Radiation Dose Associated With Common Computed Tomography Examinations and the Associated Lifetime Attributable Risk of Cancer

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DOSIMETRY QUANTITIES AND GLOSSARY OF TERMS

When radiation interacts with biological matter, the resulting biological effect depends on the amount of radiation energy absorbed into the material and the type of radiation. Organ dose or organ-specific absorbed dose is defined as the energy imparted per unit mass of an organ or tissue. The "absorbed dose" is measured in grays (Gy), defined as joules per kilogram. The gray replaced the rad (radiation absorbed dose), the traditional unit of absorbed dose, which is equal to 0.01 Gy.

Different types of radiation (eg, alpha, beta, neutron, photon) result in different amounts of biological damage, even when the absorbed doses are the same. The greater the rate at which the radiation transfers energy to tissue, the greater the biological damage. The term *equivalent dose* was introduced to reflect the different biological effects of different radiation types. The equivalent dose is calculated by multiplying "absorbed dose" by "radiation weighting factor." The radiation-weighting factor is unity for the type of radiation (photons) that comes from conventional radiography and computed tomography (CT), and therefore, equivalent dose and absorbed dose are the same for radiation exposure from CT scans. The equivalent dose is measured in sieverts (Sv). The traditional unit of equivalent dose was the roentgen equivalents human (or mammal) (rem) (1 rem=0.01 Sv).

When only a part of the body is exposed (a common situation from medical radiation exposure), the biological damage depends on the exposed organ's sensitivity to that radiation. The International Commission on Radiation Protection (ICRP) introduced the concept of a tissue-weighting factor, which represents the relative contribution of each tissue or organ to the total effects resulting from uniform irradiation of the whole body. Therefore, effective dose is defined as the tissue-weighted sum of the equivalent doses to specified organs and tissues of the body. The effective dose reflects the radiation effects of a nonuniform exposure in terms of an equivalent whole body exposure. Therefore, effective dose can be used to compare radiation exposure across the different types of CT studies and across the different medical study modalities.

Absorbed Dose: The amount of energy absorbed by ionizing radiation in a unit mass of tissue. The unit is the gray, defined as joules per kilogram. The unit of gray can be used for any type of radiation, but it does not describe the biological effects of different types of radiation.

Radiation Weighting Factor: A dimensionless factor by which the organ absorbed dose (rad or gray) is multiplied to obtain a quantity that expresses, on a common scale for all ionizing radiation, the biological damage (rem or sievert) to an exposed person. It is used because some types of radiation, such as alpha particles, are more biologically damaging internally than others. It is used to derive the equivalent dose from the absorbed dose averaged over a tissue or organ.

Equivalent Dose: A quantity used in radiation protection to place all radiation on a common scale for calculating tissue damage. This relates the absorbed dose in human tissue to the effective biological damage of the radiation. Equivalent dose is the absorbed dose in grays times the radiation-weighting factor. The radiation-weighting factor accounts for differences in radiation effects caused by different types of ionizing radiation. Some radiation, including alpha particles, causes a greater amount of damage per unit of absorbed dose than other radiation. The sievert is the unit used to measure equivalent dose.

Tissue Weighting Factor: The factor by which the equivalent dose in a tissue or organ is weighted to represent the relative contribution of that tissue or organ to the total health detriment resulting from uniform irradiation of the body.

Effective Dose: A dosimetry quantity useful for comparing the overall health effects of nonuniform exposure in terms of an equivalent to whole body exposure. It takes into account the absorbed doses received by various organs and tissues and weighs them according to present knowledge of the sensitivity of each organ to radiation. It also accounts for the type of radiation and the potential for each type to inflict biological damage. The unit of effective dose is the sievert.

