Utilization Strategies for Cumulative Dose Estimates: A Review and Rational Assessment

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Over the past several years, the cancer risks associated with radiation from diagnostic imaging have received increased attention in both the medical literature and the lay press. In the midst of this heightened scrutiny, there has been growing support for the idea of tracking cumulative dose estimates that longitudinally document the accumulated medical radiation exposure of each individual patient. The authors review the current consensus model of radiation-induced carcinogenesis and use this framework to provide a rational assessment of several potential cumulative dose estimate utilization strategies.

Key Words: Cumulative radiation dose, cumulative dose estimates, cumulative dose tracking, radiation dose, radiation dose tracking, ACR Dose Index Registry, CTDI

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As the cancer risks associated with radiation in diagnostic imaging come under increased public scrutiny [1], there is growing support for the idea of tracking cumulative dose estimates (CDEs) [2] that longitudinally document the accumulated medical radiation exposure of each individual patient. However, before we embark on the task of incorporating CDEs into the practice of medicine, we should first come to a more formal and scientifically accurate understanding of what this information truly represents and how it can best be used. For the purposes of this paper, we assume that the considerable logistic and financial barriers to CDE tracking can be overcome. We focus instead on a rational consideration of several proposed CDE utilization strategies to assess which represent genuine opportunities and which are merely pitfalls. Much of the discussion focused on the issue of CDEs has been based on faulty assumptions concerning the nature of the risk associated with diagnostic x-ray exposure, which we will first seek to clarify.

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A BRIEF REVIEW OF STOCHASTIC RISKS AND LINEAR NO-THRESHOLD MODELS

It is important to keep in mind that cancer induction represents just one of many potentially deleterious side effects from ionizing radiation. Deterministic effects are virtually certain to occur with doses exceeding established thresholds and exhibit dose-dependent severity. For example, at a skin dose of 5 Gy, there is near certainty of developing skin erythema, which will be worse at 10 Gy at which point it will be accompanied by additional complications not seen at 5 Gy. Deterministic effects are relatively easier to understand in that they mirror other kinds of "real world" medical complications and do not require elaborate probabilistic equations to detect or predict. However, deterministic effects are the exception rather than the rule in diagnostic radiology and are usually the result of an accident or operator oversight.

The risk for cancer due to radiation exposure in the diagnostic range is stochastic rather than deterministic (Table 1), meaning that only a likelihood of developing or dying from cancer can be estimated using mathematical models developed for this purpose. If a group of patients are irradiated with a dose in the stochastic range, a small fraction will go on to develop cancer due to chance (ie, bad luck), while the vast majority of those irradiated will experience no effects at all. In other words, it is the probability that an effect will occur, not the size of the effect, that is proportional to the insult when modeling a stochastic process. However, such complications are not easily detected on an individual basis because most radiation-induced cancers (apart from leukemia) lie latent for at least two decades, and when they do manifest, they are clinically, radiologically, and patho-

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Table 1. Summary of the characteristics of stochastic risks and deterministic effects of ionizing radiation

	Stochastic Risks	Deterministic Effects
Examples	Leukemia, other cancers	Burns, sterility, neutropenia, cataracts
Relevant dose level	Any	>0.3 Gy
Dose magnitude determines	Probability of cancer	Type and magnitude of injury
Thresholds	None (current consensus)	Each effect has a threshold
Time scale of effect	Generally 20-40 y*	Hours to weeks
Effect of each incremental dose	Independent	Often cumulative
Clinical relevance of dose history	None	Often useful

*Some radiation-induced malignancies (eg, leukemia) can manifest earlier than 20 years.

logically identical to all other cancers and thus cannot be reliably attributed to their cause.

