

Radiation Hormesis Should be the Basis for Establishing Radiation Protection Standards

The linear no-threshold (LNT) model is presently the basis for radiation protection standards worldwide and has been endorsed by the National Academy of Sciences (NRC, 2006) as well as most other national and international advisory bodies. The two concepts underlying the LNT model – that even a small amount of radiation causes DNA damage and mutations, and increased mutations imply increased cancers (based on the somatic mutation model of cancer) – have both turned out to be invalid. Though exposure to low levels of radiation would indeed cause some DNA damage, it would also increase the defensive responses of the body such as antioxidants and DNA repair enzymes (Feinendegen et al., 2013). With the boosted defenses, there would be less endogenous DNA damage in the subsequent period, and the ultimate result would be reduced overall DNA damage and mutations (Koana and Tsujimura, 2010) (see Figure 1). In addition, the somatic mutation model of cancer – based on which the LNT model predicts increased cancers following low-dose radiation exposures – is not supported by evidence, and so is not a valid model (Doss, 2016). For example, it has been observed that cancer mortality rate (for the age range of 0-18) increases by a factor of ~80 when the immune system is suppressed in organ-transplant patients (Acuna et al., 2016) (see Figure 2). Can this huge increase in cancers be explained using the mutation model of cancer? No. Since the mutation model of cancer cannot explain such a large increase in cancers, the model cannot be considered to be valid. Hence, the

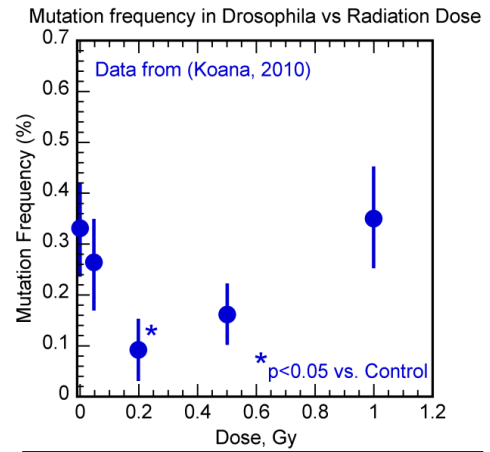


Figure 1. The effect of low-dose radiation on mutations in drosophila melanogaster. Data from Koana et al. (Koana and Tsujimura, 2010)

LNT model, which is based on the mutation model of cancer, cannot be considered to be valid either, and should be rejected. On the other hand, there is plenty of evidence supporting the immune suppression model of cancer (Doss, 2016). Low-dose radiation enhances immune system response (Yang et al., 2014) and so would be expected to reduce cancers, a phenomenon known as radiation hormesis. This has indeed been observed in many cohorts accidentally or incidentally exposed to low-dose radiation (Kostyuchenko and Krestinina, 1994, Berrington et al., 2001, Sponsler and Cameron, 2005, Hwang et al., 2006) (Doss, 2016) (see Figure 3).

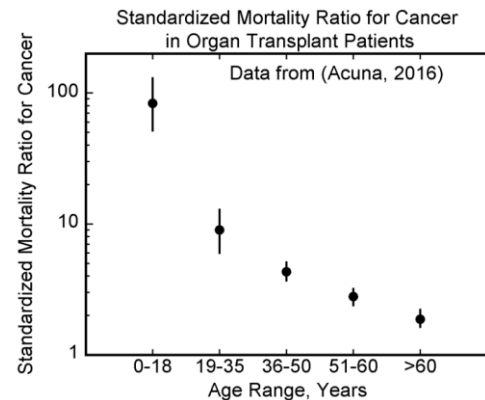


Figure 2. Standardized mortality ratio (SMR) for cancers as a function of age in organ transplant recipients. Data from Acuna et al. (Acuna et al., 2016)

