Radiation Safety

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Introduction

Life on earth depends on electromagnetic radiation. Plants live by converting energy through photosynthesis to grow and thrive and in turn provide food for many of the earth's animals. In our modern age, we depend on radiation-emitting devices, from the sun to our cell phones to radios, from medical imaging technologies to the electricity that powers our homes. In medicine, we derive benefits from many of these radiation-emitting devices, but there are also potential adverse health effects. To effectively explore the health effects of radiation exposure, it is necessary to examine the physics of radiation.

The electromagnetic spectrum is roughly divided into ionizing and nonionizing radiation. The distinction depends on the amount of energy carried by the radiation, which is directly related to the frequency of vibration of the electric and magnetic fields. When the frequency (and hence energy) is high enough, the radiation can separate electrons from atoms, ionizing the material it passes through.

Nonionizing radiation includes ultraviolet, visible, infrared, microwaves, radio, television, and power transmission. Ionizing radiation includes high-energy radiation such as cosmic rays, x-rays, or gamma rays generated by nuclear decay. Ionizing radiation includes several types of subatomic particles such as beta radiation (high-energy electrons) and alpha radiation (helium ions – two protons and two neutrons). Medical x-rays are an example of a common exposure to ionizing radiation used for our benefit. Nuclear radiation is used to generate electricity and cure disease, but is also an important element in military weapons. Nuclear radiation can pose significant risks regarding human exposure and environmental contamination.

History

The turn of the twentieth century marked the beginning of rapid progress in understanding and exploring the power of radiation. This period ushered in a growing appreciation of the potential adverse effects of radiation exposure. In 1903, Marie Curie and Pierre Curie, along with Henri Becquerel, were awarded the Nobel Prize

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in physics for their contributions to understanding radioactivity, including the properties of uranium. The "curie" and the "becquerel" are still used as units of measure in radiation. In 1895, Wilhem Conrad Roentgen discovered x-rays, and in 1901 he was awarded the first Nobel Prize for physics. These discoveries lead to significant advances in medicine. However, by 1911, workers exposed to x-rays and radium (including Marie Curie) were noted to have higher rates than normal of leukemia. In addition, many of those exposed were childless or had children born with significant birth defects.

Once these associations were made, significant challenges were evident in the determination of safe or tolerable radiation dosages. Initial estimates were based on empirical observations. The construction of the Geiger-Muller counter in the 1920s helped quantify radiation intensity but did not edify health-care workers about safe levels of radiation exposure. The first safety standard was based on a measure called the erythema dose (the amount of radiation which would produce reddening of Caucasian skin). At a 1928 meeting in Stockholm, radiologists arbitrarily chose a 0.01 erythema dose per month as the upper limit of exposure. Subsequently, the Committee of Radiation Safety met with commercial manufacturers to define maximal tolerance doses. However, it was not until the United States moved into the era of nuclear weapon development and deployment with the Manhattan Project and the use of nuclear weapons on Japan that scientists were able to more fully assess the short- and long-term health effects of radiation exposure. Even today, exposure limits remain somewhat arbitrary given the low-dose exposure that we receive from naturally occurring radioactivity and cosmic rays [1, 2]. It should be remembered that we evolved with a background exposure to naturally occurring ionizing radiation and we continue to be exposed to low levels of natural background radiation. Some have estimated that 1 in 100 cancers are the result of this background exposure.

Work by Enrico Fermi and others lead to the first sustained nuclear chain reaction in a laboratory beneath the University of Chicago football stadium on December 2, 1942. Subsequently, this knowledge was used to develop the atomic bombs that were dropped on Japan in an effort to end World War II. Much of our understanding of the effects of nuclear radiation exposure has come from the victims in Japan as well as the many workers in uranium mines.

Biologic and Physical Properties

Ionizing Radiation

Ionizing radiation has sufficient energy to produce ion pairs as it passes through matter so that is it frees electrons and leaves the rest of the atoms positively charged such that there is enough energy to remove an electron from an atom. This generates free radicals that will combine with adjacent molecules. The most common free radical generated is produced from water and is a highly reactive hydroxyl radical. Similarly, the ejected free electron is left to alter the structure and activity of adjacent molecules. The energy released is enough to break bonds in DNA leading to significant cellular damage and potential cause cancer. The health effects and dose–response relationship for radiation exposure are well established from human exposures to radiation and from other research. The four main types of ionizing radiation are alpha particles, beta particles (electrons), gamma rays, and x-rays.

