

QUESTION: *Could you please explain the conversion of R to rem; rem to rad air; rad water, rad tissue, rad LiF etc.? Also cite the references to look up the numbers.*

ANSWER: This is a great question, and the answer includes why bones show up on x-rays!

The units roentgens (unit symbol: R), rads (unit symbol: rad), and rems (unit symbol: rem) can be related for x-ray photons and gamma photons, as long as the energy isn't too high (energy greater than 3000 kiloelectronvolts, keV) or too low (less than 10 keV), and, in the case of rems, if there aren't too many of them (say, over a few hundred rems).

The R, rad, and rem are *units* of the physical quantities exposure, absorbed dose, and dose equivalent, respectively.

Exposure in R is defined only for photons in air (not for alpha or beta particles or neutrons in any material, and not for photons in any material other than air). It is the amount of electric charge, that is, ionization, caused by the radiation as it is partially absorbed by the air as it passes through. Thus exposure is the amount or quantity of radiation energy that is deposited as ionization, expressed per unit mass:

Exposure (R) = Electric Charge / Mass

Using a relationship called the Bragg-Gray law, and knowing the radiation absorption properties of materials, one can relate a measurement of exposure in air to the amount of absorbed dose in any material (including air). For air, since it takes 33.97 joules of ionizing energy to liberate a coulomb of charge (or 33.97 eV to liberate an ion pair), then an exposure of one coulomb per kilogram of air produces an absorbed dose of 33.97 joules per kilogram of air. Since $1 \text{ R} = 2.58 \times 10^{-4}$ coulomb per kilogram, then 1 R produces 0.00876 joule per kilogram of air. Since a rad is 0.01 joule per kilogram, this amounts to 0.876 rads in air. This conversion is good for most photon energies.

For materials other than air, the Bragg-Gray law requires an additional correction that depends on the elemental makeup of the material and the energy of the radiation. We're usually interested in rads to parts of people (muscle, fat, bone) or materials that are similar to people (water).

In the old days, people used tables of numbers called *f*-factors, that were simply rads/R for the materials listed above. These can be found in the tables in the back of any edition of Johns and Cunningham's *Introduction to Radiological Physics*, (Johns and Cunningham 1983) or in the *Handbook of Health Physics and Radiological Health* (Shleien et al. 1999). But the *f*-factors are simply the ratios of the *mass-energy absorption coefficients* for the materials in question, available at the NIST web site (<http://physics.nist.gov>) or in the references above, multiplied by 33.97 J/C.

Well, it turns out that muscle and water are pretty similar, but fat is less absorbing than muscle, and bone, at some energies, is very strongly absorbing (over four times greater than air!). The energies at which bone is strongly absorbing are right in the middle of the

diagnostic x-ray imaging range. If you tried to take an x-ray with high-energy radiation, for example, the gamma rays from ^{60}Co , the bones would show up hardly at all.

The two graphs show the dependence of these factors on energy and tissue type.

