

Death of the ALARA Radiation Protection Principle as Used in the Medical Sector

Dose-Response:
An International Journal
April-June 2020:1-12
© The Author(s) 2020
Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/1559325820921641
journals.sagepub.com/home/dos



Paul A. Oakley¹  and Deed E. Harrison²

Abstract

ALARA is the acronym for “As Low As Reasonably Achievable.” It is a radiation protection concept borne from the linear no-threshold (LNT) hypothesis. There are no valid data today supporting the use of LNT in the low-dose range, so dose as a surrogate for risk in radiological imaging is not appropriate, and therefore, the use of the ALARA concept is obsolete. Continued use of an outdated and erroneous principle unnecessarily constrains medical professionals attempting to deliver high-quality care to patients by leading to a reluctance by doctors to order images, a resistance from patients/parents to receive images, subquality images, repeated imaging, increased radiation exposures, the stifling of low-dose radiation research and treatment, and the propagation of radiophobia and continued endorsement of ALARA by regulatory bodies. All these factors result from the fear of radiogenic cancer, many years in the future, that will not occur. It has been established that the dose threshold for leukemia is higher than previously thought. A low-dose radiation exposure from medical imaging will likely upregulate the body’s adaptive protection systems leading to the prevention of future cancers. The ALARA principle, as used as a radiation protection principle throughout medicine, is scientifically defunct and should be abandoned.

Keywords

ALARA, LNT, radiation protection, X-ray, CT scan, low-dose radiation

Introduction

Radiological imaging (eg, X-rays and computed tomography [CT] scans) by medical doctors, dentists, chiropractors, and others in the setting of health care is clearly an evidence-based practice. Imaging of human anatomy leads to a definitive diagnosis, including ruling out suspected pathology, as well as guides particular healthful interventions, for example, in the treatment of dental caries, spinal deformity/subluxation, coronary artery disease, and in the triage of physical traumas such as for the assessment of intracerebral hemorrhage and spine and pelvic fractures.

ALARA or “As Low As Reasonably Achievable” is the acronym used for the concept of dose reduction in radiation protection.¹ Although first introduced for the nuclear energy sector, it was later adopted for use in the medical sector to caution doctors, radiologists, and the like to use radiological imaging judiciously. This is because of the prevailing ideology borne from the linear no-threshold (LNT) model and its assumption that any, and all ionizing radiation is harmful (ie, carcinogenic), and that it is also cumulative (dose additivity).²

ALARA, of course, is the corollary of the LNT model.^{3,4} The LNT is the prevailing model used for radiation protection

standards as formally adopted in 1977.⁵ Recently, however, there has been a surge of evidence that has surfaced that points to the fact that the LNT ideology was adopted for political over scientific reasons.^{6,7} There has also been an increasing amount of criticism of the continued use of the LNT model as used in radiation protection as it lacks scientific support in the low-dose range.⁸ Further, and most importantly, a recent analysis of the life span study (LSS) data for which the entire premise of the LNT rests has been found to be better represented by a hormetic (linear-quadratic) model rather than a linear one.^{9,10} Validity pitfalls of the LNT have been extensively discussed in its use for risk assessment from medical imaging.¹¹⁻¹³

¹ Private Practice, Newmarket, Ontario, Canada

² CBP NonProfit, Inc, Eagle, ID, USA

Received 09 January 2020; received revised 31 March 2020; accepted 03 April 2020

Corresponding Author:

Paul A. Oakley, Private Practice, Newmarket, ON, Canada L3Y 8Y8.
Email: docoakley.icc@gmail.com



Creative Commons Non Commercial CC BY-NC: This article is distributed under the terms of the Creative Commons Attribution-NonCommercial 4.0 License (<https://creativecommons.org/licenses/by-nc/4.0/>) which permits non-commercial use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (<https://us.sagepub.com/en-us/nam/open-access-at-sage>).

The most current evidence does not support the use of the LNT model for use in radiation protection in low-dose exposure ranges.^{8,14} Thus, the ALARA concept as used in the medical sector has no scientific basis. Herein, we provide examples where the use of the ALARA principle does more harm than good as used in the crusade to limit radiation exposures to patients receiving X-rays during the delivery of health care.

Reluctance to Order Radiological Exams

At the highest level of ALARA employment is the pressure on doctors to only choose radiological imaging when *absolutely* necessary (eg, “Image Wisely”¹⁵; “Image Gently”¹⁶; “Choosing Wisely”¹⁷; and “ACR Appropriateness Criteria”¹⁸ campaigns). Caught between balancing the practice of ethical and conscientious medicine (“better being safe than sorry”) and limiting a possible source of presumed future carcinogenicity (“first do no harm”), the choice toward opting for a radiological image is made within this tug-of-war of competing interests.

In reality, the choice for a radiological image should only be weighed on the merits of scientific evidence and the “working diagnosis” based on an attending doctor’s medical assessment. Unfortunately, there are doctors who are becoming more and more reluctant to take radiographic imaging stemming from unwarranted carcinogenic fears from medical imaging from radiation reduction campaigns and/or patient pressures to avoid them, and therefore, are skewing their practice more toward the practice of uncertain medicine. As the practice of medicine is often a sea of uncertainty,¹⁹ when it comes to simply ruling out (or ruling in) a certain diagnosis, it would seem doctors should practice in the realm of most certainty (ie, take an image to make a definitive diagnosis/undiagnosis) versus uncertainty.

An example of how health-care providers are becoming more reluctant in ordering radiological imaging is demonstrated when they are asked to base their decision on the patient’s radiation exposure history. Griffey et al showed that among emergency physician’s, 87% would reconsider radiological imaging if made aware of a patient’s previous cumulative CT count as well as if they have had multiple CTs for a similar health condition.²⁰ Pandharipande et al demonstrated that 92% of radiologists would incorporate past exposure history “risks” into current risk–benefit decision-making analysis and that this typically leads to the recommendation for lower dose imaging options.²¹ Alternatively, when patients are informed of the risks of radiological imaging prior to an X-ray, more become concerned about carcinogenicity²² and many elect to withdraw consent.²³ For this reason, there is current dialogue about whether even to disclose potential (perceived) risks prior to performing CT scans.²⁴ Obviously, initiating this type of conversation constrains the physician with the burden of having a difficult dialogue, and for which they may not be able to effectively communicate,^{25,26} or have the time for.

As can be seen when faced with ordering a radiological image, “doctors are stuck between the proverbial rock and a hard place when it comes to ordering these tests.”²⁷ One may argue, however, that imaging will always be favorable due to

insurance structures that are “fee for service” compensation. While it may be logical to suspect that imaging may be ordered more often than not to increase compensation, since the 1970s, physicians have been facing increasing numbers of medical malpractice claims.²⁸ Medical imaging is one specialty most liable to claims of medical negligence.²⁸ Thus, avoiding malpractice fuels pro-imaging to ascertain timely and accurate diagnosis unrelated to considerations over compensation and insurance coverages.²⁰ Further, newer diagnostic guidelines and decision tools attempt to dissuade physicians from overutilizing radiological imaging²⁹; thus, it is assumed that the majority of health-care providers strive for evidence-based and ethical practice, where radiological imaging use always ultimately comes down to a physician’s clinical expertise.

It is ironic that when faced with LNT-based ALARA (ie, radiophobia misinformation), different patient management decisions are taken (or are forced to be taken due to patient nonconsent) than if there were no concerns about radiation exposures—this affects diagnostic accuracy. The fact is the use of X-rays and CT scans have transformed medical diagnostic accuracy. A spinal surgeon’s surgical success is dependent upon a preoperative full-spine radiographic analysis of essential spinopelvic parameters for which surgical outcomes can be accurately predicted.^{30,31} An emergency consultation for many common presentations (eg, abdominal complaints, chest pains, and headache) has routinely had diagnostic changes to the “leading diagnosis” after obtaining a CT image^{32,33}; this is also consistent in primary care general practice.³⁴ Accurate diagnosis leads to more efficient health care and better patient outcomes. It is tragic and unacceptable when “relieving anxiety has taken precedence over diagnostic accuracy”³⁵ in the arena of medicine.