Alpha particles are heavyweight and relatively low-energy emissions from the nucleus of radioactive material. The transfer of energy occurs over a very short distance of about 10 cm in air. A piece of paper or layer of skin will stop an alpha particle. The primary hazard occurs in the case of internal exposure to an alpha-emitting material. Cells close to the alpha-particle-emitting material will be damaged. Typical sites of accumulation include bone, kidney, liver, lung, and spleen (see Fig. 7.1).

Beta particles, in contrast, are high-energy, high-speed positrons or electrons that emit ionizing radiation in the form of beta rays. The production of beta particles is termed beta decay. There are two forms of beta decay, β^- and β^+, which respectively give rise to the electron and the positron. Of the three common types of radiation given off by radioactive materials,

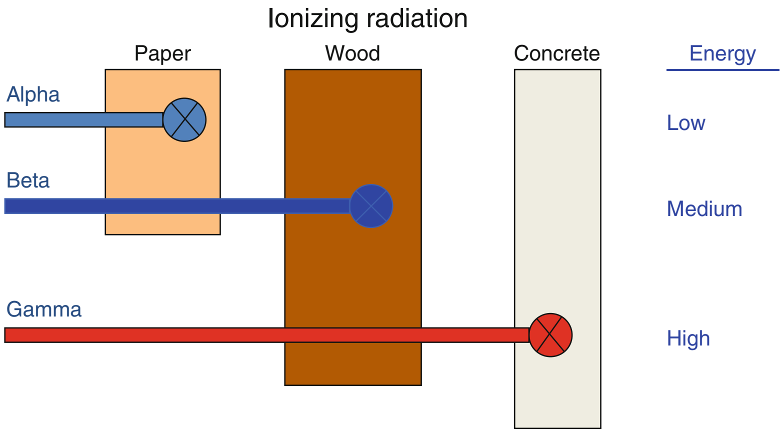

Fig. 7.1 Ionizing energy transmission associated with radiation particles (Adapted from "A Small Dose of Toxicology", with permission)

alpha (Fig. 7.1), beta, and gamma, beta has the medium penetrating power and the medium ionizing power. Although the beta particles given off by different radioactive materials vary in energy, most beta particles can be stopped by a few millimeters of metal such as aluminum or lead. Since it is composed of charged particles, beta radiation is more strongly ionizing than gamma radiation. Beta radiation is used to treat some malignancies, and beta decay is a source of positrons for PET (positron emission tomography) scans where a radiolabeled sugar (fludeoxyglucose) emits positrons that are converted to pairs of gamma rays to localize malignancies since they are typically more metabolically active than other surrounding tissues.

Gamma radiation is a high-frequency, high-energy radiation typically produced by the decay of atomic nuclei in high-energy states such as radium. Unlike alpha and beta particles, gamma rays represent a form of radiation rather than a source of radiation. Gamma rays are distinguished by x-rays by their source of origin; gamma rays are emitted by atomic nuclei, whereas x-rays are emitted by electrons [3]. Protection from gamma rays requires large amounts of mass in contrast to beta and alpha particles. Gamma radiation is used in imaging technologies such as PET scans. Other uses include technetium 99-m that emits gamma rays in the same energy range as diagnostic x-rays. During a technetium 99-m scan, a gamma camera can be used to form an image of the radioisotope's distribution by detecting the gamma radiation emitted.

X-rays are a form of electromagnetic radiation with a wavelength range of 0.01–10 nm with associated energies in the range 100 eV–100 keV. The wavelengths are shorter than those of ultraviolet radiation and typically longer than gamma radiation. X-rays are useful in imaging technology because they can penetrate tissue without significant absorption or scattering. X-ray interaction with matter for the purposes of imaging modalities occurs through photoelectric absorption.

Exposures to ionizing radiation include air travel; this increases our exposure to cosmic and solar radiation that is normally blocked by the atmosphere. Radiation intensity is greater across the poles and at higher altitudes, thus individual exposure varies depending on the route of travel. Storms on the sun can produce solar flares that can release larger amounts of radiation than normal. For the occasional traveler, this radiation exposure is well below recommended limits established by regulatory authorities. However, frequent fliers and airline workers can be exposed to levels of radiation that exceed established guidelines.

