APPENDIX-A

Dose-Units and Dose-Levels of Ionizing Radiation

• Part 1. Where Xrays Fit, among a Variety of Ionizing Radiations

Ionizing radiation is radiation with enough energy not only to "kick" electrons out of their normal atomic orbits, but also to endow these liberated electrons with kinetic energy which sets them into high-speed linear travel (details in Gofman 1990, Chapters 20 + 32). Ionizing radiation can be divided into two classes.

• One class begins as photons (xrays, gamma rays), which spend their energy on kicking electrons out of orbit and endowing them with the kinetic energy for high-speed linear travel. As they travel, these high-speed high-energy electrons drop portions of their energy, like small bombs or grenades, upon various molecules in their paths. These energy-deposits do the damage.

• The other class begins as high-speed high-energy particles (such as alpha particles, beta particles, positrons, etc.), which also drop portions of their energy upon various molecules in their paths. Usually, the source of these high-speed high-energy "bullets" is the natural decay of unstable (radioactive) atomic nuclei. Our monograph says little else about this second category, because XRAYS are certainly the main source of exposure from diagnostic and interventional uses of medical radiation. Exposure to alpha-radiation is discussed elsewhere (Gofman 1976 + 1981 + 1994).

• Part 2. The Relatively Reliable Dose-Units: Rad (Centi-Gray) and Roentgen

• Rad abbreviates "radiation absorbed dose." The rad is defined as the following amount of energy deposited by ionizing radiation PER GRAM OF TISSUE:

10^-5 joule. (^ is our sign for exponent.) Or the equivalent:
6.24 * 10^10 KeV. (* is our sign for multiplication.) Or the equivalent:
100 ergs.

In the way that the price of candy is a ratio of dollars per gram, the rad is a ratio of energy per gram. 100 rads means that the ratio rises by 100-fold --- e.g., 100 rads would be 10^-3 joule per gram of tissue, or 6.24 * 10^12 KeV per gram, or 10,000 ergs per gram.

• The milli-rad is one-thousandth of a rad: 0.001 rad or 10^-3 rad.

• Centi-gray (cGy) is a more recent name for rad. The two dose-units are identical. We (and many others) prefer the shorter term. There are 100 centi-grays (or 100 rads) per Gray. Thus a dose of 0.2 Gray (Gy) is the same as 20 rads. A dose of 0.2 milli-gray (mGy) is the same as 20 milli-rads (mrads).

• Roentgen (abbreviated R, or r) is a dose-unit for xrays and gamma rays which, in the energy range of 100 to 3,000 KeV, produces 0.96 rad in tissue (Shapiro 1990, p.48). In other words, rad and roentgen can be considered as nearly equivalent, for most xrays and gamma rays.

<u>Two Billion Photons ... 675 Million Cells</u>

If a gram of tissue has received a dose of 1 rad, from medical xrays with an average energy of

30 KeV per photon, it turns out that about TWO BILLION photons have delivered all of their energy within that gram of tissue (from Gofman 1990, Table 20-C). It also turns out that, on the average, every cell-nucleus in that gram has been traversed 1.33 times by a primary high-speed high-energy electron (Appendix-B, Part 1b). There are an estimated 675 million cell-nuclei, on the average, in a gram of human tissue (Gofman 1990, Chapter 20, Part 2).

• Part 3. The Less Reliable Dose-EQUIVALENT Unit: Rem (Centi-Sievert)

There is little doubt that, at EQUAL rads to the same tissue, some types of ionizing radiation do more damage than other types. Alpha radiation is particularly violent. Thus, it is correct to say that radiations differ in their "Relative Biological Effectiveness" (RBE) --- with "effectiveness" as a euphemism for harmfulness. The type of harmfulness which relates to this book is mutagenic potency. In Chapter 2 (Part 7), we discussed the evidence that, at EQUAL rads, medical xrays are 2 to 4 times more harmful than the high-energy gamma rays of the Hiroshima-Nagasaki bombs. Because of this distinction, we spoke of "bomb rads" and "medical rads" (Chapter 2, Part 7d).