Resistance of Patients/Parents to Receive Radiological Exams

On the other side of the doctor–patient encounter is the resistance of patients and parents of children who require diagnostic imaging that emit radiation. Spinal X-rays are commonly used to assess bone breaks, fractures, spinal subluxation, and deformities, and CT scans are the technique of choice for assessing head injury, spine, pelvis, or abdominal trauma, characterizing parenchymal lung diseases, as well as staging and treatment planning for solid tumours.³⁶ As mentioned, medical imaging including X-rays are essential in effective health-care management.

A patient who is fearful to receive diagnostic imaging based on authentic but misinformed understanding of radiation effects (ie, unaware of the safety of low-dose exposures) are expressing “radiophobia.”^{37,38} Due to propagating dangers of future cancers from medical imaging throughout the media,³⁵ radiophobia is ubiquitous in the eyes of the patient who is presented with the referral for radiological imaging. Often a patient/parent raises concerns and objections which constrains the medical management of their condition.^{22,23}

Parents informed of theoretical cancer risks associated with CT scans, for example, as compared to parents not informed of the risks are 20% less likely to consent for a head CT scan for their child who had just received a head injury and requires screening for possible brain hemorrhage.²³ This is concerning for several reasons. First, a CT scan is low dose (5-30 mSv³⁶) and there is no evidence of carcinogenic effects at such low exposures. In fact, it is universally accepted that there is no harm at doses below 100 to 200 mSv.³⁹⁻⁴¹ Second, there is evidence showing upregulation of the body's adaptive protection systems at low-doses consistent with exposures from CT scans⁴⁰⁻⁴² and for this reason, head CT scans are being used in a clinical trial, not for the imaging but for the purposeful delivery of radiation for the treatment of Alzheimer disease.⁴² Third, the needless avoidance of important medical imaging may lead to actual real harm for the child from a "missed diagnosis."^{40,41} Finally, real harm may also result from alternate procedures used to avoid radiation exposures, such as using magnetic resonance imaging (MRI) which often requires the use of general anesthesia for children; this adds considerable risk.⁴³ Further, sedation is potentially detrimental for the cognitive development of children.⁴⁴

Recent reports confirm that more patients are indeed more aware of the perceived dangers of medical radiation (ie, LNT ideology of risks). Zwank et al found an increase of patient awareness from only 3% in 2002 to 25% in 2010.⁴⁵ A more recent study showed nearly half of all patients were aware of CTs theoretical risks of future carcinogenicity.²³ Despite this increased awareness, many patients are still not educated in radiogenic risks; however, half of all patients will inquire about imaging risks on their own⁴⁶; in fact, most all perceive radiation as a "unique hazard."⁴⁷ This is why patient resistance remains a factor in radiological imaging because in this day and age of "shared decision-making," it is highly encouraged to properly inform the patient of potential risks of radiation imaging.⁴⁸⁻⁵⁰ When these risks are discussed there is more resistance to this type of imaging.^{22,47}

The problem of patient radiation hesitance is a greater issue in certain types of clinical scenarios. For instance, in emergency medicine, a physician has limited knowledge of a patients' medical history as well as limited time and would be more inclined to choose radiological imaging.⁵¹ When a patient is provided with a choice between "observation" and CT, the patient tendency is to avoid the radiation.²² However, taking the CT is likely more cost-effective and ethical, for example, for nontraumatic, nonspecific abdominal pain, since it has been shown that a substantial proportion of these patients will continue to suffer,^{52,53} even 5-years later.⁵⁴ Thus, initial CT imaging often aids to provide a definitive and timely diagnosis and changes the intended medical triage.^{33,55-58} More specifically, patients initially assessed and deemed for "admittance for observation" have up to a two-thirds reduction in admittances after receiving an abdominopelvic CT scan.^{33,56-58} Computed tomography scans have also reduced unnecessary surgical interventions.^{33,57,58} Thus, radiological imaging, often considered costly, is actually cost-effective as

they often avoid costly hospital stays and surgeries that both present risks of iatrogenic errors⁵⁹ and nosocomial infections (ie, hospital-acquired infections, otherwise known as "superbugs").

Radiological reduction campaigns such as ALARA, lead to "racing to the bottom"⁶⁰; that is, the overly aggressive attempt to reduce radiation exposures, and in turn, may compromise the quality of the images required for medical review. Further, the usual application of ALARA tends to "amplify" detrimental aspects of radiation.⁶¹⁻⁶³ In fact, often associated with fears over radiation exposures, "media-driven social amplification" occurs^{47,64} which stigmatizes radiation in medicine and fuels the radiophobia and the reluctance of patients to receive necessary imaging. Problematically, all too often only the (presumed) risks of medical diagnostic radiation exposures are propagated, and as Wagner states "with only casual, incidental, or no reference to the benefits experienced by patients."⁶³ It has been suggested that any estimates of cancers thought to be caused by medical imaging be conveyed with a cautionary statement that such estimates are "highly speculative" and should also only be presented with simultaneous estimates of the reductions in morbidity and mortality from the use of these imaging procedures.¹³

Another point is in relation to incidental findings (IFs), which are potentially relevant findings on medical imaging which were not anticipated or screened for but were inadvertently discovered. While IFs are unintentionally diagnosed, they are important and can be medically urgent. Rogers et al, for example, determined the incidence of IFs in assessing head CT scans in children due to recent head trauma was 4%, and importantly, 1% "warranted immediate intervention or outpatient follow-up."⁶⁵ Although the rationale to take imaging is not primarily for screening for IFs, they are important and can lead to urgent or altered medical treatment that would not have occurred if the imaging had not been performed.

Doctors, dentists, and radiologists are inundated by patients with concerns over receiving medically necessary X-rays, and the overestimation of radiation risks from imaging may deprive patients of the benefit of medically indicated imaging.⁶⁶ This constrains the practitioner and impedes the practice of efficient and effective health care. Those patients that are stern against radiological imaging are outright sabotaging best practices and sadly this reluctance or hesitancy stems from propagated misinformation and radiophobia by ALARA and image avoidance campaigns.

Increased Radiation Exposures by Aligning With ALARA

In the attempt to better align with ALARA, many practices lead to increased radiation exposures rather than achieving the goal of decreasing them. These include the use of lower exposure parameters, use of lead shielding, and the elimination of "unnecessary" initial screening X-rays in the triage of some pathologies.

Although efforts to optimize radiological imaging parameters to obtain quality images is encouraged, the reduction of settings (eg kilovoltage potential) to decrease patient exposure may lead to suboptimal image quality which may either lead to a retake which would essentially double the exposure or lead to a missed diagnosis^{40,41,67}; either scenario is undesirable. Doubling the exposure to the patient, although not harmful, is ironically contradictory to practicing the principle of ALARA. Missing a diagnosis due to poor image quality resulting from suboptimal imaging parameters in the attempt to reduce patient exposures by an infinitesimal amount is practically negligent.

The use of gonadal shielding was originally adopted in the mid-twentieth century to protect radiosensitive tissues from exposure; however, its use has recently been called into question.^{68,69} Some agencies, for example, the American Association of Physicists in Medicine, advocate for its discontinued use.⁷⁰ Gonadal shielding does little to reduce patient radiation exposures as it cannot stop internal scatter from the exposed anatomy desired to be imaged. Further, shielding is often poorly placed, obscuring anatomy needed to be viewed leading to repeated imaging. Also, even if the shielding is properly placed (ie, over the ovaries), the automatic exposure control photo timing cells may be covered leading to increased radiation output from 63% to 147%!⁷¹ McKenney et al argues that gonadal shielding is nothing more than “good intentions.”⁷¹

In the attempt to decrease patient radiation exposures, traditional X-ray screening of many conditions (eg, low back pain [LBP] and hip dislocations) have been called into question.^{72,73} Ironically, these efforts are not proving successful. In assessing degenerative spinal conditions, for example, it has been shown that routine X-ray examinations prove cost-effective as they often eliminate the need for more costly CT or MRI imaging.⁷⁴ Further, even with doctors not specialized to treat LBP, patients who requested and received imaging of their backs were more satisfied and had better long-term prognosis than comparative patients.^{75,76} It should be mentioned that certain conditions such as osteoarthritis, spondylolisthesis, and the essential biomechanical parameters of the spine and pelvis can only be assessed by X-ray which is why there is a parallel movement endorsing the routine use of X-ray imaging of all spine care patients.^{30,77-82}