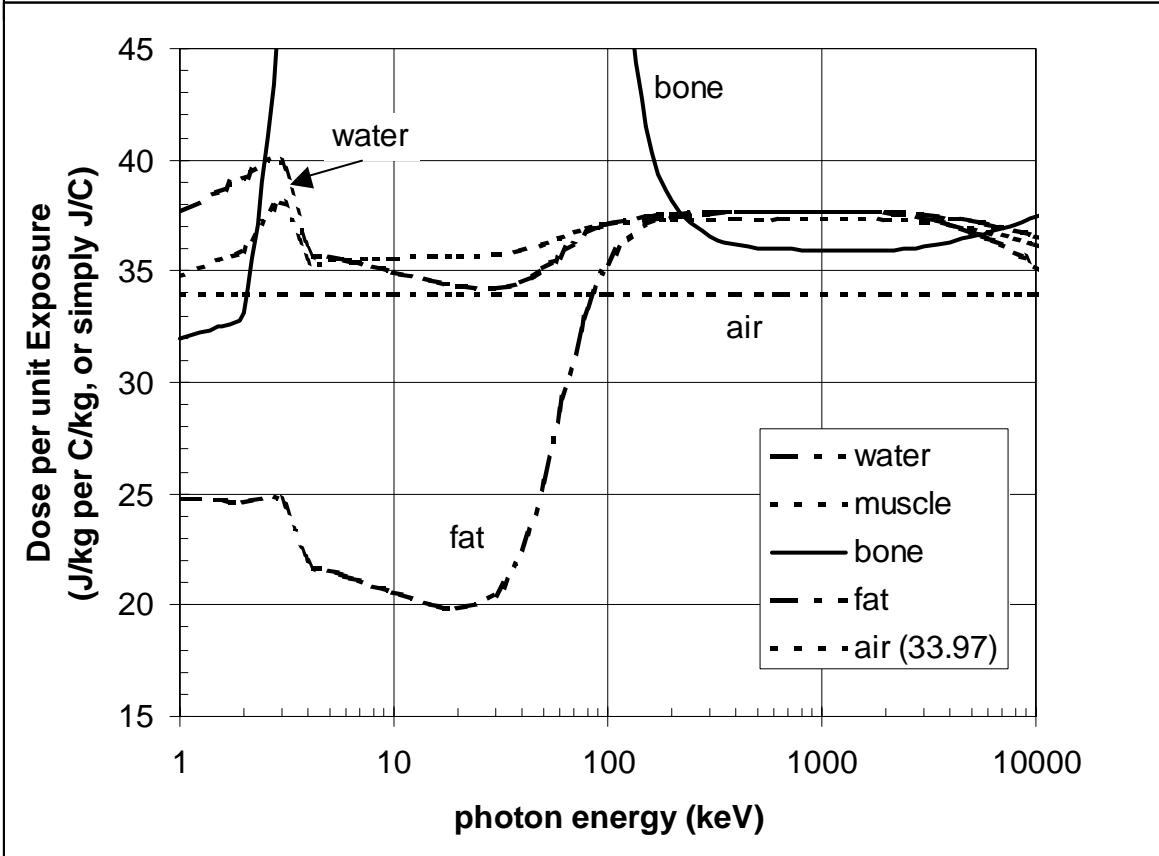
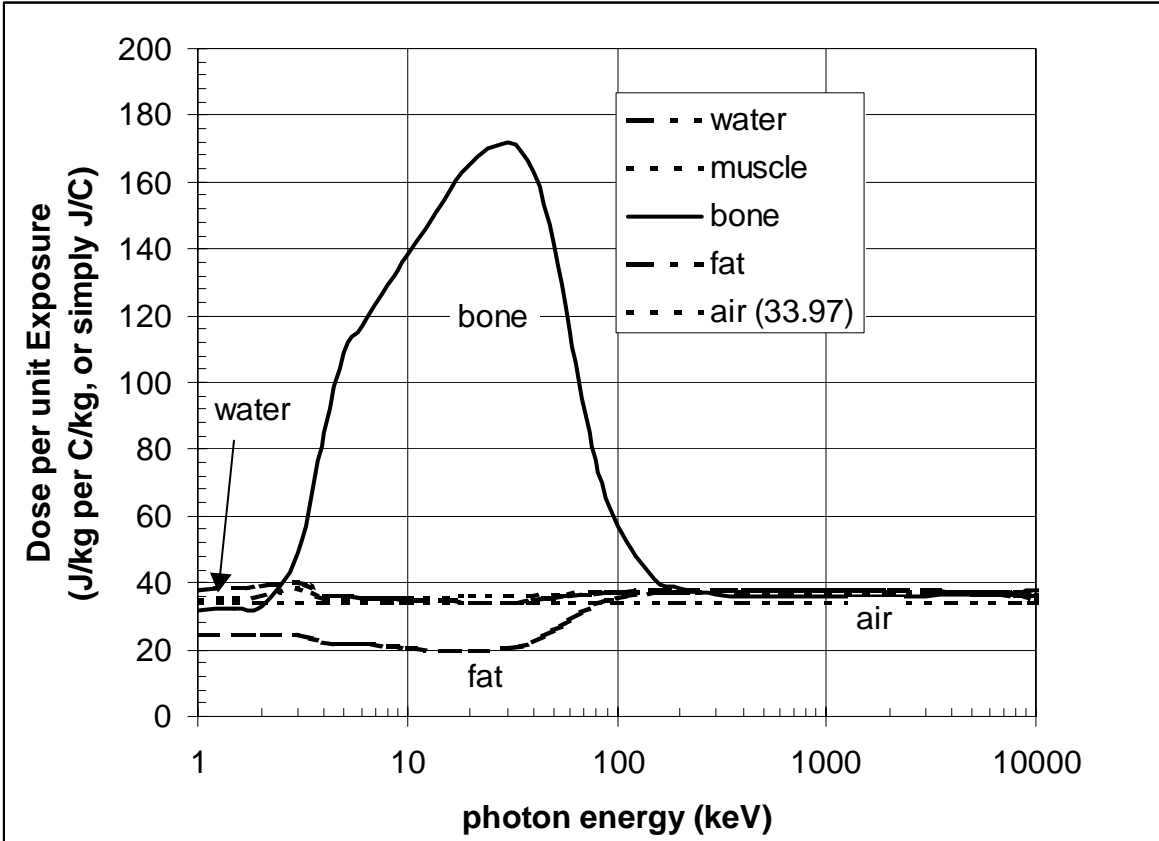
To make a long story short, however, an R in air produces about 0.92 to 0.96 rads in muscle.

To convert from rads in air to rads in LiF, one needs the ratio of the *mass-energy absorption coefficients* for the air and LiF for the energy or energy range of interest.

Converting rads to rems, that is, converting absorbed dose to dose equivalent, depends on the kind of radiation, and sometimes its energy, too. For x-ray and gamma photons, and for electrons (known as beta particles) and positrons, one rad is one rem. For other kinds of radiation, such as alpha particles and neutrons, the absorbed dose in rads must be multiplied by a quality factor Q (more recently, a radiation weighting factor w_R). The values of Q depend on what country one is in, and what regulator one is dealing with. For alphas, Q is generally 20 today. For “fast” neutrons in the USA, Q is usually 10, although it’s 20 in most other countries. For “thermal” neutrons in the USA, Q is usually taken to be 3, although it’s 5 in most other countries. Quality factors are recommended by the ICRP (International Commission on Radiological Protection (ICRP) 1991), the NCRP (National Council on Radiation Protection and Measurements (NCRP) 1993), the ICRU (International Commission on Radiation Units and Measurements (ICRU) 1986). But for regulatory purposes, one must use the factors of the U.S. Nuclear Regulatory Commission (United States Nuclear Regulatory Commission 1978) or the U.S. Department of Energy (U.S. Department of Energy (DOE) 1993), or other regulator.

For quantities and units, the best references are ICRU Reports 51 (International Commission on Radiation Units and Measurements (ICRU) 1993) and 60 (International Commission on Radiation Units and Measurements (ICRU) 1998). For the basic physics, Cember (Cember 1996), Turner (Turner 1995), or Johns & Cunningham (Johns and Cunningham 1983) are all great.

Having said all this, the whole picture is much simpler in international metric units, the SI unit system (<http://physics.nist.gov/cuu>), since 1 J/kg is called a gray (unit symbol: Gy), and the unit of dose equivalent (more recently, equivalent dose) is the sievert (unit symbol: Sv).



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