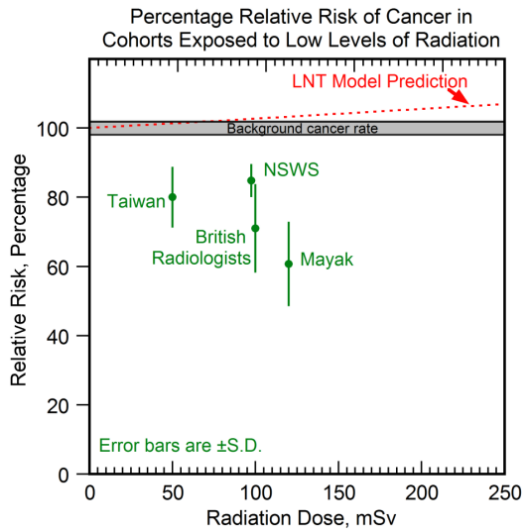


Figure 3. Percentage relative risk of cancer in population groups exposed to low-dose radiation versus radiation dose. Data labels: **Mayak** - evacuated residents of villages near Mayak Nuclear Weapons Facility, **British Radiologists** - British radiologists who entered service during the period 1955 to 1979, **Taiwan** - residents of radio-contaminated apartment buildings in Taiwan. **NSWS** - radiation workers in Nuclear Shipyard Worker Study. All the cohorts showed reduced risk of cancer compared to equivalent control populations not subjected to the radiation exposures. Data from (Kostyuchenko and Krestinina, 1994, Berrington et al., 2001, Sponsler and Cameron, 2005, Hwang et al., 2006). Data from (Doss, 2016)

The atomic bomb survivor data are widely recognized to be the most important data for establishing health effects of radiation. These data have traditionally been analyzed utilizing the LNT model to fit the data in order to extract the excess relative risk for cancer mortality (Ozasa et al., 2012). The resulting dose-response shape has a significant curvature because of lower than expected cancer rates in the 0.3-0.7 Gy region (see Figure 4), completely inconsistent with the LNT model that was used for fitting the data.

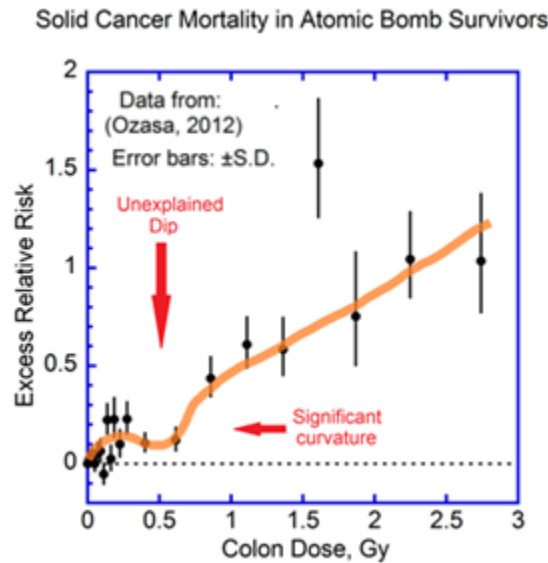


Figure 4. Excess relative risk (ERR) for all solid cancer mortality in atomic bomb survivors in relation to radiation exposure. Data from (Ozasa et al., 2012).

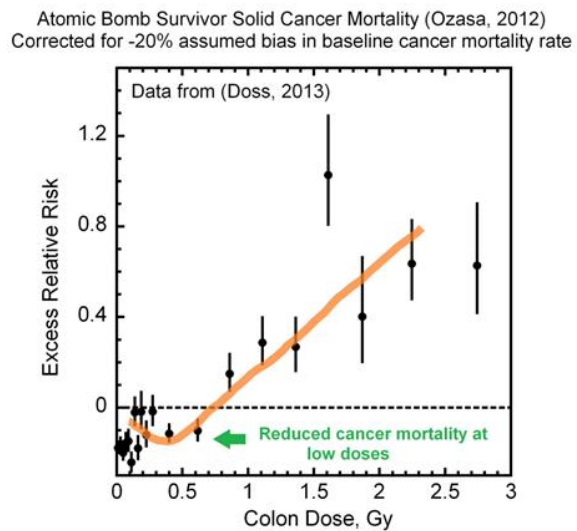


Figure 5. Excess relative risk (ERR) for all solid cancer mortality in atomic bomb survivors corrected for -20% bias in baseline cancer mortality rate plotted as a function of colon dose. Data from (Doss, 2013)

Thus, the LNT model does not provide a consistent explanation of the atomic bomb survivor data and so should be rejected. During the fitting process used by Ozasa et al. (Ozasa et al., 2012), the data from the lowest dose cohorts – extrapolated to zero dose – were used as the baseline cancer rates for estimating excess relative risks¹ (ERRs). Considering the reduction of cancer risk observed following low-dose radiation exposures (see Figure 3), the baseline cancer rates used would be lower than the background cancer rates by about 20%, skewing the calculated ERRs. Correcting the data for this negative bias results in a J-shaped dose-response curve that is consistent with radiation hormesis (Doss, 2012, Doss, 2013) (see Figure 5) (See Appendix A for derivation of the correction for the bias in the baseline cancer rate).