Concerning hip dislocations, the pre-CT screening by plain X-rays have, to some, been considered wasteful, as it is argued the patient should triage straight to a CT scan (skipping the plain X-ray screen).⁷³ Since hip dislocations are highly morbid injuries, a prompt reduction is necessary as well as postreduction assessment for both fracture and incarcerated fragments. In assessing the choice of pre-hip reduction imaging in the treatment of acute hip dislocations, however, Walker et al determined that the choice of *not* taking a plain film pre-CT X-ray often resulted in repeated CT scanning and therefore much more radiation exposures.⁸³ Also, the time to hip reduction was longer in patients not receiving a screening X-ray prior to the CT scan. They conclude “Initial trauma pelvic radiography prior to CT is still important in the setting of suspected hip

pathology to decrease time to hip reduction and unnecessary radiation exposure.”⁸³

Stifling of Low-Dose Radiation Research and Treatment

When unwarranted concerns exist about low-dose radiation imaging being harmful, the openness toward the same low-dose radiation for actual treatment of disease is stifled. Long forgotten were the days of effective treatments to various diseases by the purposeful exposure to radiation, so-called low-dose irradiation (LDI) or radiotherapy.⁴²

It has been recently documented⁴² that many common ailments including arthritis,⁸⁴ bronchial asthma,⁸⁵ carbuncles,⁸⁶ cervical adenitis,⁸⁷ deafness,⁸⁷ furuncles,⁸⁶ gas gangrene,⁸⁸ necrotizing fasciitis,⁸⁹ otitis media,⁸⁷ pertussis,⁹⁰ pneumonia,⁹¹ sinus infection,⁹² tendonitis,⁹³ and bursitis⁹³ have all been successfully treated by radiotherapy. Typical success rates ranged from 75% to 90% and relief was often reported after even a single exposure.⁹⁴ It is important to note the estimated doses for these traditional treatments were in the range of 30 to 100 roentgen⁹⁴ (263-877 mSv)—which is a dose many times larger than typical X-ray imaging (1-3 mGy) or CT scanning (~10 mGy).

Further, other trials have previously shown that the treatment of cancers from LDI therapy had good success rates as opposed to today’s standard high-dose radiation.⁹⁵ In fact, patients with non-Hodgkin’s lymphoma, ovarian, colon, and hematological cancers have been shown to be successfully treated.⁹⁶⁻¹⁰⁰ The typical LDI protocol for cancer is an exposure to a total dose of 150 rad (1500 mGy) over a 5-week duration.^{101,102} Again, it is noted that health benefits are shown to occur from radiation doses many times higher than that given by X-ray and CT scans.

It must be mentioned that the benefits of radiotherapy are found in the body’s innate adaptive response systems (ie, DNA damage-control biosystem).¹⁰¹⁻¹⁰⁹ Numerous and redundant tissue inherent innate mechanisms collectively either prevent, repair, or remove any damage resulting from radiation exposures (Figure 1).¹⁰⁶ These repair mechanisms are also fast-acting and result in an “over-repair” and therefore cause a net loss of damage or essentially a higher level of fitness in living organisms. For example, Lobrich et al¹¹⁰ showed that CT scans do cause DNA double-strand breaks (DSB) immediately after exposure in humans; however, as early as 24 hours post-scan, there is an overall reduction in baseline DNA DSB damage.

One last consideration is that radiation damage caused by X-rays are only about one 1-millionth the damage caused from endogenous production of reactive oxygen species and hydrogen peroxide from aerobic respiration (breathing air).^{81,103,106} Thus, the amount of damage from X-rays is negligible, and of course, this damage along with the damage many orders of magnitude greater from normal metabolism gets mitigated.^{81,103-110} The evidence as discussed shows the reality of radiation hormesis and the failure of LNT ideology for low-dose radiation exposures. Thus, critics who clutch to outdated

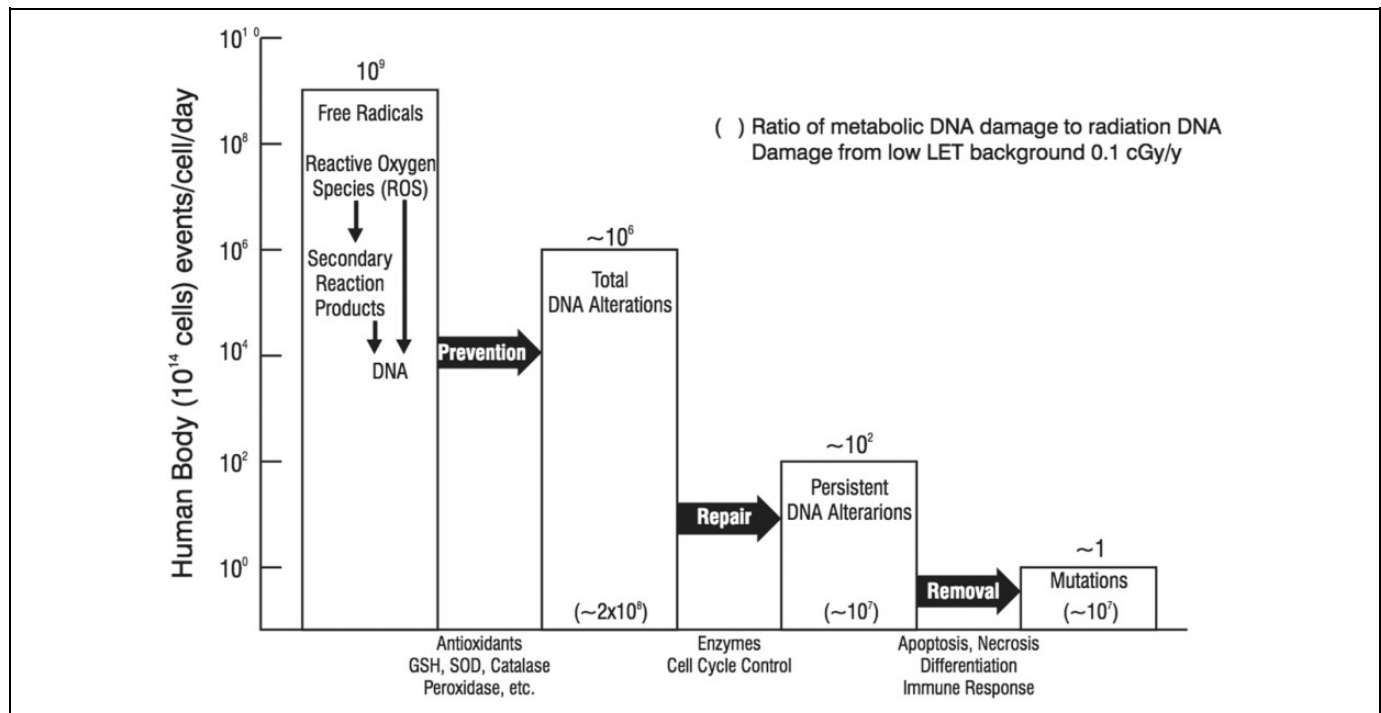


Figure 1. The adaptive response systems very efficiently prevent, repair, or remove virtually all DNA alterations.¹⁰⁶

single-hit theory¹¹¹ and dose additivity¹¹² for risk assessment are misguided as these concepts are both considered invalid for lower radiation exposures, certainly for doses from diagnostic X-rays. The reality of nonlinearity and failure of LNT concepts has led to newer theories concerning human health and disease including cancer etiology.^{113,114}

It is only through the reexamination of the evidence of LDI radiotherapy can one fathom the exciting possibilities for rediscovering effective treatments for human diseases, as has begun to emerge recently.^{42,115-119} Again, radiation doses that are healthful cannot simultaneously be harmful; it is the LNT mythology that continues to perpetuate false notions of low-dose radiophobia that only stifles the research and acceptance of using LDI for treating human disease.

