientific literature for decades till re-appearance in 1982. Reference data is number of papers with keywords: *DNA damage ionizing radiation*. Pay attention that the reference values should be multiplied by 20, i.e. the fraction of hormesis papers is still of about 5%. Source: Science Citation Index Expanded (SCI 2012).

2.2 *LNT case study I: Chernobyl*

The Chernobyl nuclear accident occurred on April 26, 1986. Two employees were killed outright, and 28 more died within several weeks after receiving lethal doses of radiation. The scale of the accident was unprecedented – and probably about the largest theoretically possible. Jaworowski (2010) formulated:

"*Chernobyl was the worst possible catastrophe. It happened in a dangerously constructed nuclear power reactor with a total meltdown of the core and 10 days of free emission of radionuclides into the atmosphere. Probably nothing worse could happen.*"

Indeed, the 2011 Fukushima accident, caused by an unprecedented natural disaster, with the total meltdown of three reactors, was undoubtedly of much lower scale (IRSN 2012). We shall now consider whether such large-scale "experiment" as Chernobyl can supply evidence for LNT. For additional aspects of the Chernobyl disaster the reader is referred to (Socol 2012).

Approximately 200,000 “liquidators,” also referred to as “cleanup workers,” worked in the 30 km zone in 1986–1987 (BEIR 2006, Table 8-9, p. 202). Their average dose is estimated to be 100 mSv. According to the LNT model, taking into account that the liquidators were mainly males around their thirties, 100 mSv should cause about a 0.6% life-time cancer incidence (BEIR 2006, Table 12-6, p. 281) on top of the natural 42% (BEIR 2006, Fig. PS-4, p. 7). Namely, 1200 cancers should be diagnosed on top of 84,000 ± 300 (1σ) natural cancers. Such an excess, if not masked by systematic errors, could be statistically significant. Actually, the systematic errors are indeed high (Jemal et al. 2011). Just within the developed countries, the cancer mortality varies by ±5% (e.g. 1.05 per 1000 in North America but 1.15 per 1000 in northern Europe). The same uncertainty may be with reasonable justification applied to the cancer rate of the affected regions with their highly volatile socio-economical situation, yielding systematic error of ±4,000 and therefore making observation of 1,200 excess cancers among liquidators a formidable task.

Similar conclusions are probably valid for the population of the "strict control zone" – 270,000 people, who received an average dose below 60 mSv (BEIR 2006, Table 12-6).

Finally, about 3,700,000 people lived in the territories that were officially declared as "contaminated." The average dose for this population was below 15 mSv (BEIR 2006, Table 12-6), yielding according to the LNT model 0.1% cancer excess. Though the corresponding number of about 4,000 excess cancers was cited (Chernobyl Forum 2005), such excess cannot be observed in principle, given the uncertainties of the natural cancer incidence rate of ±5%.

We are urged to conclude therefore, that even the largest-scale nuclear disaster cannot provide positive evidence for LNT. The Chernobyl accident "as is" with 30 dead is just a large-scale industrial accident, comparable e.g. to the Tolouse fertilizer plant explosion in 2001 (Dechy et al. 2004). However, if LNT-estimated (but unobservable) 4,000 death toll is implied (Chernobyl Forum 2005) – Chernobyl becomes one of the worst industrial disasters. We must mention here, that Chernobyl actually became a real disaster with millions of victims and probably thousands of early deaths – though not because of its fallout, but because of out-of-proportion reaction to the radiation hazard (Chernobyl Forum 2005; WHO 2006). This issue will be dealt in Sec. 3 below.

2.3 LNT case study II: early British radiologists

As mentioned in Sec. 1, during the first decades of radiation use in medicine and elsewhere, people (especially radiologists) were exposed to huge – according to the present norms – doses of radiation. It is logical to exploit this fact to analyze the LNT model.

A study of British radiological society members (Smith and Doll 1981) reveals that while the pre-1921 radiologists (who had not controlled their exposure and therefore received very 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. For pre-1921 radiologists, all neoplasms lead to 62 deaths, with the expected amount being 35.39 (based on rate for medical practitioners). For post-1920 radiologists, there are 72 all-neoplasms' deaths, with the expected amount being 68.64. By the way, the total number of deaths for both cases was lower than for general medical practitioners: 319 vs. 327.97 (97%) for pre-1921, and 411 vs. 469.67 (87%) for post-1920.