Repeated application of low-dose radiation to the whole body has been used to treat cancer and has resulted in patient survival equivalent to or better than chemotherapy (Chaffey et al., 1976, Pollycove, 2007). Repeated applications of low-dose radiation to whole body or half body of radiation therapy patients has resulted in improved survival, demonstrating the cancer therapeutic effect of low-dose radiation (Sakamoto, 2004) (Figure 6).

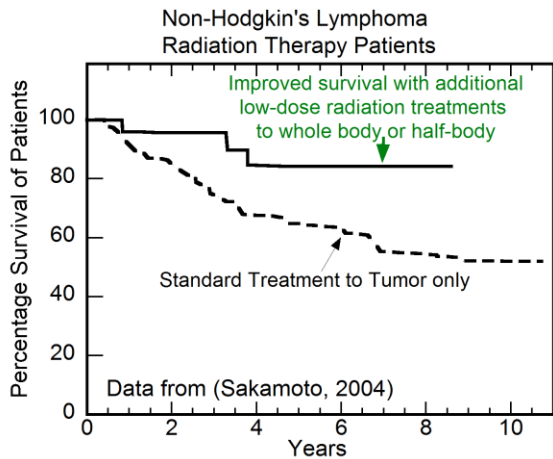


Figure 6. Survivals of patients with non-Hodgkin's lymphoma of stage I and II and with histologically intermediate and high-grade tumors, treated by the combined treatment or by local irradiation. Data from (Sakamoto, 2004)

Thus, there is indeed abundant evidence for radiation hormesis. Radiation hormesis was in fact proposed as a method of preventing cancers by Prof. Luckey in 1980 (Luckey, 1980). However it could not be studied in humans prospectively because of the acceptance of the unverified LNT model hypothesis, the resulting ALARA principle, and the ensuing carcinogenic concerns regarding low-dose radiation. This has likely resulted in over 15 million preventable cancer deaths worldwide during the past two decades, in view of the current annual global cancer death toll of 7.6 million, and assuming ~10% reduction in cancer mortality may have been achieved from the use of radiation hormesis (Doss, 2014). Considering the lack of progress in reducing cancer mortality rates in the past five decades (Murphy et al., 2015), this was indeed a major missed opportunity in the war on cancer for which the LNT

model is responsible. Also, radiophobia has caused tremendous economic harm and resulted in many unnecessary deaths due to the evacuations following the nuclear reactor accidents in Fukushima (Ichiseki, 2013). To avoid further such harms from the LNT-model-based radiophobia, and to bring the radiation safety regulations in line with science, new radiation safety regulations should be established based on radiation hormesis.

¹ Excess Relative Risk, $ERR = (R-B)/B$ where R and B are the cancer mortality rates of the irradiated and baseline cohorts respectively.