Propagation of Radiophobia

The real problem with ALARA and movements to this end (eg, “Image Wisely,” “Image Gently,” etc) is the propagation of radiophobia.^{120,121} Radiophobia can manifest as apprehension and anxiety and can escalate to obsessive thinking or compulsive behaviors; all of this stemming from fear.³⁸ Once a person has an emotional fear of something, it is difficult, if not impossible to sway them from their misguided belief with any amount of science, data, or logic. Thus, we concur with Cohen who stated: “These campaigns attempt to solve a problem that does not exist and, in turn, creates problems.”¹²²

It is no surprise that the current radiophobia originated from the historic atom bomb droppings on Hiroshima and Nagasaki during World War II that continues to this day.¹²³ The fact is,

however, the LSS data clearly show that those exposed to even fairly high radiation doses outlived controls.¹²⁴ Further, considering Cuttler has shown that the threshold for leukemia in this same population is quite high at 1100 mGy (95% confidence interval: 500-2600 mGy),¹²⁵ only demonstrates humans can tolerate surprisingly high levels of radiation without deleterious health consequences.

Radiophobia to medical imaging stems from unwarranted fears and false beliefs. This leads patients and doctors to fear radiological imaging based on the erroneous assumptions of the ALARA/LNT as applied to low-dose imaging. The fact is, however, there are no data supporting the notion that low-dose radiation exposures as given by radiographs (X-rays or CT scans) lead to future cancers.^{8,14,39-41,126-128} All studies that have propagated radiophobia from medical imaging have been found to be flawed or have misplaced conclusions.^{30,35,40,41,129}

The original studies that led to the adoption of the ALARA principle in medicine were those associating exposure to CT scans with increased cancers.^{130,131} These papers continue to be published (eg, Pearce et al,¹³² Matthews et al,¹³³ and Miglioretti et al¹³⁴) and are advertised through major media outlets which, unfortunately, go unabated.³⁵ Other articles consistent with propagating radiophobia are ones calculating excess cancers from repeated X-rays in patients with scoliosis (eg, Nash et al,¹³⁵ Levy et al,¹³⁶ Ronckers et al,¹³⁷ and Simony et al¹³⁸).

The obvious flaws with studies that predict (no actual follow-up) future cancers from CT scans¹³⁴ or scoliosis X-rays^{135,136} are that they use the LNT model and weighting factors—these are purely theoretical and not applicable for

low-dose radiation exposures.⁷⁹ The studies with actual cohort follow-up, finding increased cancers in those receiving previous CT scans,^{132,133} suffer from the criticism of reverse causation (ie, “confounding by indication”); that is “the early symptoms of undetected cancer, or of factors that predispose to cancer, that are indications for the CT scans, rather than the CT scans per se that are causing the apparent excess risk of cancer.”¹³⁹ This concept is illustrated in the paper by Journy et al who examined the relative risk of cancer incidence in patients who received CT scans prior to the age of 10 years.¹⁴⁰ The purpose was to assess how cancer-predisposing factors (PFs) affect the assessment of radiation-related risk calculations. They determined that excess relative risks for cancers from CT exposures were reduced by up to 56% when adjusted for PFs and stated: “This study made it possible to assess for the first time the cancer risks associated with exposures to CT scans while taking into account major PF, including rare genetic defects and acquired immune deficiencies.” The conclusion was that “no significant excess risk (for cancer) was observed in relation to CT exposures.”¹⁴⁰

Scoliosis cohorts who were followed-up^{137,138} and showed increased cancers are argued to be having the side effects of the spine deformity itself and not from previous low-dose X-rays that would be expected to mitigate future cancers.⁷⁹ It is estimated that these patients had received a total average cumulative exposure of less than 150 mGy.¹³⁷ The blame for this amount of exposure to have caused the cancers in this cohort is presumptuous and beyond doubtful, especially considering the fact that one cannot assess risk based on the cumulative dose concept as any damage caused by repeated spinal X-rays (1-3 mGy per session) would be repaired prior to the next imaging session. Oakley et al state “Since the body’s adaptive response will repair damage done at each X-ray event, X-ray exposures of about 1 to 3 mGy will always remain at a level that is 367 to 1100 times below the radiogenic dose threshold.”⁷⁹

As mentioned, the media often release sensationalized articles socially amplifying the dangers of medical imaging.^{35,47,64} Cohen, for example, documented dozens of fear-mongering media headlines about dangerous CT scans released in major media articles.^{141,142} This sensationalism comes from erroneous projections taken out of context; in fact, the International Commission on Radiological Protection (ICRP) clearly states: “the calculation of the number of cancer deaths based on collective effective doses from trivial individual doses should be avoided.”¹⁴³ Any attempt to assess the average adult for individual effective dose effects is associated with great uncertainty ($\pm 40\%$) due to age, gender, mass, and so on.^{144,145} Thus, “Risk is always a population-based metric and as such, its ascription to an individual patient should never be interpreted deterministically.”¹⁴⁶ Unfortunately, patients who hear these headlines typically cannot decipher elements of statistics, probability, and causation¹⁴⁷ to disengage from the fear-mongering but alternatively get caught up in the hype, misinformation, and social amplification of the perceived risks.⁶⁴

Oftentimes, the most difficult aspect of obtaining an X-ray is in convincing the patient/parent that it is warranted; that is, its benefits outweigh its risks. Sadly, in the escalating environment fostering radiophobia surrounding medical imaging, little discussion is given to the health benefits, only the risks.^{61-63,139} Brody, for example, urge clinicians to always remember to discuss the benefit side of the risk-to-benefit equation; assuming LNT projected cancer risks, he states:

we say that if a million children get CT scans, 100 will have a risk of getting cancer. But we don’t say that if a million kids receive CT scans, one half of them will avoid unnecessary surgery, 100,000 of them will receive surgery that is better because the surgeon is guided by the CT results, and 300,000 of them won’t have to go into the hospital unnecessarily.¹⁴⁸

In a risk-to-benefit ratio when there is no risk from low-dose radiation, it only amounts to benefit and certainty within the practice of health care. As stated previously:

If there is zero risk, then that leaves only benefit in a risk to benefit ratio. Therefore, as long as an imaging procedure can provide meaningful data in terms of diagnosis, differential diagnosis, monitoring treatment progress, IFs, patient satisfaction, and so on, the benefit will always outweigh a risk of zero.⁸¹

Thus, within the practice of evidenced-based medicine, as long as the use of radiological imaging materially changes patient management, the action is justified.¹⁴⁹ To help physicians, many discipline-specific radiological guidelines have been created; however, sometimes duplicate guidelines can be conflicting¹⁵⁰ and often have a bias based on who created them (ie, for or against imaging in similar clinical scenarios).^{83,151,152} Clinical guidelines are just that, a “guideline” for the purpose of assisting the clinician in navigating patient triage. The final decision to opt for radiological imaging always comes down to the doctor and patient. Radiological imaging consideration should never be based on fears of radiation, but only whether it is medically justified for the specific patient at the specific time course in the management of their particular clinical presentation; in fact, “all medical procedures require justification in the form of medical indication, but radiation exposure levels have no place in that process.”⁴¹ We concur with Wijetunga et al who states: “for justified and optimized examinations there will always be a net benefit to the patient.”¹⁴⁹

It must be mentioned that dose optimization for CT scans, particularly for children, is more commonplace. This practice is obviously reasonable as long as the practice does not result in suboptimal images that may lead to nondiagnostic scans, which has been documented to occur.^{43,148,153} The subset of patients who may be exposed to repeated scans over time, for example, children with adolescent idiopathic scoliosis or those being monitored with recurrent conditions such as inflammatory bowel diseases should not be concerned about harmful radiogenic consequences as the adaptive response systems will mitigate any damage caused.^{42,79,101-110} Based on the best available

evidence, including the LSS data, children are not more radio-sensitive to radiation than adults.^{41-43,154,155} Parents must realize that it is more risky to spend a week in the hospital under “clinical observation” (due to medical errors and/or nosocomial infections) than to get a CT scan for a definitive and timely diagnosis.¹⁴⁸

The LNT model of radiation damage is dead¹⁵⁶ and so with it dies the ALARA concept. Continued endorsement of the LNT model by regulatory and advisory bodies (eg, National Academy of Sciences Biological Effects of Ionizing Radiation Committee, National Council on Radiation Protection and Measurements, ICRP, etc) will continue to perpetuate radiophobia by giving support to the ALARA concept and the Image Gently/Wisely campaigns. Due to the detrimental impact of ALARA and image reduction campaigns, we strongly concur with others who demand that these actions be terminated.^{12,35,40,41,120-122,157,158}

Conclusion

Currently, there is no evidence supporting the use of the LNT model as a surrogate for radiation risk in the low-dose exposure range such as from medical imaging. Thus, the use of the ALARA radiation protection principle in the medical sector is obsolete. Continued use of an outdated and erroneous principle unnecessarily constrains medical professionals attempting to deliver high-quality care to patients by leading to a reluctance by doctors to order images, a resistance from patients/parents to receive images, subquality images, repeated imaging, increased radiation exposures, the stifling of low-dose radiation research and treatment, and the propagation of radiophobia and continued endorsement of ALARA by regulatory bodies. All these factors result from the fear of radiogenic cancer, many years in the future, that will not occur. We strongly urge for the discontinuation of the ALARA concept and the campaigns it underpins be terminated.


Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: P.A.O. is a paid research consultant for CBP NonProfit, Inc.; D.E.H. teaches spine rehabilitation methods and sells products to physicians for patient care that require radiography for biomechanical analysis.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by funds from CBP NonProfit, Inc.

ORCID iD

Paul A. Oakley  <https://orcid.org/0000-0002-3117-7330>

References

- National Council on Radiation Protection and Measurements. *Report No. 107. Implementation of the Principle of as Low as Reasonably Achievable (ALARA) for Medical and Dental Personnel*; 1990. NCRP Publications.
- Doss M. Linear no-threshold model VS. radiation hormesis. *Dose Response*. 2013;11(12):480-497.
- Pennington CW, Siegel JA. The linear no-threshold model of low-dose radiogenic cancer: a failed fiction. *Dose Response*. 2019;17(1):1559325818824200.
- Siegel JA, Sacks B, Greenspan BS. There is no evidence to support the linear no-threshold model of radiation carcinogenesis. *J Nucl Med*. 2018;59(12):1918.
- Clarke R, Valentin J. A history of the International Commission on Radiological Protection. *Health Phys*. 2005;88(5):407-422.
- Calabrese EJ. On the origins of the linear no-threshold (LNT) dogma by means of untruths, artful dodges and blind faith. *Environ Res*. 2015;142(5):432-442.
- Calabrese EJ. From muller to mechanism: how LNT became the default model for cancer risk assessment. *Environ Pollut*. 2018;241(1):289-302.
- Siegel JA, Brooks AL, Fisher DR, et al. A critical assessment of the linear no-threshold hypothesis: its validity and applicability for use in risk assessment and radiation protection. *Clin Nucl Med*. 2019;44(7):521-525.
- Ozasa K, Shimizu Y, Suyama A, et al. Studies of the mortality of atomic bomb survivors, report 14, 1950-2003: an overview of cancer and noncancer diseases. *Radiat Res*. 2012;177(6):229-243.
- Socol Y, Dobrzyński L. Atomic bomb survivors life-span study: insufficient statistical power to select radiation carcinogenesis model. *Dose Response*. 2015;13(1):dose-response.14-034.Socol.
- Andronikou S. Letting go of what we believe about radiation and the risk of cancer in children. *Pediatr Radiol*. 2017;47(1):113-115.
- Doss M. *Should the ALARA Concept and the Image Gently Campaign be Terminated?* Chicago, IL: Paper presented at the International Pediatric Radiology; 2016. May 17, 2016. <http://www.pedrad.org/LinkClick.aspx?fileticket=3EHivxngKs%3d&portalid=5>. Accessed March 25, 2020.
- Doss M. Future of radiation protection regulations. *Health Phys*. 2016;110(3):274-275.
- Schultz CH, Fairley R, Murphy LS, Doss M. The risk of cancer from CT scans and other sources of low-dose radiation: a critical appraisal of methodologic quality. *Prehosp Disaster Med*. 2020;35(1):3-16.
- Joint Task Force on Adult Radiation Protection. The imaging wisely campaign. 2009. <https://www.imagewisely.org/>. Accessed March 25, 2020.
- Image Gently Alliance. Alliance for radiation safety in pediatric imaging. Image gently. 2007. <https://www.imagegently.org/>. Accessed March 25, 2020.
- American Board of Internal Medicine. Choosing wisely. <https://www.choosingwisely.org>. Accessed March 25, 2020.
- American College of Radiology. <https://www.acr.org/Clinical-Resources/ACR-Appropriateness-Criteria/About-the-ACR-AC>. Accessed March 25, 2020.
- Mandrola J, Cifu A, Prasad V, Foy A. The case for being a medical conservative. *Am J Med*. 2019;132(8):900-901.

20. Griffey RT, Jeffe DB, Bailey T. Emergency physicians' attitudes and preferences regarding computed tomography, radiation exposure, and imaging decision support. *Acad Emerg Med*. 2014; 21(7):768-777.
21. Pandharipande PV, Eisenberg JD, Avery LL, et al. Journal club: how radiation exposure histories influence physician imaging decisions: a multicenter radiologist survey study. *AJR Am J Roentgenol*. 2013;200(6):1275-1283.
22. Larson DB, Rader SB, Forman HP, Fenton LZ. Informing parents about CT radiation exposure in children: it's OK to tell them. *AJR Am J Roentgenol*. 2007;189(2):271-275.
23. Boutis K, Cogollo W, Fischer J, Freedman SB, Ben David G, Thomas KE. Parental knowledge of potential cancer risks from exposure to computed tomography. *Pediatrics*. 2013;132(2): 305-311.
24. Brink JA, Goske MJ, Patti JA. Informed decision making trumps informed consent for medical imaging with ionizing radiation. *Radiology*. 2012;262(1):11-14.
25. Lee CI, Flaster HV, Haims AH, Monico EP, Forman HP. Diagnostic CT scans: institutional informed consent guidelines and practices at academic medical centers. *AJR Am J Roentgenol*. 2006;187(2):282-287.
26. Puri S, Hu R, Quazi RR, Voci S, Veazie P, Block R. Physicians' and midlevel providers' awareness of lifetime radiation-attributable cancer risk associated with commonly performed CT studies: relationship to practice behavior. *AJR Am J Roentgenol*. 2012;199(6):1328-1336.
27. Loudon G. Parent alarmed over routine CT-scan dangers. Support for testing plunges when radiation risk revealed. *World Net Daily*. July 9, 2013. <https://drginaloudon.com/2013/07/parents-alarmed-over-routine-ct-scan-dangers/>. Accessed April 17, 2020.
28. Pinto A, Brunese L. Spectrum of diagnostic errors in radiology. *World J Radiol*. 2010;2(10):377-383.
29. Eisenberg JD, Harvey HB, Moore DA, Gazelle GS, Pandharipande PV. Falling prey to the sunk cost bias: a potential harm of patient radiation dose histories. *Radiology*. 2012;263(3): 626-628.
30. Bess S, Protosaltis TS, Lafage V, et al. Clinical and radiographic evaluation of adult spinal deformity. *Clin Spine Surg*. 2016;29(1): 6-16.
31. Ames CP, Blondel B, Scheer JK, et al. Cervical radiographical alignment: comprehensive assessment techniques and potential importance in cervical myelopathy. *Spine*. 2013;38(22 suppl 1): S149-S160.
32. Pandharipande PV, Reisner AT, Binder WD, et al. CT in the emergency department: a real-time study of changes in physician decision making. *Radiology*. 2016;278(3):812-821.
33. Abujudeh HH, Kaewlai R, McMahon PM, et al. Abdominopelvic CT increases diagnostic certainty and guides management decisions: a prospective investigation of 584 patients in a large academic medical center. *AJR Am J Roentgenol*. 2011;196(2):238-243.
34. Pandharipande PV, Alabre CI, Coy DL, et al. Changes in physician decision making after CT: a prospective multicenter study in primary care settings. *Radiology*. 2016;281(3):835-846.
35. Cohen MD. Point: should the ALARA concept and image gently campaign be terminated? *J Am Coll Radiol*. 2016;13(10): 1195-1198.
36. Rehani MM, Berry M. Radiation doses in computed tomography. The increasing doses of radiation need to be controlled. *BMJ*. 2000 Mar 4;320(7235):593-594.
37. Angelidis G, Tsougos I, Valotassiou V, Georgoulas P. Low-dose radiation cancer risk hypothesis may lead to 'radiophobia'-driven imaging avoidance? *J Nucl Cardiol*. 2018;7. doi:10.1007/s12350-018-1354-0. [Epub ahead of print]
38. De Ment J. Radiophobia; a new psychological syndrome. *West J Surg Obstet Gynecol*. 1951;59(11):viii, x,602.
39. Sasaki MS, Tachibana A, Takeda S. Cancer risk at low doses of ionizing radiation: artificial neural networks inference from atomic bomb survivors. *J Radiat Res*. 2014;55(3):391-406.
40. Siegel JA, Welsh JS. Does imaging technology cause cancer? Debunking the linear no-threshold model of radiation carcinogenesis. *Technol Cancer Res Treat*. 2016;15(2):249-256.
41. Siegel JA, Pennington CW, Sacks B. Subjecting radiologic imaging to the linear no-threshold hypothesis: a non sequitur of non-trivial proportion. *J Nucl Med*. 2017;58(1):1-6.
42. Cuttler JM. Application of low doses of ionizing radiation in medical therapies. *Dose Response*. 2020;18(1):1559325819895739.
43. Brody AS, Guillerman RP. Don't let radiation scare trump patient care: 10 ways you can harm your patients by fear of radiation-induced cancer from diagnostic imaging. *Thorax*. 2014;69(8): 782-784.
44. Jevtovic-Todorovic V, Absalom AR, Blomgren K, et al. Anaesthetic neurotoxicity and neuroplasticity: an expert group report and statement based on the BJA Salzburg Seminar. *Br J Anaesth*. 2013;111(2):143-151.
45. Zwank MD, Leow M, Anderson CP. Emergency department patient knowledge and physician communication regarding CT scans. *Emerg Med J*. 2014;31(10):824-826.
46. Pahade JK, Trout AT, Zhang B, et al. What patients want to know about imaging examinations: a multiinstitutional U.S. survey in adult and pediatric teaching hospitals on patient preferences for receiving information before radiologic examinations. *Radiology*. 2018;287(2):554-562.
47. Dauer LT, Thornton RH, Hay JL, Balter R, Williamson MJ, St Germain J. Fears, feelings, and facts: interactively communicating benefits and risks of medical radiation with patients. *AJR Am J Roentgenol*. 2011;196(4):756-761.
48. Robey TE, Edwards K, Murphy MK. Barriers to computed tomography radiation risk communication in the emergency department: a qualitative analysis of patient and physician perspectives. *Acad Emerg Med*. 2014;21(2):122-129.
49. Hull A, Friedman T, Christianson H, Moore G, Walsh R, Wills B. Risk acceptance and desire for shared decision making in pediatric computed tomography scans: a survey of 350. *Pediatr Emerg Care*. 2015;31(11):759-761.
50. Boutis K, Thomas KE. Radiation dose awareness and disclosure practice in paediatric emergency medicine: how far have we come? *Br J Radiol*. 2016;89(1061):20160022.