For decades, the differences in RBE have been attributed largely to differences in LET (Linear Energy Transfer) --- which means: Attributed to differences in the average amount of energy lost, by a high-speed high-energy particle, per unit of its track-length (BEIR 1990, p.395). The higher the LET, the higher is the harmfulness. In other words, when the energy-deposits are larger and/or closer to each other, the harmfulness rises. The greater size and closer proximity of these energy "grenades" probably cause damage which is more complex and harder for a cell to repair correctly.

For electrons, the higher is the initial energy, the lower is the Linear Energy Transfer (BEIR 1972, p.215). This is consistent with the observation that lower-energy xrays are more harmful, per rad, than high-energy gamma rays from the Hiroshima-Nagasaki bombs.

• Rem is a dose-unit introduced in the hope of establishing a system to handle RBE. A rem is numerically equal to the absorbed dose in rads, multiplied by a factor equal to the applicable RBE --- with the reference value for RBE being 250 KvP xrays (BEIR 1972, p.216). Thus, if alpha radiation is estimated to be 10-fold more mutagenic per rad than 250 KvP xrays, its RBE for mutagenicity would be 10, and someone exposed to 2 rads of alpha radiation would be said to have received a dose-equivalent of 20 rems. However, if the source does not identify the chosen RBE as 10, the reader is left to wonder. Twenty rems could mean 1 rad at RBE = 20, or 2 rads at RBE = 10, or 4 rads at RBE = 5.

• Centi-sievert (cSv) is a more recent name for rem. There are 100 centi-sieverts (or 100 rems) per Sievert. Thus a dose of 0.2 Sievert (Sv) is the same as 20 rems. A dose of 0.2 milli-sievert (mSv) is the same as 20 milli-rems (mrems).

We must regard these dose-equivalent units as "less reliable" than the rad (or cGy) and the Roentgen, because the RBE values are still so uncertain. It is much easier to measure energy per gram of tissue than to establish the Relative Biological Effectiveness in humans. Moreover, the latter effort must start with reliable dose-measurements, and so it is hardly helped by the failure to make good measurements in routine medical practice.

• Part 4. The Least Reliable Dose-Unit: EFFECTIVE Dose Equivalent

The least reliable of all dose-measurements is reported, in rems or sieverts, as an EFFECTIVE dose-equivalent. The effective dose-equivalent incorporates not only significant assumptions about RBE values, but many additional assumptions. UNSCEAR describes the input as follows (UNSCEAR 1993, p.12/69):

"The various organs and tissues in the body differ in their response to radiation. To allow for this, a further quantity, effective dose, is used. The equivalent dose [in rems or sieverts] in each tissue or organ is multiplied by a tissue weighting factor, and the sum of these products over the whole body is called the effective dose. The effective dose is an indicator of the total detriment due to stochastic effects in the exposed individual and his or her descendants." And what is the input for those "tissue weighting factors"? UNSCEAR explains (1993, p.13/77):

The International Commission on Radiological Protection "takes account of the attributable probability of fatal cancer in different organs, of the additional detriment from non-fatal cancer and hereditary disorders, and of the different latency periods for cancers of different kinds. All these features are included in the selection of weighting factors for converting equivalent dose into effective dose."

The concept of evaluating "total detriment" is attractive. The big problem is the currently poor quality of the evidence required to do it. Because the quantitative evidence, needed for such tissue weighting factors, is thin to really non-existent, we regard the "effective dose equivalent" as a step very likely to introduce needless ERRORS into this field at this time.

• Part 5. Dose-Levels: What is Low ... Moderate ... High?

There are no formal cutting points, on the continuum of dosage, between very low, low, moderate, high, very high. Different analysts in different decades mean different things by such terms. What do WE mean, when we incorporate the phrase "even at very low and moderate doses" into our Hypothesis-2?