One argument commonly made by regulatory agencies and professional organizations for the continued use of the LNT model in spite of the vast evidence against it is the almost universal support for the LNT model by international and national advisory bodies. However, if one critically examines the work of these advisory bodies, it becomes clear that they have failed to exercise due diligence in the performance of their duties by accepting faulty publications that support the LNT model and not utilizing the considerable amount of available evidence against the LNT model. For example, the BEIR VII report by the National Academy of Sciences accepted the results from the 15-country study of radiation workers (Cardis et al., 2005) (See Figure 7). A review of the Cardis data shows that the Canadian data are inconsistent with most of the other countries' data, and exclusion of the Canadian data would result in negating the conclusion of the study of significant increased risk of cancer in the radiation workers. Instead of asking the authors to re-examine the Canadian data, the BEIR VII committee included discussion of the 15-country study in a special addendum to the report, justifying cancer risk from low-dose radiation (NRC, 2006). A few years after the publication of the BEIR VII report, the Canadian Nuclear Safety Commission withdrew the Canadian data because of major flaws identified in the data (CNSC, 2011), effectively negating the conclusion of the 15-country study (Zablotska et al., 2004). The BEIR VII report also completely missed the importance of the immune system in preventing cancers and the immune-boosting effect of low-dose radiation (Doss, 2016) by ignoring many publications available at the time of the report. It also ignored much data available at the time of the report that showed no increase in cancers or reduction of cancers with low radiation exposures, contradicting the LNT model (Frigerio et al., 1973, Chaffey et al., 1976, Choi et al., 1979, Rowland et al., 1983, Miller et al., 1989, Kostyuchenko and Krestinina, 1994, Howe and McLaughlin, 1996, Berrington et al., 2001, Sakamoto, 2004, Sponsler and Cameron, 2005). Other advisory bodies such as ICRP, UNSCEAR, IAEA, WHO, NCRP, etc. did not identify these flaws in the BEIR VII report and they continue to support the use of the LNT model. Thus, given the poor quality of the work by these advisory bodies, EPA should evaluate the evidence on its own and come to a conclusion regarding the carcinogenicity of low-dose radiation. In such an assessment, careful consideration of the research is necessary, as there are many publications that support the LNT model that have major flaws in their approach, data, analysis, interpretation, etc. The naïve acceptance and use of such flawed research by advisory bodies have enabled them to justify continuing support for the LNT model while maintaining the façade of following the scientific method. EPA should challenge the advisory bodies to justify the use of the LNT model in view of all of the evidence supporting radiation hormesis. If they are unable to refute the vast amount of evidence for radiation hormesis and show valid evidence for the LNT model, EPA should declare that it would no longer use the LNT model for radiation protection regulations.

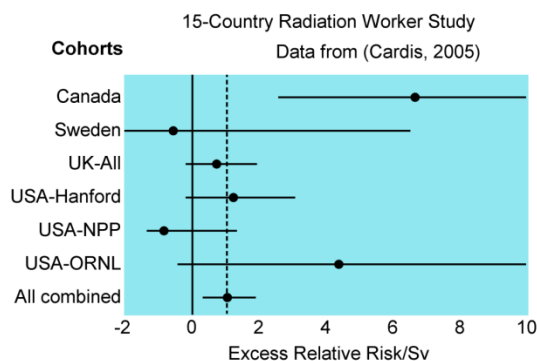


Figure 7. Excess relative risks per Sv for all cancer excluding leukemia in cohorts with more than 100 deaths. Data from (Cardis, 2005)

Radiation protection would become very much simplified with the use of radiation hormesis as the basis of the regulations. Since there is no harm from low radiation doses, there should be no

regulations for low radiation doses. For higher doses that are carcinogenic, there should be regulations to prevent such doses from occurring. A few examples of the approach to the regulations are discussed here.

For acute doses, atomic bomb survivor data indicate the cancer risk does not increase until a threshold dose of about 75 cGy (Figure 5). Certainly such a dose should be avoided for acute exposures. Using a safety factor of 5, the regulatory guidance would be to maintain acute doses below 15 cGy. Given the large safety factor, this should not be considered as a strict “dose limit” as exceeding it slightly would not increase cancer risk.

With regard to exposures over longer periods of time, a radiation dose of 1.5 Gy delivered to the half body or whole body over 5 weeks had a cancer therapeutic effect and led to better survival than the standard treatment to the tumor only (Sakamoto, 2004) (Figure 6). This indicates that such radiation doses over extended periods of time eliminated metastatic disease, i.e. such doses had a cancer preventive effect. Radiation dose higher than 2 Gy dose during 5 weeks was observed to increase leukemia rates (Travis et al., 1996). Such doses during 5 weeks should also be avoided. Using a safety factor of ~5, the regulatory guidance would be to maintain radiation doses over 5 weeks below 40 cGy. Again, given the large safety factor, this should not be considered as a strict dose limit since exceeding it slightly would not increase cancer risk. Considerations such as these should be used with available data to set up guidelines for radiation exposures over extended periods of time to stay well below the known harmful levels.