51. Shyu JY, Sodickson AD. Communicating radiation risk to patients and referring physicians in the emergency department setting. *Br J Radiol.* 2016;89(1061):20150868.
52. Gunnarsson OS, Birgisson G, Oddsdottir M, Gudbjartsson T. [One year follow-up of patients discharged from the emergency department with non-specific abdominal pain]. *Laeknabladid.* 2011;97(4):231-236.
53. Ravn-Christensen C, Qvist N, Bay-Nielsen M, Bisgaard T. Pathology is common in subsequent visits after admission for non-specific abdominal pain. *Dan Med J.* 2019;66(7):A5549.
54. Banz VM, Sperisen O, de Moya M, et al. A 5-year follow up of patients discharged with non-specific abdominal pain: out of sight, out of mind? *Intern Med J.* 2012;42(4):395-401.
55. Nagurney JT, Brown DF, Chang Y, Sane S, Wang AC, Weiner JB. Use of diagnostic testing in the emergency department for patients presenting with non-traumatic abdominal pain. *J Emerg Med.* 2003;25(4):363-371.
56. Barksdale AN, Hackman JL, Gaddis M, Gratton MC. Diagnosis and disposition are changed when board-certified emergency physicians use CT for non-traumatic abdominal pain. *Am J Emerg Med.* 2015;33(11):1646-1650.
57. Gardner CS, Jaffe TA, Nelson RC. Impact of CT in elderly patients presenting to the emergency department with acute abdominal pain. *Abdom Imaging.* 2015;40(7):2877-82.
58. Rosen MP, Sands DZ, Longmaid HE 3rd, Reynolds KF, Wagner M, Raptopoulos V. Impact of abdominal CT on the management of patients presenting to the emergency department with acute abdominal pain. *AJR Am J Roentgenol.* 2000;174(5):1391-1396.
59. Makary MA, Daniel M. Medical error-the third leading cause of death in the US. *BMJ.* 2016;353:i2139.
60. Newman B, Callahan MJ. Reply to commentary—"CT radiation dose reduction: can we do harm by doing good?". *Pediatr Radiol.* 2012;42(4):399-401.
61. Kasraie N, Jordan D, Keup C, Westra S. Optimizing communication with parents on benefits and radiation risks in pediatric imaging. *J Am Coll Radiol.* 2018;15(5):809-817.
62. Wagner LK. Toward a holistic approach in the presentation of benefits and risks of medical radiation. *Health Phys.* 2011;101(5):566-571.
63. Wagner LK. Should risk from medical imaging be assessed in the absence of benefit and vice versa? *Pediatr Radiol.* 2014;44(Suppl 3):414-417.
64. Kasperson R, Renn O, Slovic P, et al. The social amplification of risk: a conceptual framework. *Risk Anal.* 1988;8(7):177-187.
65. Rogers AJ, Maher CO, Schunk JE, et al. Incidental findings in children with blunt head trauma evaluated with cranial CT scans. *Pediatrics.* 2013;132(5):e356-e363.
66. Tubiana M. Computed tomography and radiation exposure (letter to the editor). *N Engl J Med.* 2008;358(8):850.
67. Cohen MD. CT radiation dose reduction: can we do harm by doing good? *Pediatr Radiol.* 2012;42(4):397-398.
68. Karami V, Zabihzadeh M, Shams N, Saki Malehi A. Gonad shielding during pelvic radiography: a systematic review and meta-analysis. *Arch Iran Med.* 2017;20(2):113-123.
69. Kaplan SL, Magill D, Felice MA, Xiao R, Ali S, Zhu X. Female gonadal shielding with automatic exposure control increases radiation risks. *Pediatr Radiol.* 2018;48(2):227-234.
70. American Association of Physicists in Medicine. *AAPM Position Statement on the Use of Patient Gonadal and Fetal Shielding.* Policy No. PP 32-A, April 2, 2019. <https://www.aapm.org/org/policies/details.asp?id=468&type=PP¤t=true>. Accessed April 17, 2020.
71. McKenney S, Gingold E, Zaidi H. Gonadal shielding should be discontinued for most diagnostic imaging exams. *Med Phys.* 2019;46(3):1111-1114.
72. Jenkins HJ, Downie AS, Moore CS, French SD. Current evidence for spinal X-ray use in the chiropractic profession: a narrative review. *Chiropr Man Therap.* 2018;26:48.
73. Soto JR, Zhou C, Hu D, Arazoza AC, Dunn E, Sladek P. Skip and save: utility of pelvic x-rays in the initial evaluation of blunt trauma patients. *Am J Surg.* 2015;210(6):1076-1079.
74. Kim JS, Dong JZ, Brener S, Coyte PC, Rampersaud YR. Cost-effectiveness analysis of a reduction in diagnostic imaging in degenerative spinal disorders. *Health Policy.* 2011;7(2):e105-e121.
75. Kendrick D, Fielding K, Bentley E, Kerslake R, Miller P, Pringle M. Radiography of the lumbar spine in primary care patients with low back pain: randomized controlled trial. *BMJ.* 2001;322(7283):400-405.
76. Kendrick D, Fielding K, Bentley E, Miller P, Kerslake R, Pringle M. The role of radiography in primary care patients with low back pain of at least 6 weeks duration: a randomized (unblinded) controlled trial. *Health Technol Assess.* 2001;5(30):1-69.
77. Scheer JK, Tang JA, Smith JS, et al. Cervical spine alignment, sagittal deformity, and clinical implications: a review. *J Neurosurg Spine.* 2013;19(2):141-159.
78. Oakley PA, Navid Ehsani N, Harrison DE. Repeat radiography in monitoring structural changes in the treatment of spinal disorders in chiropractic and manual medicine practice: evidence and safety. *Dose Response.* 2019;17(4):1-9.
79. Oakley PA, Navid Ehsani N, Harrison DE. The scoliosis quandary: are radiation exposures from repeated X-rays harmful? *Dose Response.* 2019;17:1559325819852810.
80. Oakley PA, Cuttler JM, Harrison DE. X-ray imaging is essential for contemporary chiropractic and manual therapy spinal rehabilitation: radiography increases benefits and reduces risks. *Dose Response.* 2018;16(2):1-7.
81. Oakley PA, Harrison DE. Radiophobia: 7 reasons why radiography used in spine and posture rehabilitation should not be feared or avoided. *Dose Response.* 2018;16(2):1-10.
82. Oakley PA, Harrison DD, Harrison DE, Haas JW. Evidence-based protocol for structural rehabilitation of the spine and posture: review of clinical biomechanics of posture (CBP) publications. *J Can Chiropr Assoc.* 2005;49(4):270-296.
83. Walker MR, El Naga AN, Atassi OH, Perkins CH, Mitchell SA. Effect of initial emergency room imaging choice on time to hip reduction and repeat imaging. *Injury.* 2019;50(5):686-689.
84. Kuhns JG, Morrison SL. Twelve years' experience in roentgenotherapy for chronic arthritis. *N Engl J Med.* 1946;235(1):399-405.