First: We Mean Absorbed Organ-Doses

First, we mean absorbed organ-doses, which can be quite a bit lower than the xray dose measured when the beam first touches the skin. The following ratios come from Gofman 1985 (p.404), where the beam quality and other conditions are specified:

Example 1: If the skin receives 1.0 rad of entrance dose from an xray beam, traveling from front to back, the heart may receive an average dose of 0.50 rad. Now: Reverse the direction of the xray beam. If the skin receives 1.0 rad of entrance dose from an xray beam, traveling from back to front, the heart may receive an average dose of about 0.06 rad.

Example 2: Change heart to kidneys. From 1.0 rad of entrance dose, with the xray beam traveling front to back, the kidneys receive an average dose of about 0.07 rad. But reverse the beam, so that it travels back to front, and the kidneys receive an average dose of about 0.75 rad.

Example 3: Change kidneys to breasts. From 1.0 rad of entrance dose, with the beam traveling from front to back, the breasts receive an average dose of about 0.70 rad. Reverse the beam, and they receive about 0.04 rad.

Second: We Mean Accumulated Organ-Dose

The existing evidence is that radiation-induced mutations endure for decades, and probably for the entire subsequent lifespan --- unless the mutated cell dies without reproducing itself. To a good "first approximation," we have to say that carcinogenic and atherogenic mutations accumulate with each additional dose. Therefore, Hypothesis-2 refers to accumulated dosage from medical radiation.

Division of the Dose-Spectrum into Levels

The doses below refer to increments above the accumulated background dose from natural sources. Reminder: Any divisions are arbitrary, and they vary from author to author and vary with the RBE of the radiation.

- Very low-dose accumulated increment: Up to 5 rads to any organ from medical xrays.

- Low-dose accumulated increment: 5 to 10 rads to any organ from medical xrays.

- Moderate-dose accumulated increment: 10 to 50 rads to any organ from medical xrays.

- High-dose accumulated increment: 50 to 200 rads to any organ from medical xrays.

- Very high-dose accumulated increment: Over 200 rads to any organ from medical xrays. Appendix-J discusses the non-atherogenic coronary effects of heart-irradiation by a thousand or more rads.

• Part 6. Possible Leveling and Decline of Dose-Response at High Doses

The evidence from experiments with cells and with animals is that the dose-response, for carcinogenesis and mutagenesis, frequently levels off at high doses and then declines at very high doses (NCRP 1980, p.17; discussion in Gofman 1990, Chapter 23). Such findings are a warning that estimates of risk-per-rad at very low dose-levels probably will be underestimated, if their basis includes much high-dose evidence.

• Part 7. A Contrast: Natural Background Dose vs. Promptly Lethal Dose

The Accumulated Dose from Natural Background Radiation

At sea-level, people accumulate radiation exposure from natural radiation sources at an average rate of about 100 milli-rems or 0.1 rem per year --- about 7.5 rems of whole-body dose by age 75 (excluding the "effective dose equivalent" from radon daughter-products; BEIR 1990, p.18). Natural background dose varies with altitude and other factors. "Natural" radiation, which puts ionization tracks through cell-nuclei, is surely responsible for a share of Inherited Afflictions (Gofman 1998) and Cancer and --- according to the evidence uncovered in this book --- Ischemic Heart Disease.

The Promptly Lethal Whole-Body Dose

The high-speed high-energy particles from ionizing radiation can damage EVERY kind of molecule in their pathways --- not only the genetic molecules. As dose rises, the level of mayhem and chaos rises. For some critical systems, there will be a dose-level at which too many cells become so damaged, in so many ways, that they do not recover quickly enough to perform their essential functions. The person dies promptly --- not from Cancer or Ischemic Heart Disease, but from "acute radiation syndrome." Some of the workers who tried to extinguish the fire at the Chernobyl nuclear power plant, in 1986, died of that syndrome.

For HALF of the humans exposed, promptly-lethal doses have been estimated by the radiation community at around 300 or 400 internal-organ rads, accumulated in one week or less by the whole body (NCRP 1989-b, p.70, p.73). Radiotherapy for Cancer delivers total doses far above 300 or 400 rads, but (a) only a small section of the body is irradiated, and (b) the total dose is delivered in fractions, with time for some recovery between doses.

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