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MODULE 17
IONIZING RADIATION EXPOSURE

Presenter: Capt. Mario E. Fajardo, M.D.
Occupational Medicine Physician
Human Factors Division (G-WKS-3)

Disclosure: Capt. Fajardo does not have any financial arrangements or affiliations with any corporate organizations that might constitute a conflict of interest with regard to this continuing education activity.

Goals:

1. Learn the principles of Ionizing Radiation Exposure.
2. Know the effects of radiation on organ system function.
3. Understand the basis of the clinical evaluation.
4. Learn the management of radiation exposures
5. Understand Radon Exposure

As part of this lecture the reader should become familiar with the following reading material, included as part of this presentation:

Radon Toxicity- case studies in Environmental Medicine from the Agency for Toxic Substances and Disease Registry (ATSDR).

IONIZING RADIATION

Roentgen's discovery of the X ray and Becquerel's recognition of natural reactivity has allowed scientists to understand how radiation is produced and how it interacts with organic matter. Radiation is the transfer of energy though space (distance). This signifies the presence of a space around the source of the radiation that is full of hazardous energy. That is the area where harmful effects would occur without proper protection. This area can be markedly reduced by the use of proper shielding, thus allowing workers to work in close proximity without risk of contamination. The type and quantity of the radiation determines the degree of the effects. There are two types of radiation: low energy (nonionizing) and high energy (ionizing).

Ionizing radiation physically disrupts neutrons by dislodging orbiting electrons that form an ion pair with the residual atom. These chemically reactive ion pairs are capable of producing cellular toxic agents that interfere with life. Nonionizing radiation, on the other hand, does not dislodge electrons and does not impact the integrity of the impacted atom. Ionizing radiation damages tissue directly or by secondary reactions. Ionizing radiation exists as either particles or electromagnetic waves, all of which have different biologic effects. Particulate radiation (e.g. alpha particles, beta particles, protons and neutrons) has detrimental effects. Electromagnetic radiation, on the other hand, consists of electric and magnetic forces moving at the speed of light in consistent patterns of varying wavelengths that make up the electromagnetic spectrum. High-energy short wavelength radiation (e.g., X-rays, gamma rays), like particulate radiation, has the capability of ionizing matter, unlike the longer wavelengths of the electromagnetic spectrum. The latter would include radio waves, microwaves, and infrared (visible and ultraviolet), which are of low energy and thus are nonionizing.

Occasionally accidental release of radiation occurs. Accidents such as the much publicized Three Mile Island in Pennsylvania in 1979 and Chernobyl in the Ukraine in 1986 exposed workers to dangerous levels of radiation. The situation at Chernobyl resulted in over 30 deaths and significant residual radiation in most of Eastern Europe, Asia, parts of Western Europe and the United States. Despite this high-risk occupation, nuclear reactor workers receive routine exposure, which is much less than the exposure received by workers in the medical and industrial settings. Another significant risk of exposure is reported among workers involved in radioactive waste cleanup, disposal and storage. In our setting, sources of ionizing radiation include high-energy diagnostic and therapeutic X-rays, radium and other radioactive materials (radon), nuclear reactors, cyclotrons, linear accelerators and other radioactive sources (cobalt, cesium) used for cancer therapy. Any of these settings has the potential of causing exposure during any of the many activities involved, from the procurement, delivery and recovery of the radioactive substances to the handling of utensils and care of radioactively treated patients.

Units used to measure ionizing radiation reflect the following characteristics: level of energy, decay rate, effect in air, biologic effect and ability to be absorbed by matter. These units are the roentgen, gray and sievert. The **roentgen (R)** is the amount of x or γ ionizing radiation in air. **Gray (Gy)** is the amount of radiation absorbed by tissue. A common multiple of the gray is the milligray (1mGy= 10^{-3}) The **sievert (Sv)** equals the Gy adjusted by a quality factor (Q) to account for the different types of biologic effects induced by the various forms of radiation. The **Relative Biological Effectiveness (RBE)** is a measure of this variability. The **Q** is generally taken as 1 for X-ray, gamma photons and β particles, thus for β, γ, and X radiation, 1 mGy produces 1 mSv. In current nomenclature the Gy and the Sv have replaced the rad and the rem (Gy = 100 rad; Sv = 100 rem). One **rad** is 100 ergs (energy unit) absorbed per gram of any substance. The **rem** (roentgen equivalent in man) is a unit dose equivalent. *NOTE*: The absorbed dose (rad) times the RBE, for any particular type of ionizing radiation, provides a measure of the dose equivalent in rem. Reports of exposures, in the lay press, are expressed as low level (0.2-0.3 Gy) or high level (>0.3 Gy). In the medical community exposures are usually reported as < 0.05 Gy and frequently < 0.01 Gy. The current Ionizing Radiation Occupational Limit is 50mSv/year.