The authors of (Smith and Doll 1981) estimated that post-1920 radiologists could be exposed to 100-500R of radiation. In our opinion, the upper estimation is likely. We will use economical reasoning to support this estimation.

Namely, as mentioned above the safe dose was suggested in 1920-s to be 0.2 R/day, roughly 50 R/year assuming 250 working days per year. As mentioned, this dose already contained a safety factor of 100. Economically, it seems highly improbable that the professionals added on average additional safety factor of 10 over the recommended value: such additional protection would have been on their own account – more massive and expensive screens, more sensitive and expensive films etc.

Let us compare the above results to the LNT predictions. For adults (ages 18-65), 4% cancer mortality per each 100R is assumed (BEIR 2006, Table 12-6, p. 281), while typical error bars (2σ) are about (–50% / +100%). If we assume that the actual dose was only 10% of the recommended safe level (that is, 5 R/year), with 20 years of practice this yields 100 R. This would yield 4% of 411, or roughly additional 16 cancer deaths over 69 expected (2σ, σ≈√69), while 3-4 were actually observed. Taking much more plausible assumption of actual exposure of 50% of the recommended safe level, we have 500 R in 20 years, and therefore 20% additional cancer deaths. 20% of 411 total deaths is 82, which is definitely significant (10σ), but was not observed.

However, the results for pre-1921 radiologists may be even more convincing. The very idea of radiation safety came out on the wake of rather frequent accidents, caused by acute effects. Acute radiation effects are caused by short-time (days) doses of at least 100 R (Glasstone and Dolan 1977). Therefore, it is more than reasonable to estimate, that actual pre-1921 doses were at least 200 R/year (and easily – by an order of magnitude higher). Taking average 10 years of practice, this yields 2000 R, or 80% cancer deaths – nearly ten-fold the actual number 27/319 ≈ 9%.

We see therefore that the data for early radiologists provide evidence against the LNT.

3. MORAL AND ETHICAL ASPECTS: HUMAN COST OF OUT-OF-PROPORTION RADIATION PROTECTION

From the economical point of view, realization of the present policy advice is very costly – both for the state budget and for the general public. For example, according to the researchers from the Harvard School of Public Health, spending $100,000,000 per year on controlling radiation emissions might save 1 life-year per year (Graham 1995). As mentioned by Jaworowski (1999), such a cost is not only absurd but also immoral, since it causes the effective loss of life, as median medical program costs $19,000 per life-year saved (Graham 1995). It can be said that instead of one person hypothetically saved assuming LNT is valid (and zero, if LNT is false) – 5,000 real patients can be saved. Proponents of stringent nuclear regulations can argue that the above consideration is not valid since the saved money will not necessarily be spent on life-saving programs, and even if it is – the cost of saving life will be considerably higher, than the median one. However, the effective loss of life due radiophobia – irrational fear of low-dose radiation – is not just under-funding of public life-saving programs. As a rule, wealthier people have healthier lifestyle (gyms etc.), consume healthier food, take less risky jobs, use safer products (e.g., cars) and more. The net effect is that extraneous public expenditure on safety (here – radiation safety) leads to statistical life shortening. The US Office of Management and Budget cited evidence in the literature pointing to a loss of one statistical life (life, *not* life-year) for every expenditure of $7,250,000 (Lutter and Morrall 1992). Viscusi (1994) put the life-loss expenditure much higher, at $30-70 million, but even the highest limit is by more than order of magnitude lower, than actual spending on nuclear risk reduction: multiplying $100 million per life-year by 11 years of average life shortening per cancer death – see (BEIR 2006, Tab. 12-4, p. 278) – yields $1,100 million per life saved. One can say that per each statistical life saved by nuclear regulations (if LNT is valid), there are 15 – 150 "statistical murders" (the term used by Graham (1995)).

The human cost of radiophobia goes beyond the life-shortening effect of extraneous public spending. Another important point was stressed by the American Association of Physicists in Medicine (AAPM 2011):

"*Predictions of hypothetical cancer incidence and deaths in patient populations exposed to such low doses are highly speculative and should be discouraged. These predictions are harmful because they lead to sensationalistic articles in the public media that cause some patients and parents to refuse medical imaging procedures, placing them at substantial risk by not receiving the clinical benefits of the prescribed procedures.*"

Finally, it should be mentioned that radiophobia provides strong incentives for radiological terrorism and nuclear proliferation (Socol et al. 2012). As an illustration let us remind the Goiânia accident in Brazil (1987). This accident was not a terror attack but it demonstrated how effective may be radiological terror – to literally terrorize large populations. In the accident, a radioactive source was stolen from a local hospital; as a result of the exposure, 4 died and 16 more required treatment. However, some 112,000 overwhelmed hospitals (IAEA 1988), i.e. above 5,000 victims per each actual casualty.