Sources of ionizing radiation or exposed populations:

- Medical x-ray devices (patients, health-care employees)
- Radioactive material producing alpha, beta, and gamma radiation (laboratory workers, health-care employees, patients)
- Cosmic rays from the sun and space (air travel)

Radiation Units

The units used to describe exposure and dose of ionizing radiation to living material are confusing, at best. First, the units have changed to an international system, SI (Systeme Internationale). The subsequent description will use the SI system. Different methods exist to measure radiation. The radiation dose that the patient experiences can be measured directly. So, while the fundamental descriptive unit of ionizing radiation is the amount energy, expressed in coulombs or joules per kilogram of air, and is the unit of exposure in air, the absorbed dose is the amount of energy absorbed by a specific material such as the human body and is described as the gray (Gy), previously the rad (radiation absorbed dose). The gray is used to assess absorbed dose in any material. One gray delivers 1 J of energy per kilogram of matter. However, the energy transfer of the different particles and gamma rays is different. A weighting factor is used to allow comparison between these different energy transfers. Further, tissues and organs have different sensitivities to radiation. As a consequence, equivalent and effective dose concepts were developed.

The unit for the equivalent dose is the sievert (Sv). The Sv is used to estimate the stochastic (see below) biologic effect of ionizing radiation on tissue and has an equivalent, effective and committed dose weighted averaging for each biologic tissue. For example, while 1 Sv = 1 J/kg = 1 Gy, the absorbed dose of 1 mGy of alpha radiation would be equal to 20 mSv because of the weighting factors of alpha radiation. A further refinement is possible that applies a weighting factor to each type of tissue. Recommended limits on radiation exposure are expressed in sieverts. Radiation imaging exposure units include milliampere-seconds (MAS).

Air kerma rate is also used to as a radiation unit. Kerma (kinetic energy released in matter) represents the kinetic energy absorbed per unit mass of a small amount of air when it is irradiated. It is associated only with indirectly ionizing radiation and is used as a replacement quantity for absorbed dose when the absorbed dose is difficult to calculate such as in fluoroscopy. Air kerma rate is the rate calculated using (u/p) value for air and is measured in Gy per unit time (Gy/h).

Several derivations on this unit exist including air kerma–area product (Pka) and air kerma at the reference point (Ka,r) [4]. Cumulative dose (CD) represents the air kerma accumulated at a specific point in space relative to the interventional reference point (typically the fluoroscope gantry). This is also referred to as cumulative air kerma. Other units include dose–area product (DAP). This measurement represents the integral of air kerma across the entire x-ray beam emission and serves as a surrogate measurement for the entire amount of energy delivered. DAP is measured in $\mathrm{Gy \cdot cm^2}$.

Health Effects: Ionizing Radiation

Ionizing radiation is more harmful that nonionizing radiation because it has enough energy to remove an electron from an atom and thus directly damage biological material. The energy is enough to damage DNA, which can result in cell death or induce cellular neoplastic change (cancer). The study of ionizing radiation is a large area of classical toxicology, which has produced a tremendous understanding of the dose–response relationship of exposure. The primary effect of ionizing radiation resides in its effect on DNA. It can also affect the developing fetus of mothers exposed during pregnancy. Radiation exposure has a direct dose–response relationship.

Our knowledge of the effects of radiation developed gradually from experience over the last century. Early in the century, researchers such as Marie Curie died of cancer possibly related to her radiation exposure. Occupational exposure has also informed our understanding of radiation exposure risks. Young women employed to paint radium on watch dials died from bone cancer in the 1920s and 1930s [5, 6]. During this time, radium was promoted as a cure of many maladies and even recognized by the American Medical Association as a therapeutic option.

A great deal was learned from the atomic bomb survivors at Nagasaki and Hiroshima. The US military dropped the first atomic bomb on

Hiroshima, Japan, on August 6, 1945, and a second on Nagasaki, Japan, 3 days later. The bombs used two different types of radioactive material, ^{235}U in the first bomb and ^{239}PU in the second. It is estimated that 64,000 people died from the initial blasts and radiation exposure. Approximately 100,000 survivors were enrolled in follow-up studies, which confirmed an increased incidence of cancer. Ionizing radiation was also used to treat disease. From 1905 to 1960, ionizing radiation was used to treat ringworm in children and ankylosing spondylitis as well [7]. Experience with the use and misuse of ionizing radiation has demonstrated that the greater the dose, the greater the likelihood of developing cancer and that latency periods need to be measured in decades (from 10 to 60 years).