Humans are continuously exposed to radiation from both natural and man-made sources. Decaying radioactive elements from the earth crust can be a significant source of terrestrial radiation.

Radon- *Radon-222, an inert gas, (alpha emitting radionuclide) is one of the products formed during the decay of uranium 238. Radon has a half-life of 3.8 days decaying into several chemically reactive by-products: polonium 218, lead 214, bismuth 214, and polonium 214. Studies of uranium miners indicate that inhalation of radon-222 increases the risk of lung cancer. The carcinogenic effects of radon are attributed to the aforementioned by-products, which in contrast to radon, adhere to respiratory tissue. The bulk of radon enters buildings as a soil gas, though tap water, building products and occasionally natural gas have been cited as additional sources. Radon primarily affects the lower levels of a building with concentrations diminishing at the higher levels. Concerns over radon radiation have risen as a result of estimates indicating that radon level exceeds 8pCi/L (indoor avg. 1.5 pCi/L) in 1-3% of U.S. homes.*

Exposure is affected and modified by altitude and geology. For example, cosmic radiation at sea level is two-fold less than at higher elevations where there is less atmosphere to shield the effects. A greater exposure occurs during airline travel though the exposure time is relatively short making this an insignificant exposure source. Areas with high level of naturally occurring radioactive elements, primarily uranium, include the Rocky Mountains; Kerala, India; coastal regions of Brazil; the northern Nile Delta; and granite rock areas of France. Lowest radiation areas in the U.S. include the sandy soil areas of the Atlantic and the Gulf coastal plains. Other sources of radiation include construction materials such as wood, granite and brick, which contain terrestrial radioactive materials. Contamination from these materials, albeit small, is dependent on the material, room size, ventilation and location. Masonry structures tend to emit higher radiation levels than wood frame buildings.

Additional sources of radiation exposure include fallout from man-made atomic weapons detonations, production of nuclear fuel, nuclear reactors, medical devices and various consumer products. Tobacco represents the consumer product with the greatest radiation hazard, particularly to smokers. Tobacco smoke contains polonium, lead and alpha emitting radon decay products derived from uranium found in phosphate fertilizers. These radioactive products are volatilized when the cigarette is lit entering the lung and depositing tin the bronchial lining. This radioactive exposure is associated with the carcinogenicity of both passive and active smoking. Radiation exposure from medical sources is also a major component of non-naturally occurring radiation. Worldwide medical and dental diagnostic X-ray procedures, radiation therapy and radioactive treatment courses number in the billions. In the U.S. nearly one-half to three quarters of the population is exposed to some form of X-ray radiation. However, in contrast to environmental exposures, medical procedures restrict radiation to limited areas.

Exposure to low-level radiation occurs mostly in the workplace. The most commonly related activities include workers at: nuclear power plants, nuclear powered naval vessels, nuclear industrial facilities involved in the purification, enrichment and fabrication of uranium and workers at nuclear waste storage and disposal facilities. Other high-risk professions include medical technicians, uranium miners, cave guides, radiographers, researchers, miners, and geologists. The general public can be exposed through the release of industrial or mining waste into the air and drinking water. Accidental exposures, as previously mentioned, and release of radioactive material during transport or at storage sites also represent sources of potential public contamination. Exposure can also result from externally applied (irradiation) or internally implanted sources in the management of specific organic disease (thyroid) or in the treatment of certain cancers (bladder/uterus). Regardless of its origin radiation exposure from naturally occurring or man-made sources can be considered a chronic exposure.

Physiologic Effects of Radiation Exposure:

Radioactive materials enter the body through inhalation, ingestion or through skin absorption. Inhalation is the most common route, where depending on particle size, the aerosolized contaminant can pass through the self-cleaning mucociliatory process and deposit deep in the lung tissue. The solubility of the particulate further determines its biologic fate. Insoluble (radionuclide) aerosols may be transferred by macrophages to regional lymph nodes with eventual entry into the circulatory system. The heavier radionuclides (atomic weight) may deposit in bone or liver and remain there for prolonged periods. Radionuclides with the greatest potential for contamination include: cesium-137; plutonium-239; radon-222; strontium-90; tritium; and uranium-238.