Let us consider now the policy of forced evacuation in case of nuclear or radiological accident. It should be born in mind that the evacuation itself bears high human price in addition to the monetary one. For example, after Fukushima more than 50 patients of evacuated hospitals died during or just after the evacuation (Tanigawa et al. 2012) due to logistical flaws unavoidable in such situations. By the way we should mention here, that the perception of the Tōhoku devastating earthquake and tsunami disaster which claimed above 20,000 lives (Kubo 2012), as predominantly Fukushima nuclear accident that did not cause any loss of life whatsoever regarding the direct radiation consequences, does not look ethically-grounded.

Next, large-scale compulsory relocations (like Chernobyl and Fukushima) cause businesses destruction, job losses, disruption of family routine etc. These in turn lead to increased number of depressions, excessive alcohol consumption and even suicides in the displaced populations. Displaced populations are known to develop psychological and psycho-somatic problems. It is reasonable to suggest that the above factors shorten their lives in addition to causing direct (temporary?) suffering. For example, as pointed by Du et al. (2010), social disruption and economical hardships, caused by unexpected compulsory evacuation, lead to decreased basic hygiene. The World Health Organization concluded after Chernobyl (WHO 2006):

"*… evacuation and relocation proved a deeply traumatic experience to many people because of the disruption to social networks and having no possibility to return to their homes. For many there was a social stigma associated with being an 'exposed' person.*"

Self-esteem crash and psychological consequences were studied in the work published in *The Lancet* (Stuckler et al. 2009). The study stresses grave consequences of social disruption and failure to support self-respect, caused by long-term occupation loss. These consequences include statistically significant life shortening. By the way, "green" activists tend to accent evacuation harms in the context of supporting their claim to ban atomic energy (Greenpeace 2012).

This certain human cost of evacuations should be compared with the hypothetic LNT-predicted health benefit of evacuation. The authors are not aware of any such comparison in the scientific literature. The recent evacuation after the Fukushima accident will be considered now.

It was estimated that the Fukushima evacuees would have been exposed to up to 100 mSv during the first year (IRSN 2012), assuming 12 hours spent outdoors on daily basis (which is an overestimation by itself). According to the LNT, 100 mSv cause in mixed-aged population 0.5% cancer deaths (BEIR 2006, Table 12-6, p. 281). Assuming LNT is valid, additional 0.5% cancer deaths were expected in the most contaminated areas if nobody was evacuated. Average longevity loss per cancer death is 11 years (BEIR 2006, Tab. 12-4, p. 278), so the corresponding life expectancy shortening is 5.5×10^{-2} year, that is about 3 weeks. Taking into account that in most areas the radiation level was less than 1/3 of the maximum (IRSN 2012), and also that people usually spend much less than 12 hours outdoors, the corresponding life expectancy shortening should be taken as less than 1 week. It is hardly arguable that the human cost of the forced evacuation was higher, even if we suggest that the immediate loss of above 50 lives of sick and elderly people (described above) could have been avoided.

Speaking about decision-making on evacuation in case of nuclear accidents, we should also mention the simple fact that in every country the life expectancy varies a lot for different locations due to socio-economical, environmental and other reasons. This difference is typically of several years, and in the extreme case of Calton in the UK – 25 years below the country average (Reid 2011) due to poor socio-economical conditions, crime and suicides. However, forced evacuation of shorter-life-expectancy locations is nowhere considered as a viable option.

Lauriston Taylor, the late president of the U.S. National Council on Radiological Protection and Measurements, deemed LNT-based estimates to be a "*deeply immoral uses of our scientific heritage*" (Taylor 1980). As we saw above, he had good reasons for that statement.

4. DECISION MAKING BIASES

As we saw above, the present policy of radiation protection is inefficient and at best questionable from the ethical point of view. In this section we will discuss the decision making on nuclear hazards. It was already mentioned in the literature, that the decision-makers are both human and political: they are subject to hazard perception biases and to political pressures. The researchers from the Harvard Law School pointed, that such biases and pressures lead regulators to solutions, inefficient from the public welfare point of view (Viscusi and Hamilton 1999). We analyze here an additional aspect, namely that regulators are not only human and political, but also "economical": they respond to incentives and act in their own interests. Such analysis has significant implications regarding the efficiency of regulator decisions. As it will be shown below, economical incentives lead the state officials to be biased towards too stringent regulation.