ESTIMATING EFFECTIVE RADIATION DOSE

Because dose modulation techniques (automatic programs that adjust settings throughout the CT examination to minimize radiation dose) were used on many of the patient scans in our study, technical parameters needed for more detailed dose estimation could not always be
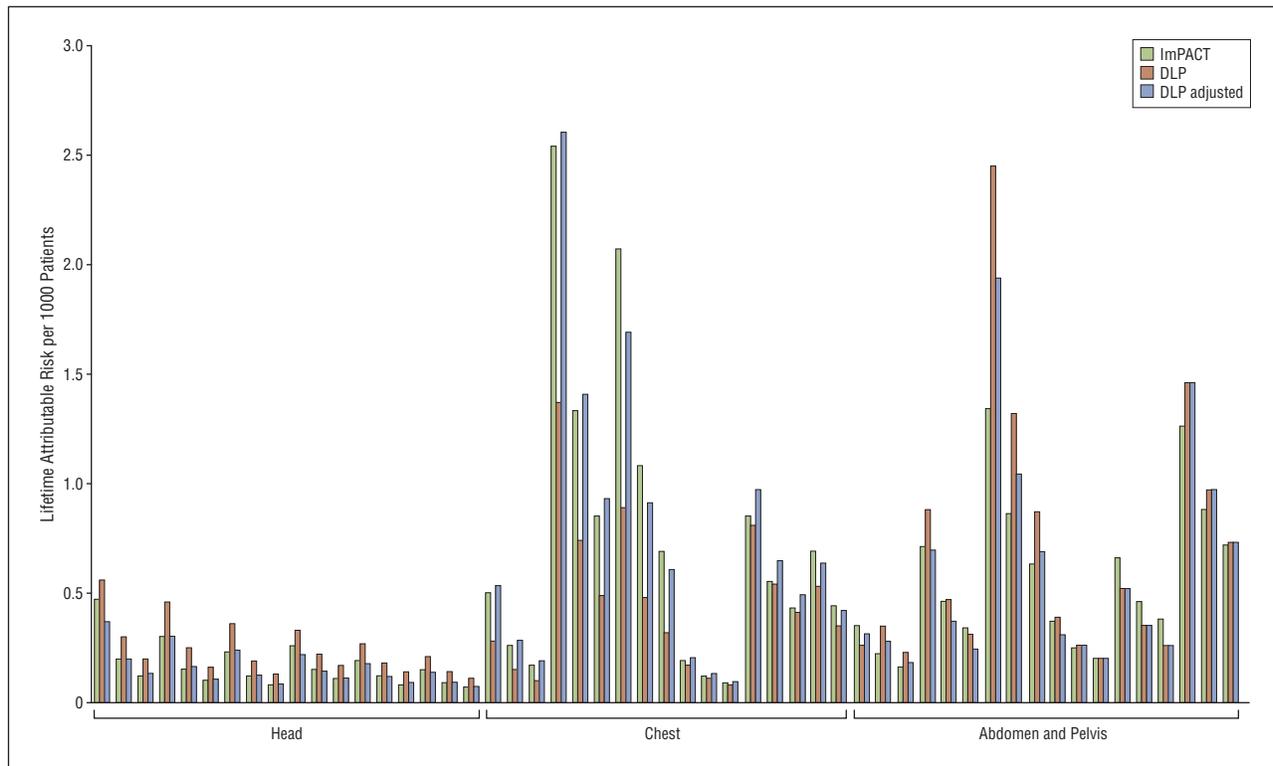
eFigure. Lifetime attributable risk (LAR) of cancer associated with a sample of computed tomographic examinations, estimated using scanner-derived dose-length product (DLP), ImPACT CT dosimetry (computer simulation [ImPACT]), and scanner-derived DLP with adjustment (DLP adjusted).

easily extracted. Our method that relies on dose-length product automatically accounts for the variation in dose due to modulation software. However, for a random subset of 18 patients who had undergone a head, chest, or abdominal CT examination, we compared the dose estimates from our approach to a more detailed approach based on a commercially available computer software program (ImPACT CT Patient Dosimetry Calculator version 0.99x).[17] This involved abstracting dose data within each patient's scan for each set of images that used a similar mAs (milliamperes per second) setting and was thus very time consuming, given the widespread use of dose modulation techniques. Similar to a prior report,[37] we found high levels of agreement in the 2 methods for estimating effective dose (concordance correlation coefficient [r_c] = 0.94; 95% confidence interval [CI], 0.84-0.98).

ESTIMATING LIFETIME ATTRIBUTABLE RISK OF CANCER

We compared 2 methods of estimating the lifetime attributable risks (LARs) of cancer, one based on using total effective dose and the second using organ-specific dose. These 2 methods of assessing the LAR of cancer were compared in a random subset of 18 patients who had undergone a head, chest, or abdominal CT examination, and we estimated the LAR of cancer based on sex and 3 ages

at the time of exposure (ages 20, 40, and 60 years). For each examination, we used the organ-specific radiation doses generated using the ImPACT CT software, combined with the age and organ-specific Biological Effects of Ionizing Radiation (BEIR) VII risk estimates,[7] to generate a LAR for each type of cancer. We then summed the LARs for each individual cancer to calculate the LARs for all cancers. We found moderate levels of concordance between these 2 methods of estimating the LAR of cancer: head (r_c = 0.77; 95% CI, 0.65-0.85), chest (r_c = 0.65; 95% CI, 0.43-0.80), and abdomen (r_c = 0.79; 95% CI, 0.62-0.89). In the head, our method of estimating LAR based on using total effective dose slightly overestimated risk in both men and women; in the chest, our method underestimated risk, especially in women; and in the abdomen, our method overestimated risk in women only (**eFigure**). To improve agreement, we developed an adjustment to our method of estimating LAR. To adjust the LARs, we multiplied the sex-specific mean of the ratio of the organ-specific method to our method (head, 0.66 for women and men; chest, 1.9 for women and 1.2 for men; and abdomen, 0.79 for women and no adjustment for men). The adjusted LAR of cancer showed an even higher degree of agreement with the organ-specific approach in the head (r_c = 0.95; 95% CI, 0.91-0.98), chest (r_c = 0.98; 95% CI, 0.96-0.99), and abdomen (r_c = 0.91; 95% CI, 0.84-0.95) and was used to calculate the LARs of cancer.