The approach suggested here - no regulations for exposure to low levels of radiation which are beneficial and no strict dose limits but guidance not to exceed recommended dose levels to ensure safety - may sound like a radical departure from the current LNT model based strict regulations which regulate even small amounts of radiation use with extraordinary requirements of licensing, documentation, etc. An analogy with medicines would show that the suggested approach is not a radical one but an appropriate one for radiation safety, in view of radiation hormesis. With medicines which are beneficial at low doses but would be dangerous at high doses, we do not specify a dose limit, but we do guide the public not to exceed some dose levels, e.g. “do not take more than 10 caplets in 24 hours”. There are no license requirements to buy such over-the-counter drugs and there is no regulator monitoring how many caplets we have taken or asking us to document our usage of the medicine.

Since there is a vast gap between the low radiation doses that are beneficial and the threshold dose for increased cancer risk, beneficial uses of radiation are unlikely to result in doses approaching the cancer threshold. Therefore, little regulation would be needed for beneficial uses of low-dose radiation. However, if some use of low-dose radiation could result in high enough doses to be of cancer-causing concern, caution should be advised and such use of low-dose radiation should be regulated to ensure its safe use.

Who should be assigned the job of developing the new regulations based on radiation hormesis? Use of radiation hormesis requires a complete rethink of the radiation protection concept. Hence, new personnel that do not have the LNT model legacy should be hired to examine the data and establish the regulations for the use of radiation.

Let us now discuss the legal basis of the radiation protection regulations, and examine how EPA has approached its responsibilities. Section 161(b) of the Atomic Energy Act of 1954 authorized the Atomic Energy Commission (AEC) “to **establish** by rule, **regulation**, or order, such standards and instructions to govern the possession and use of special nuclear material, source material, and byproduct material as the Commission may deem necessary or desirable to promote the common defense and security or **to protect health or to minimize danger to life** or property”. EPA’s radiation protection regulations were promulgated under this authority, which it inherited from the AEC. Therefore, since exposure to low radiation doses does not cause danger to life but is beneficial, EPA does not have the legal authority to regulate low radiation doses. The attitude of the staff of the EPA to the observed beneficial effects of radiation (radiation hormesis) is summarized in their report on risk assessment practices (EPA, 2004) in which they state “as the purpose of risk assessment is to identify risk (harm, adverse effect, etc.), effects that appear to be adaptive, non-adverse, or beneficial may not be mentioned”. This attitude of the EPA staff is indeed bizarre. Instead of informing the public as to how they could improve their health using low-dose radiation, and concluding that there is no need/authority to regulate low radiation doses if they are beneficial, the EPA staff have collectively decided to cover up the beneficial effects of low radiation doses by preventing their discussion, thereby endangering public health, and completely violating the Congressional mandate, which is to **protect health or to minimize danger to life**.

The use of the radiation hormesis concept for radiation protection regulations is likely to eliminate most current regulations based on the LNT model, and would result in very much reduced compliance and enforcement related manpower and costs. This should be welcomed, and would be in sharp contrast to the enormous waste of resources the EPA has caused with its LNT model based regulations during the past several decades, with no benefit. With the new regulations, and with the education of the public and professionals on this subject, the fear of low levels of radiation would be very much reduced and so there would be much less disruption of life in case of nuclear accidents that may release radioactivity into the environment. This will be in sharp contrast to the disasters caused by the LNT model based fear and evacuations in Fukushima and Chernobyl. The absence of fear of low levels of radiation would enable the study of beneficial health effects of low-dose radiation such as the cancer preventive effect of low-dose radiation. Evidence also indicates that low-dose radiation may be effective in control of neurodegenerative diseases such as Alzheimer’s (Wei et al., 2012) and Parkinson’s (El-Ghazaly et al., 2013) for which there are presently no effective methods of treatment or control.

In summary, the use of radiation hormesis for radiation protection regulations would be tremendously beneficial for public health by enabling study of use of low-dose radiation to prevent currently intractable diseases, would result in tremendous reduction of regulatory costs to the public, and would reduce the adverse impact of any future nuclear accidents. Hence, the changes suggested should be implemented promptly to end the adverse impact of the current LNT model based regulations.