Medical Imaging

Medical imaging has become so commonplace in the United States and other resource-rich countries that the medical standard of care necessitates its use. The last two decades have seen the advancement and popularization of new imaging modalities such as magnetic resonance imaging (MRI), positron emission technology (PET) in addition to the standard use of fluoroscopy, and ultrasound technologies. It is a rare patient who has not received any imaging studies. With the widespread use of prenatal ultrasonography, most young people have experienced an imaging study even prior to birth. While ultrasound-imaging technology does not use ionizing radiation, some health concerns exist around its use. The Food and Drug Administration (FDA) has set limits on exposure at 4 T for infants less than 1 month old and 8 T for adults [8].

Nonionizing Modalities

Some modalities like ultrasonography and MRI are not associated with ionizing radiation and so are considered to have low to nonhazardous health risks to humans. The high-magnetic fields used in clinical MRI range up to 3 T. Ultrasonography employs high-frequency sound waves for visualization. The power levels used for imaging are currently believed to be below the threshold to cause short-term or long-term tissue damage.

The long-term effects due to ultrasound exposure at diagnostic intensity are still unknown, but ultrasonography as a diagnostic modality has been used in increasing frequency over the last half century [8]. The ALARA (as low as reasonably achievable) principle has been employed in this field of radiology—to minimize scanning time and power settings as low as possible while still achieving imaging goals. Nonmedical uses are discouraged under this principle as well.

Nonionizing imaging modalities are the imaging modalities of choice for children because of the recognized risks associated with ionizing radiation and cancer mortality [9]. However, ionizing radiation modalities provide diagnostic ease and clarity that cannot be reproduced by nonionizing modalities and where the risk–benefit ratio clearly rests on the side of using the study [10].

Ionizing Modalities

Radiology modalities that involve the use of ionizing radiation include diagnostic fluoroscopy, nuclear medicine imaging, and computerized tomography (CT) [11]. While the use of all these imaging modalities has increased over time, the use of CT in pediatrics has increased particularly rapidly largely because of the advent of helical CT which allows for increased accuracy in imaging over a shorter period of time [9]. This allows one to avoid the need for sedation to produce a useful study. The increase in exposure from ionizing radiation imaging modalities has increased 600 % from 1980 to 2006 (0.54–3 mSv) with medical radiation now accounting for half of the total radiation exposure in the United States. Repeated postnatal exposure of children to ionizing radiation to evaluate scoliosis is associated with increased rates of breast cancer later in life. This has raised concern for increased risk for other malignancies as well [12, 13].

Concern for increased lifetime risk for malignancies secondary to radiation exposure from these modalities was brought to attention in the late 1990s. Cancer risk estimations for children exposed to a CT (using adult radiation exposure doses) were calculated by Brenner who found a 0.18 % (abdominal) and 0.07 % (head) increased lifetime risk for cancer. These percentages were an order of magnitude higher in children than in adults based on the increased lifetime risk-dose exposure. These estimates were derived from cancer risk calculations and mortality data from atomic bomb survivors in Japan. That data demonstrated increased cancer mortality data with doses greater than 100 mSv with decreasing risk for lower radiation exposures [14–18].

Risk Assessment

Radiation risk can be considered in the following categories:

1. Stochastic risk to the individual
2. Stochastic risk to society
3. Deterministic risk to the individual
4. Pregnancy exposure-related risks

Deterministic risks represent radiation-induced tissue damage that manifests itself within days to weeks after exposure. This includes radiodermatitis and radiation-induced skin ulceration. Interventional fluoroscopic procedures represent the most common mechanism for this type of exposure. In particular, complex interventional procedures with prolonged fluoroscopy times increase deterministic risks associated with ionizing radiation exposure. Deterministic effects of tissues such as the skin, lenses of the eyes, and hair follicles are a by-product of damage to supporting tissues and sterilization of stem cells. Tissue damage occurs when the ability of the affected organ to repair itself by cellular division is overwhelmed by the cell loss due to radiation damage. Lethal levels of radiation are used to intentionally kill cancer cells. Consequently, the extent and timing of tissue damage is related to cell proliferation kinetics of the irradiated organs [19]. Deterministic risks are uncommon in general and even more uncommon in pediatrics [20, 21]. Deterministic effects occur at high doses over short exposure times and are usually seen at doses over 0.1 Gy or high-dose rates (0.1 Gy/h).