85. Calabrese EJ, Dhawan G, Kapoor R. The use of X rays in the treatment of bronchial asthma: a historical assessment. *Radiat Res.* 2015;184(2):180-192.
86. Calabrese EJ. X-Ray treatment of carbuncles and furuncles (boils): a historical assessment. *Hum Exp Toxicol.* 2013;32(8):817-827.
87. Calabrese EJ, Dhawan G. Historical use of x-rays: treatment of inner ear infections and prevention of deafness. *Hum Exp Toxicol.* 2014;33(5):542-553.
88. Calabrese EJ, Dhawan G. The role of x-rays in the treatment of gas gangrene: a historical assessment. *Dose Response.* 2012;10(4):626-643.
89. Dhawan G, Kapoor R, Dhamija A, Singh R, Monga B, Calabrese EJ. Necrotizing fasciitis: low-dose radiotherapy as a potential adjunct treatment. *Dose Response.* 2019;17(3):1559325819871757.
90. Calabrese EJ, Dhawan G, Kapoor R. Radiotherapy for pertussis: an historical assessment. *Dose Response.* 2017;15(2):1559325817704760.
91. Calabrese EJ, Dhawan G. How radiotherapy was historically used to treat pneumonia: could it be useful today? *Yale J Biol Med.* 2013;86(4):555-570.
92. Calabrese EJ, Dhawan G. The historical use of radiotherapy in the treatment of sinus infections. *Dose Response.* 2013;11(5):469-479.
93. Calabrese EJ, Dhawan G, Kapoor R. Use of X-rays to treat shoulder tendonitis/bursitis: a historical assessment. *Arch Toxicol.* 2014;88(8):1503-1517.
94. Calabrese EJ, Dhawan G, Kapoor R, Kozumbo WJ. Radiotherapy treatment of human inflammatory diseases and conditions: optimal dose. *Hum Exp Toxicol.* 2019;38(8):888-898.
95. Oakley PA. Is use of radiation hormesis the missing link to a better cancer treatment? *J Can Therap.* 2015;6(4):601-605.
96. Chaffey JT, Rosenthal DS, Moloney WC, Hellman S. Total body irradiation as treatment for lymphosarcoma. *Int J Radiat Oncol Biol Phys.* 1976;1(5):399-405.
97. Choi NC, Timothy AR, Kaufman SD, Carey RW, Aisenberg AC. Low dose fractionated whole body irradiation in the treatment of advanced non-Hodgkin's lymphoma. *Cancer.* 1979;43(4):1636-1642.
98. Sakamoto K, Myogin M, Hosoi Y, et al. Fundamental and clinical studies on cancer control with total or upper half body irradiation. *JASTRO Japanese Soci Therap Radiol Oncol.* 1997;9(6):161-175.
99. Sakamoto K. Radiobiological basis for cancer therapy by total or half-body irradiation. *Nonlin Biol Toxicol Med.* 2004;2(2):293-316.
100. Richaud PM, Soubeyran P, Eghbali H, et al. Place of low-dose total body irradiation in the treatment of localized follicular non-Hodgkin's lymphoma: results of a pilot Study. *Int J Radiat Oncol Biol Phys.* 1998;40(3):387-390.
101. Cuttler JM, Pollycove M, Welsh JS. Application of low doses of radiation for curing cancer. *Can Nuclear Soci Bull.* 2000;21:45-50. https://www.researchgate.net/publication/338831926_Application_of_Low_Doses_of_Radiation_for_Curing_Cancer. Accessed March 25, 2020.
102. Pollycove M, Feinendegen LE. *Cellular and Organism Dose-Response: Biopositive (Health Benefit) Effects*. Washington, DC: Proceedings of International Symposium on Health Benefits of Low-Dose Radiation—The Science and Medical Applications; 2000.
103. Feinendegen LE, Cuttler JM. Biological effects from low doses and dose rates of ionizing radiation: science in the service of protecting humans, a synopsis. *Health Phys.* 2018;114(6):623-626.
104. Feinendegen LE, Pollycove M, Neumann RD. Hormesis by low dose radiation effects: low-dose cancer risk modeling must recognize up-regulation of protection. In: Baum RP, ed. *Therapeutic Nuclear Medicine*. Berlin, Heidelberg: Springer; 2012:789-805.
105. Pollycove M. Radiobiological basis of low-dose irradiation in prevention and therapy of cancer. *Dose Response.* 2006;5(1):26-38.
106. Pollycove M, Feinendegen LE. Radiation-induced versus endogenous DNA damage: possible effect of inducible protective responses in mitigating endogenous damage. *Human Exp Toxicol.* 2003;22(6):290-306.
107. Feinendegen LE, Pollycove M. Biologic responses to low doses of ionizing radiation: detriment versus hormesis, part 1: dose responses of cells and tissues. *J Nucl Med.* 2001;42(7):18N-27N.
108. Pollycove M, Feinendegen LE. Biologic responses to low doses of ionizing radiation: detriment versus hormesis, part 2: dose responses of organisms. *J Nucl Med.* 2001;42(9):26N-37N.
109. Feinendegen LE, Loken MK, Booz J, Muhlenstepen H, Sondhaus CA, Bond VP. Cellular mechanisms of protection and repair induced by radiation exposure and their consequences for cell system responses. *Stem Cells.* 1995;13(suppl 1):7-20.70.
110. Lobrich M, Rief N, Kuhne M, et al. In vivo formation and repair of DNA double-strand breaks after computed tomography examinations. *Proc Natl Acad Sci U S A.* 2005;102(25):8984-8989.
111. Calabrese EJ. Flaws in the LNT single-hit model for cancer risk: an historical assessment. *Environ Res.* 2017;158:773-788.
112. Mitchel REJ. Cancer and low dose responses in vivo: implications for radiation protection. *Dose Response.* 2007;5(4):284-291.
113. Bogen KT. Inflammation as a cancer co-initiator: new mechanistic model predicts low/negligible risk at noninflammatory carcinogen doses. *Dose Response.* 2019;17(2):1559325819847834.
114. Doss M. Changing the paradigm of cancer screening, prevention, and treatment. *Dose Response.* 2016;14(4):1559325816680539. eCollection 2016 Oct-Dec.
115. Kojima S, Tsukimoto M, Shimura N, Koga H, Murata A, Takara T. Treatment of cancer and inflammation with low-dose ionizing radiation: three case reports. *Dose Response.* 2017;15(1):1559325817697531.
116. Kojima S, Thukimoto M, Cuttler JM, et al. Recovery from rheumatoid arthritis following 15 months of therapy with low doses of ionizing radiation: a case report. *Dose Response.* 2018;16(3):1559325818784719.
117. Kojima S, Cuttler JM, Shimura N, Koga H, Murata A, Kawashima A. Radon therapy for autoimmune diseases pemphigus