Sincerely,

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Note: All signers of this letter are members or associate members of SARI (Scientists for Accurate Radiation Information, <http://radiationeffects.org/>) and/or members of the XLNT Foundation (<https://www.x-lnt.org/>). The above letter represents the professional opinions of the signers, and does not necessarily represent the views of their affiliated institutions.

APPENDIX A

Derivation of *ERR* corrected for percentage bias in the measured background cancer mortality rate

Let *B* and *R* be the measured cancer mortality rate of the baseline cohort and the radiated cohort respectively. Then, *ERR* is defined by the equation:

$$\frac{R}{B} = 1 + ERR \quad (1)$$

Let *B(corr)* be the correct baseline cancer mortality rate and let δ be the percentage bias in the measured baseline cancer mortality rate. *B* is then given by:

$$B = B(corr) \times \left(1 + \frac{\delta}{100}\right) \quad (2)$$

Hence,

$$B(corr) = \frac{100 \times B}{(100 + \delta)} \quad (3)$$

The *ERR* corrected for the bias in the measured background cancer mortality rate would be defined by the equation:

$$\frac{R}{B(corr)} = 1 + ERR(corr) \quad (4)$$

Substituting Equation (3) in (4),

$$\frac{R \times (100 + \delta)}{100 \times B} = 1 + ERR(corr) \quad (5)$$

Substituting for *R/B* from Equation (1),

$$\frac{(1 + ERR) \times (100 + \delta)}{100} = 1 + ERR(corr) \quad (6)$$

Solving for *ERR(corr)*,

$$ERR(corr) = \frac{(1 + ERR) \times (100 + \delta)}{100} - 1 \quad (7)$$

References:

- Acuna, S. A., Fernandes, K. A., Daly, C. & et al. 2016. Cancer mortality among recipients of solid-organ transplantation in ontario, Canada. *JAMA Oncology*, 1-8. Available: <http://dx.doi.org/10.1001/jamaoncol.2015.5137>
- Berrington, A., Darby, S. C., Weiss, H. A. & Doll, R. 2001. 100 years of observation on British radiologists: mortality from cancer and other causes 1897-1997. *Br J Radiol*, 74, 507-19. Available: <http://www.ncbi.nlm.nih.gov/pubmed/11459730>
- Cardis, E., Vrijheid, M., Blettner, M., Gilbert, E., Hakama, M., Hill, C., Howe, G., Kaldor, J., Muirhead, C. R., Schubauer-Berigan, M., Yoshimura, T., Bermann, F., Cowper, G., Fix, J., Hacker, C., Heinmiller, B., Marshall, M., Thierry-Chef, I., Utterback, D., Ahn, Y. O., Amoros, E., Ashmore, P., Auvinen, A., Bae, J. M., Solano, J. B., Biau, A., Combalot, E., Deboodt, P., Diez Sacristan, A., Eklof, M., Engels, H., Engholm, G., Gulis, G., Habib, R., Holan, K., Hyvonen, H., Kerekes, A., Kurtinaitis, J., Malker, H., Martuzzi, M., Mastauskas, A., Monnet, A., Moser, M., Pearce, M. S., Richardson, D. B., Rodriguez-Artalejo, F., Rogel, A., Tardy, H., Telle-Lamberton, M., Turai, I., Usel, M. & Veress, K. 2005. Risk of cancer after low doses of ionising radiation: retrospective cohort study in 15 countries. *The BMJ*, 331, 77. Available: <http://www.ncbi.nlm.nih.gov/pubmed/15987704>