Stochastic risks represent cancer-induction risks associated with radiation exposure. They are attributable to the aftermath of DNA damage that results in malignant transformation of a cell. These risks are impacted by the tissue exposed, the severity and duration of radiation exposure, latency effects, and genetic susceptibility of the exposed individual [19]. A latency period of years to decades is taken into consideration when calculating the stochastic risks involved in radiation exposure [22]. The consensus of the nuclear industry and many government regulatory agencies is that the incidence of cancers due to ionizing radiation can be modeled linearly with an effective dose (see below) at a rate of 5.5 % per Sv [23]. Individual studies, alternate models, and earlier versions of the industry consensus have produced other risk estimates scattered around this consensus model. The BEIR VII report offers estimates of lifetime attributable to radiation exposure of specific organs [24]. This risk estimate includes cancer-related deaths that would have occurred without exposure but occurred at a younger age than anticipated as a consequence of the exposure. It is important to consider that fluoroscopic procedures do not result in whole-body irradiation so that stochastic risk estimates are better tailored for organ-specific exposures in this instance [4].

Effective dose (E) is a unit developed in an effort to quantitate the stochastic effect of a radiation dose. To calculate this dose, assumptions are made based on age, gender, and health status of the general population. In relation to fluoroscopic procedures, E is usually evaluated using Pka in addition to a procedure-specific coefficient based on Monte Carlo simulations (thermoluminescent-dosimeter measurements in phantoms) (see Fig. 7.2). This has been done for pediatric patients as well [25]. Because of the assumptions built into E calculations, the NCRP currently does not recommend using E for quantitative estimates of stochastic risk for individual patients or patient groups [4].

Consensus agreement exists that infants and children are at increased risk for the stochastic effects of ionizing radiation. As noted above,

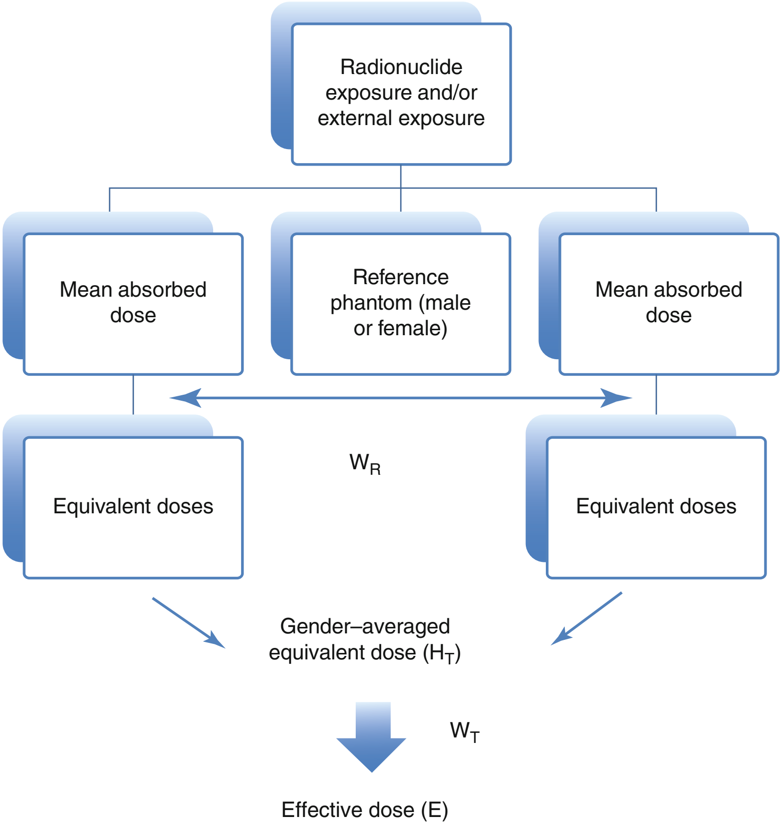

Fig. 7.2 Schematic illustration of the method used to calculate effective dose. W_R radiation weighting factor, W_T tissue weighting factor, H_T tissue weighting factor