- and diabetes: 2 case reports. *Dose Response*. 2019;17(2):1559325819850984.
118. Kojima S, Cuttler JM, Inoguchi K, et al. Radon therapy is very promising as a primary or an adjuvant treatment for different types of cancers: 4 case reports. *Dose Response*. 2019;17(2):1559325819853163.
 119. Cuttler JM, Moore ER, Hosfeld VD, Nadolski DL. Second update on a patient with alzheimer disease treated by CT scans. *Dose Response*. 2018;16(1):1559325818756461.
 120. Siegel JA, Sacks B, Welsh JS. Time to terminate LNT: radiation regulators should adopt LT. *J Radiol Oncol*. 2017;1(5):49-53.
 121. Siegel JA, Sacks B, Welsh JS. Time to eliminate LNT: The NRC needs to adopt LT and eliminate ALARA. *Nucl Med Biomed Imaging*. 2017;2(3):1-5.
 122. Cohen MD. Reply to dr. andronikou: disavowing the ALARA concept in pediatric imaging. *Pediatr Radiol*. 2017;47(1):116-117.
 123. Oakley PA, Harrison DD, Harrison DE, Haas JW. On “phantom risks” associated with diagnostic ionizing radiation: evidence in support of revising radiography standards and regulations in chiropractic. *J Can Chiropr Assoc*. 2005;49(4):264-269.
 124. Sutou S. Low-dose radiation from A-bombs elongated lifespan and reduced cancer mortality relative to un-irradiated individuals. *Genes Environ*. 2018;40:26.
 125. Cuttler JM. Evidence of dose threshold for radiation-induced leukemia: absorbed dose and uncertainty. *Dose Response*. 2019;17(1):1559325818820973.
 126. Siegel JA, Sacks B. Eliminating use of the linear no-threshold assumption in medical imaging. *J Nucl Med*. 2017;58(6):1014-1015.
 127. Vaiserman AM. Radiation hormesis: historical perspective and implications for low-dose cancer risk assessment. *Dose Response*. 2010;8(2):172-191.
 128. Vaiserman A, Koliada A, Zabuga O, Socol Y. Health impacts of low-dose ionizing radiation: current scientific debates and regulatory issues. *Dose Response*. 2018;16(3):1559325818796331.
 129. Doss M. Radiation doses from radiological imaging do not increase the risk of cancer. *Br J Radiol*. 2014;87(1036):20140085.
 130. Berdon WE, Slovis TL. Where we are since ALARA and the series of articles on CT dose in children and risk of long-term cancers: what has changed? *Pediatr Radiol*. 2002;32(10):699.
 131. Goodman TR, Mustafa A, Rowe E. Pediatric CT radiation exposure: where we were, and where we are now. *Pediatr Radiol*. 2019;49(4):469-478.
 132. Pearce MS, Salotti JA, Little MP, et al. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. *Lancet*. 2012;380(9840):499-505.
 133. Mathews JD, Forsythe AV, Brady Z, et al. Cancer risk in 680,000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians. *BMJ*. 2013;346:f2360.
 134. Miglioretti DL, Johnson E, Williams A, et al. The use of computed tomography in pediatrics and the associated radiation exposure and estimated cancer risk. *JAMA Pediatr*. 2013;167(8):700-707.
 135. Nash CL Jr, Gregg EC, Brown RH, Pillai K. Risks of exposure to X-rays in patients undergoing long-term treatment for scoliosis. *J Bone Joint Surg Am*. 1979;61(3):371-374.
 136. Levy AR, Goldberg MS, Mayo NE, Hanley JA, Poitras B. Reducing the lifetime risk of cancer from spinal radiographs among people with adolescent idiopathic scoliosis. *Spine*. 1996;21(13):1540-1547.
 137. Ronckers CM, Land CE, Miller JS, Stovall M, Lonstein JE, Doody MM. Cancer mortality among women frequently exposed to radiographic examinations for spinal disorders. *Radiat Res*. 2010;174(1):83-90.
 138. Simony A, Hansen EJ, Christensen SB, Carreon LY, Andersen MO. Incidence of cancer in adolescent idiopathic scoliosis patients treated 25 years previously. *Eur Spine J*. 2016;25(10):3366-3370.
 139. Walsh L, Shore R, Auvinen A, Jung T, Wakeford R. Risks from CT scans—what do recent studies tell us? *J Radiol Prot*. 2014;34(1):E1-E5.
 140. Journy N, Rehel JL, Ducou Le Pointe H, et al. Are the studies on cancer risk from CT scans biased by indication? elements of answer from a large-scale cohort study in France. *Br J Cancer*. 2015;112(1):185-193.
 141. Cohen MD. Understanding the problem of a parent’s fear of their child getting cancer from CT scan radiation. *J Pediatr Surg*. 2016;51(7):1222-1227.
 142. Cohen MD. ALARA, image gently and CT-induced cancer. *Pediatr Radiol*. 2015;45(4):465-470.
 143. International Commission on Radiological Protection. *The 2007 recommendations of the International Commission on Radiological Protection: ICRP publication 103*. Ann ICRP; 37:1-332.
 144. Martin CJ. Effective dose: how should it be applied to medical exposures? *Br J Radiol*. 2007;80(956):639-647.
 145. Martin CJ. The application of effective dose to medical exposures [Published online of print October 20, 2007]. *Radiat Prot Dosimetry*. 2008;128(1):1-4.
 146. Samei E, Tian X, Paul Segars W, Frush DP. Radiation risk index for pediatric CT: a patient-derived metric. *Pediatr Radiol*. 2017;47(13):1737-1744.
 147. Rehani MM. I am confused about the cancer risks associated with CT: how can we summarize what is currently known? *Am J Radiol*. 2015;205:W2-W3.
 148. Scudder L, Brody AS. CT radiation in kids: How much of a risk, really? *Medscape*. June 5, 2014. <https://www.medscape.com/viewarticle/826119>. Accessed March 25, 2020.
 149. Wijetunga C, Brady Z, Varma DK. Responsible use of advanced imaging technology. how well are risks and benefits of radiation recognised? *Injury*. 2018;49(5):883-884.
 150. O’Connell NE, Cook CE, Wand BM, Ward SP. Clinical guidelines for low back pain: a critical review of consensus and inconsistencies across three major guidelines. *Best Pract Res Clin Rheumatol*. 2016;30(6):968-980.
 151. Oakley PA, Harrison DE. Selective usage of medical practice data, misrepresentations, and omission of conflicting data to support the ‘red flag only’ agenda for chiropractic radiography

- guidelines: a critical review of the Jenkins et al. article: “current evidence for spinal x-ray use in the chiropractic profession.” *Ann of Vertebral Subluxation Res.* 2019;2019(1):141-157. https://www.researchgate.net/publication/336853365_Selective_Use_of_Medical_Practice_Data_Misrepresentations_and_Omission_of_Conflicting_Data_to_Support_the_'red_flag_only'_Agenda_for_Chiropractic_Radiography_Guidelines_A_Critical_Review_of_the_Jenk. Accessed March 25, 2020.
152. Oakley PA, Cuttler JM, Harrison DE. Response to letters from Anderson and Kawchuk et al: X-ray imaging is essential for contemporary chiropractic and manual therapy spinal rehabilitation: radiography increases benefits and reduces risks. *Dose Response.* 2018;16(4):1559325818809584.
153. Goske MJ, Strauss KJ, Coombs LP, et al. Diagnostic reference ranges for pediatric abdominal CT. *Radiology.* 2013;268(1):208-218.
154. Doss M. Pediatric computed tomography scans and cancer risk. *JAMA Pediatr.* 2018;172(11):1099-1100.
155. Harvey HB, Brink JA, Frush DP. Informed consent for radiation risk from CT Is unjustified based on the current scientific evidence. *Radiology.* 2015;275(2):321-325.
156. Marcus CS. Destroying the linear no-threshold basis for radiation regulation: a commentary. *Dose Response.* 2016;14(4):1559325816673491.
157. Siegel JA, Sacks B, Pennington CW, et al. Dose optimization to minimize radiation risk for children undergoing CT and nuclear medicine imaging is misguided and detrimental. *J Nucl Med.* 2017;58(6):865-868.
158. Siegel JA, McCollough CH, Orton CG. Advocating for use of the ALARA principle in the context of medical imaging fails to recognize that the risk is hypothetical and so serves to reinforce patients' fears of radiation. *Med Phys.* 2017;44(1):3-6.