- Chaffey, J. T., Rosenthal, D. S., Moloney, W. C. & Hellman, S. 1976. Total body irradiation as treatment for lymphosarcoma. *International Journal of Radiation Oncology*Biology*Physics*, 1, 399-405. Available: <http://www.ncbi.nlm.nih.gov/pubmed/823140>
- Choi, N. C., Timothy, A. R., Kaufman, S. D., Carey, R. W. & Aisenberg, A. C. 1979. Low dose fractionated whole body irradiation in the treatment of advanced non-Hodgkin's lymphoma. *Cancer*, 43, 1636-42. Available: <http://www.ncbi.nlm.nih.gov/pubmed/582159>
- CNSC. 2011. *Verifying Canadian Nuclear Energy Worker Radiation Risk: A Reanalysis of Cancer Mortality in Canadian Nuclear Energy Workers (1957-1994), Summary Report, INFO-0811* [Online]. Canadian Nuclear Safety Commission. Available: http://nuclearsafety.gc.ca/pubs_catalogue/uploads/INFO0811_e.pdf [Accessed May 11, 2017].
- Doss, M. 2012. Evidence supporting radiation hormesis in atomic bomb survivor cancer mortality data. *Dose Response*, 10, 584-92. Available: <http://www.ncbi.nlm.nih.gov/pubmed/23304106>
- Doss, M. 2013. Linear No-Threshold Model vs. Radiation Hormesis. *Dose Response*, 11, 480-497. Available: <http://www.ncbi.nlm.nih.gov/pubmed/24298226>
- Doss, M. 2014. Correcting systemic deficiencies in our scientific infrastructure. *Dose Response*, 12, 185-201. Available: <http://www.ncbi.nlm.nih.gov/pubmed/24910580>
- Doss, M. 2016. Changing the Paradigm of Cancer Screening, Prevention, and Treatment. *Dose Response*, 14, 1559325816680539. Available: <http://www.ncbi.nlm.nih.gov/pubmed/27928220>
- El-Ghazaly, M. A., Sadik, N. A., Rashed, E. R. & Abd El-Fattah, A. A. 2013. Neuroprotective effect of EGb761(R) and low-dose whole-body gamma-irradiation in a rat model of Parkinson's disease. *Toxicol Ind Health*. Available: <http://www.ncbi.nlm.nih.gov/pubmed/23696346>
- EPA 2004. *United States Environmental Protection Agency Risk Assessment Task Force, Office of the Science, Advisor. An examination of EPA risk assessment principles and practices.*, Washington, DC.
- Feinendegen, L. E., Pollycove, M. & Neumann, R. D. 2013. Hormesis by Low Dose Radiation Effects: Low-Dose Cancer Risk Modeling Must Recognize Up-Regulation of Protection. In: BAUM, R. P. (ed.) *Therapeutic Nuclear Medicine*. Springer. Available: http://link.springer.com/chapter/10.1007/174_2012_686