Brenner and his colleagues raised awareness of these stochastic risks for a pediatric population by estimating the risks of inducing a fatal cancer from the ionizing radiation exposure of a computerized tomographic (CT) imaging study [9]. In this study, the authors estimated organ-dose exposures as a function of age at diagnosis for common CT examinations and then estimated lifetime cancer risks from this exposure using standard models that assumed a linear risk extrapolation. They arrived at a lifetime risk for cancer mortality for a 1-year-old exposed to a standard CT to be 0.18 % for an abdominal CT and 0.07 % for a head CT. These increased risks were attributable to an increased dose per milliampere-second and the increased lifetime risk per unit dose because of the longer latency period involved in pediatric exposures compared to adults [9].

A subsequent epidemiological study by Pearce and his colleagues of 178,064 children who received an abdominal CT or head CT between 1985 and 2002 demonstrated an increased incidence of leukemias and brain cancers that were remarkably close to the estimates of the Brenner study [26]. These studies have focused on leukemias and brain cancers because of their short latency period from radiation exposure to tumor formation. Studies of the atomic bomb survivors in Japan estimate that lifetime risk estimates for an irradiated population may need to extend 50–60 years [27].

Roughly 85 million CT scans are being performed each year in the United States, and a growing number of these are being performed on children. Several investigators have noted a high frequency of imaging studies ordered for children with an increased frequency of higher radiation exposure studies especially for diagnoses of abdominal pain, headache, and head injury [28]. The utility of imaging modalities of the CT scans due to its image quality and speed remains unsurpassed. Consequently, it is widely used in pediatric trauma situations despite the increased awareness of the long-term effects of the radiation exposure from these studies [29]. Tepper and colleagues found a mean effective ionizing radiation dose of 11.4 mSv for CT scans performed within the first 24 h for pediatric trauma patients in the North Carolina Trauma Registry [30]. In the field of pediatric urology, Page and his coworkers performed a retrospective audit of the radiation doses of patients receiving voiding cystourethrograms and nuclear medicine studies and compared them to CT scans and found the dose exposures to be comparable [31].

Reducing Exposure

In recognition of this trend and in light of increased public awareness of the stochastic risks of ionizing radiation exposure in children, pediatric imaging societies have produced new recommendations to limit ionizing radiation exposure for children from these imaging modalities. These recommendations include (1) increasing education and awareness of stochastic risks among the radiology community, (2) advocating for the use of nonionizing imaging modalities such as ultrasonography when it is an appropriate alternative, and (3) pediatric imaging protocols that reduce radiation exposure without compromising image quality [32–34]. The Image Gently campaign (http://www.pedrad.org/associations/5364/ig/) is among the best known of various efforts to reduce risk with ionizing radiation imaging sources in pediatrics. The leaders of this campaign recently published a list of goals yet to be accomplished [35]. Surveys of physicians and medical students suggest that educational gaps exist. In one survey, 25 % of physicians and 43 % of medical students were unaware that interventional procedures used ionizing radiation. The group surveyed also believed CT scans were associated with the least exposure to ionizing radiation [36].

Regulatory Standards

The first organized effort to protect people from radiation exposure began in 1915 when the British Roentgen Society adopted a resolution to protect people from x-rays.

In 1922, the United States adopted the British protection rules, and various government and nongovernmental groups were formed to protect people from radiation. In 1959, the Federal Radiation Council was formed to advise the president and recommend standards. In 1970, the US Environmental Protection Agency was formed and took over these responsibilities. Now several government agencies are responsible for protecting people from radiation-emitting devices.

Standards for Radiation Exposure

Recommended exposure limits are set by the US National Council on Radiation Protection (NCRP) and worldwide by the International Council on Radiation Protection (ICRP). The occupational exposure guidelines are 100 mSv in 5 years (average, 20 mSv per year) with a limit of 50 mSv in any single year. For the general public, the standard is 1 mSv per year. This must be put in the context of natural background radiation, which is approximately 3 mSv/year depending upon location (such as elevation) as well as other variables.

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