Following Niskanen (1971), we describe here an "ideal" state official, free of any kind of corruption and sincerely interested in public welfare – according to his understanding. However he is also a human being. As such, he is probably interested in career opportunities, stability of occupation, public recognition and prestige of his occupation (services). Due to both altruistic reasons (public welfare) and personal ones (career opportunities etc.), he must be interested in maximizing the resources redistributed under his control and in bigger amount and complexity of regulations.

The trend to be "on the safe side" regarding nuclear hazards objectively serves the above aims. In reality, since the probability of a nuclear disaster seems pretty low, general public is reluctant to seek for in-depth considerations. People are rationally ignorant, so they are ready to rely on the "expert opinion" provided for free (by state-run or state-dependent media), if the issue does not seem to them important enough (Downs 1957).

Radiophobia-driven policy also excellently fits the known trend of coercive salvation and expansion of the functions of the state (Buchanan 1975). Such policy calls for centralized state-run protection instead of decentralized (commercial, non-government voluntary, families & individuals), while the latter proved their efficiency. Claiming all the radiation-related problems to be exclusively in the governmental domain, in our opinion, serves the interests of state officials to extend their power and budget.

In the framework of democratic society, these interests cannot be eliminated (Stigler 1971; Olson 1982). However, they should be properly acknowledged and mitigated by proper transparency and independent scientific scrutiny.

Economical reasoning also helps to explain why the LNT model is firmly backed by the official bodies in spite of the scientific controversy. The LNT, no matter whether valid or not, optimally meets officials' demand for simple and defendable decision-making procedure. The model itself is extremely simple and rather famous, being taught as a scientific fact for half a century (though, as we showed in Sec. 1 above, it has never been such).

There is another serious problem. It has been shown that "*greater scrutiny from residents pushes regulators away from decisions likely to maximize social welfare*" (Viscusi and Hamilton 1999). The counter-productive effect of public scrutiny is probably connected to the mentioned above "rational ignorance" of the average citizen. Taking into account all the above, we are urged to stress the importance of education regarding nuclear and radiation hazards. The scientists and medical practitioners have, in our opinion, moral obligation to refute radiophobia, and also to stress that LNT is an overcautious hypothesis, bearing high price tag in both human and economical terms. It is also very important that the society develops incentives for the state officials to be properly informed themselves and to inform the general public.

CONCLUSIONS

While the Linear No-Threshold (LNT) model of radiation damages is presently widely accepted by public and regulatory bodies, it is still ill-founded. LNT emerged after the atomic bombings of Japan and is connected in public perception with the nuclear apocalypse. However, even according to its proponents this model is neither proven nor disproved. Accumulated (and still emerging) scientific evidence points that there is probably rather high practical threshold for adverse health effects of the radiation. Moreover, it is even probable that low levels of nuclear radiation are beneficial for human health.

Excessive radiation regulation imposes high cost on the society, which statistically causes loss of, rather than saving, life. Compulsory and coercive relocation in Chernobyl or Fukushima led to businesses destruction, job losses, disruption of family routine etc. Those in turn led to excessive alcohol consumption, mental health problems and even suicides in the displaced populations. This definite grave cost should be compared with hypothetic LNT-predicted health benefits of the evacuation. Therefore, both the present radiation regulation and the guidelines for forced evacuation should be subject to new scrutiny with due cost-benefit analyses.

The decision-making state officials are subjected to economical incentives, as well as to human biases and political pressures. As such, they are objectively interested in being "on the safe side" regarding the nuclear hazards, regardless of the high cost (including the human cost). While these interests cannot be eliminated in the framework of democratic society, they should be properly acknowledged and mitigated.

Keeping in mind the high cost that the radiophobia imposes on the society, education about nuclear issues becomes very important, and this is especially true for politicians and decision-makers. It is very important for the society to develop incentives for them to be properly informed themselves and to inform the general public. The official bodies should by no means promote radiophobia, but rather stress that LNT is an overcautious hypothesis, bearing high price tag in both human and economical terms.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Jerry Cuttler (Cuttler & Associates Inc.) for providing a significant part of the historical background and extremely valuable comments, Prof. Yigal Ronen (Ben-Gurion University) for careful reading the manuscript and constructive criticism which led to considerable improvement of the paper, and Prof. André Maïsseu for important comments and references.

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