The linear no-threshold (LNT) theory refers to the graph relating the incidence of excess cases of lethal cancer (y) due to a radiation dose (x), which is assumed to be a straight line that passes through the origin. According to a conservative interpretation of the available evidence, there is no threshold: all radiation exposure is assumed to carry some risk for cancer, and thus there are no safe doses, only tolerable levels of risk that must be weighed against the possible benefits of the scan. It is the manifold implications of linearity that are more easily overlooked. A straight line has a constant slope, so a given dose increment produces the same incremental increase in risk for cancer regardless of where it falls along the x axis. The clinical correlate of this is that the 1st CT scan is just as "dangerous" in terms of absolute cancer risk as the 10th or even the "nth" scan [3], assuming the same body part is scanned, using a similar technique, and so on. There is no buildup of sensitivity with increasing dose from repeated CT scans. If there were, the response would not be linear, and all our current LNT-based risk estimates would be worthless.

Figure 1 is derived from the report of the National Academy of Sciences' Seventh Committee on the Biological Effects of Ionizing Radiation (BEIR VII) [4] and shows solid tumor cancer risk as a function of radiation exposure on the basis of epidemiologic data from the Japanese Life Span Study (LSS) fitted to the constraints of the LNT model (ie, a best-fit line passing through the origin). One striking feature of these data is their relatively large error range, easily understood when one considers that the LSS is a retrospective attempt to salvage data from an uncontrolled "experiment" in which the subjects received an instantaneous dose consisting of a mixture of x-rays, γ-rays, neutrons, α particles, and β particles. A great deal of uncertainty arises when applying the BEIR VII risk model to contemporary imaging patients who accrue cumulative dose gradually through many small exposures, the vast majority of which are due to x-rays. Furthermore, the total exposure levels for the most convincing LSS data points lie above 100 mSv, whereas most diagnostic imaging examinations result in acute exposures well below 50 mSv. As a result, risk estimates in this region are derived by extrapolation, introducing more uncertainty.

Although this issue lies beyond the scope of this paper, we concede that cogent scientific arguments can be made both against linearity and for a threshold [5]. However, the LNT theory is not unique in this regard, as most standards of care in medicine derive from consensus opinions or meta-analyses assembled from numerous studies, each of which is flawed and none of which is perfect. For the purposes of this review, we consider that the continued strong support of the last 3 consecutive BEIR committees [4] and the most recent recommendations of the International Commission on Radiological Protection [6] provide sufficient evidence that LNT models are an ethical and transparent interpretation of

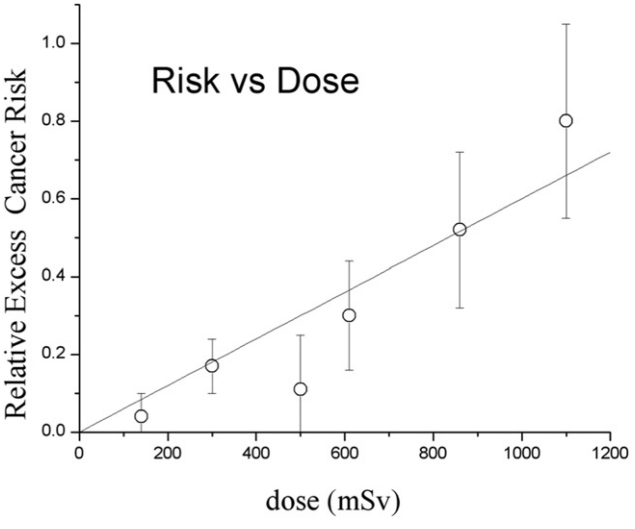

Fig 1. Excess relative risks of solid cancer for Japanese atomic bomb survivors. Plotted points are estimated excess relative risks of solid cancer incidence (averaged over both genders for exposure at age 30 years and surviving to age 60 years). The linear no-threshold model is illustrated using regression analysis to construct a line passing through the origin that best fits these data. The operating region for CT scans and medical x-ray examinations is below 100 mSv, and the risks of radiation exposure in this range are based on extrapolation rather than primary data. Adapted from National Research Council [4].