- Frigerio, N. A., Eckerman, K. F. & Stowe, R. S. 1973. *Argonne Radiological Impact Program (ARIP). Part I. Carcinogenic hazard from low-level, low-rate radiation* [Online]. Argonne National Lab., Ill. . Available: <http://www.osti.gov/scitech/servlets/purl/4368021> [Accessed ANL/ES--26(PT.1)].
- Howe, G. R. & McLaughlin, J. 1996. Breast cancer mortality between 1950 and 1987 after exposure to fractionated moderate-dose-rate ionizing radiation in the Canadian fluoroscopy cohort study and a comparison with breast cancer mortality in the atomic bomb survivors study. *Radiation Research*, 145, 694-707. Available: <http://www.ncbi.nlm.nih.gov/pubmed/8643829>
- Hwang, S. L., Guo, H. R., Hsieh, W. A., Hwang, J. S., Lee, S. D., Tang, J. L., Chen, C. C., Chang, T. C., Wang, J. D. & Chang, W. P. 2006. Cancer risks in a population with prolonged low dose-rate gamma-radiation exposure in radiocontaminated buildings, 1983-2002. *International Journal Radiation Biology*, 82, 849-58. Available: <http://www.ncbi.nlm.nih.gov/pubmed/17178625>
- Ichiseki, H. 2013. Features of disaster-related deaths after the Great East Japan Earthquake. *Lancet*, 381, 204. Available: <http://www.ncbi.nlm.nih.gov/pubmed/23332962>
- Koana, T. & Tsujimura, H. 2010. A U-shaped dose-response relationship between x radiation and sex-linked recessive lethal mutation in male germ cells of *Drosophila*. *Radiat Res*, 174, 46-51. Available: <http://www.ncbi.nlm.nih.gov/pubmed/20681798>
- Kostyuchenko, V. A. & Krestinina, L. 1994. Long-term irradiation effects in the population evacuated from the east-Urals radioactive trace area. *Science of the Total Environment*, 142, 119-25. Available: <http://www.ncbi.nlm.nih.gov/pubmed/8178130>
- Luckey, T. D. 1980. *Hormesis with ionizing radiation*, Boca Raton, Fla., CRC Press.
- Miller, A. B., Howe, G. R., Sherman, G. J., Lindsay, J. P., Yaffe, M. J., Dinner, P. J., Risch, H. A. & Preston, D. L. 1989. Mortality from breast cancer after irradiation during fluoroscopic examinations in patients being treated for tuberculosis. *N Engl J Med*, 321, 1285-9. Available: <http://www.ncbi.nlm.nih.gov/pubmed/2797101>
- Murphy, S. L., Kochanek, K. D. & Xu, J. 2015. Deaths: final data for 2012. *Natl Vital Stat Rep*, 63, 1-116. Available: http://www.cdc.gov/nchs/data/nvsr/nvsr63/nvsr63_09.pdf
- NRC 2006. *Health risks from exposure to low levels of ionizing radiation : BEIR VII Phase 2, National Research Council (U.S.). Committee to Assess Health Risks from Exposure to Low Level of Ionizing Radiation.*, Washington, D.C., National Academies Press.
- Ozasa, K., Shimizu, Y., Suyama, A., Kasagi, F., Soda, M., Grant, E. J., Sakata, R., Sugiyama, H. & Kodama, K. 2012. Studies of the mortality of atomic bomb survivors, report 14, 1950-2003: an overview of cancer and noncancer diseases. *Radiation Research*, 177, 229-43. Available: <http://www.ncbi.nlm.nih.gov/pubmed/22171960>
- Pollycove, M. 2007. Radiobiological basis of low-dose irradiation in prevention and therapy of cancer. *Dose Response*, 5, 26-38. Available: <http://www.ncbi.nlm.nih.gov/pubmed/18648556>
- Rowland, R. E., Stehney, A. F. & Lucas, H. F. 1983. Dose-response relationships for radium-induced bone sarcomas. *Health Phys*, 44 Suppl 1, 15-31. Available: <http://www.ncbi.nlm.nih.gov/pubmed/6862895>
- Sakamoto, K. 2004. Radiobiological basis for cancer therapy by total or half-body irradiation. *Nonlinearity Biol Toxicol Med*, 2, 293-316. Available: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2657505/>
- Sponsler, R. & Cameron, J. R. 2005. Nuclear shipyard worker study 1980 1988: a large cohort exposed to low-dose-rate gamma radiation. *International Journal of Low Radiation*, 1, 463-478. Available: <http://www.inderscience.com/info/inarticle.php?artid=7915>
- Travis, L. B., Weeks, J., Curtis, R. E., Chaffey, J. T., Stovall, M., Banks, P. M. & Boice, J. D., Jr. 1996. Leukemia following low-dose total body irradiation and chemotherapy for non-Hodgkin's lymphoma. *J Clin Oncol*, 14, 565-71. Available: <http://www.ncbi.nlm.nih.gov/pubmed/8636772>
- Wei, L. C., Ding, Y. X., Liu, Y. H., Duan, L., Bai, Y., Shi, M. & Chen, L. W. 2012. Low-dose radiation stimulates Wnt/beta-catenin signaling, neural stem cell proliferation and neurogenesis of the

- mouse hippocampus in vitro and in vivo. *Current Alzheimer Research*, 9, 278-89. Available: <http://www.ncbi.nlm.nih.gov/pubmed/22272614>
- Yang, G., Kong, Q., Wang, G., Jin, H., Zhou, L., Yu, D., Niu, C., Han, W., Li, W. & Cui, J. 2014. Low-dose ionizing radiation induces direct activation of natural killer cells and provides a novel approach for adoptive cellular immunotherapy. *Cancer biotherapy & radiopharmaceuticals*, 29, 428-34. Available: <http://www.ncbi.nlm.nih.gov/pubmed/25402754>
- Zablotska, L. B., Ashmore, J. P. & Howe, G. R. 2004. Analysis of mortality among Canadian nuclear power industry workers after chronic low-dose exposure to ionizing radiation. *Radiat Res*, 161, 633-41. Available: <http://www.ncbi.nlm.nih.gov/pubmed/15161357>