The immediate effects of high-level ionizing radiation exposure include cytotoxic changes affecting cellular function or causing cell death. The cytotoxicity varies among cell types and tissues according to the total dose, the dose rate (radiation dose/unit of time), and the distribution of the dose within the body. As the total dose or dose rate increase the probability of measurable effects also increases. In addition, the more rapid the turnover of the cell the greater its sensitivity. Generally, the most sensitive are lymphoid cells followed by the gonads, proliferating bone marrow, bowel, epidermis, hepatic, kidney, endothelial, nerve, bone, muscle and connective tissue cells. On the other hand, muscle cells, neurons, erythrocytes, and polymorphonuclear granulocytes tend to be relatively resistant to the effects of radiation. The effects of radiation may also depend on the amount of body area exposed. Mild clinical symptoms with increased risk of cancer and possible genetic effects are noted in some individuals at 1 Gy. The whole body can probably absorb a non-fatal dose of up to 2 Gy, however, increasing the dose to 4.5 Gy increases mortality by 50 % (LD_{50}). Doses > 6 Gy are almost always fatal. Delivering similar high doses over a long period to a small area of the body, such as done in cancer therapy, can be more easily tolerated. When providing radiation therapy it is prudent to shield the vulnerable areas, so that otherwise fatal high whole-body radiation can be tolerated.

It has been suggested that one of the possible mechanisms of action for radiation toxicity involves the formation of ions which interact with water to create inhibitory toxic chemicals and free radicals which destroy the integrity of the cell protein, DNA and other cellular components. Evidence of the carcinogenic properties of high-level radiation is derived from survivors of the Hiroshima and Nagasaki nuclear explosions in WWII. Leukemia was the first recognized malignancy with a latent period of 2-15 years from nuclear exposure to clinical diagnosis. Other solid tumors appeared later with cancer of the thyroid being most prominent. Increased incidence of multiple myelomas, cancers of the breast, lung, stomach, small intestine, colon and rectum, brain, nervous system, ovary, uterus, urinary tract and salivary glands were also reported. An increased incidence of congenital neurologic birth defects was also noted with the gestational period of 8-15 weeks being the most sensitive. Neurodevelopmental defects were also reported, as was the increased incidence of miscarriages, stillbirths and neonatal deaths. In tissues that undergo continual renewal (bone marrow, gonads) radiation exposure produces a dose-dependent hypoplasia, atrophy and eventually fibrosis. Injured cells with the capability for mitosis may pass through one or two generative cycles producing abnormal progeny.

ACUTE RADIATION SYNDROMES

Acute radiation syndromes include subsyndromes involving the cerebral, gastrointestinal, and hematopoietic systems depending on dose rate, body area and time of exposure.

Cerebral Syndrome- this syndrome is usually a result of high whole-body dose exposure (>30Gy), which is usually fatal. This syndrome consists of three phases: a prodrome of nausea and vomiting; a period of listlessness and drowsiness ranging from apathy to prostration; followed by tremors, convulsions, ataxia and death. The syndrome lasts only from a few hours to days.

Gastrointestinal Syndrome- this is commonly the result of whole-body radiation exposures $\geq$ 4 Gy. Symptoms include intractable nausea, vomiting, and diarrhea leading to severe dehydration and decreased plasma volume with subsequent vascular collapse. This syndrome is a result of tissue necrosis compounded by progressive atrophy of the gastrointestinal mucosa. Bowel necrosis leads to bacteremia and loss of intestinal villi functionality with massive loss of plasma into the intestine. The process may be ameliorated with massive plasma replacement and antibiotics allowing the intestinal epithelium to regenerate and keeping the patient alive. However, hematopoietic failure typically ensues within 2-3 weeks leading to a fatal outcome.

Hematopoietic Syndrome- this syndrome results from whole-body radiation doses of 2-10 Gy. Initially it manifests with anorexia, apathy, nausea and vomiting, which peak at 6-13 hours before subsiding completely within 24-36 hours. During this latent period of apparent recovery there is progressive atrophy of the bone marrow, spleen and lymph nodes that leads to a pancytopenia- within 24-36 hours lymphopenia develops in the peripheral blood, which is followed shortly after by neutropenia and 3-4 weeks later by thrombocytopenia. The mechanism of action is two-fold: the direct killing of radiosensitive cells and inhibition of new cell production. Susceptibility to infection results from a decrease in the circulating levels of granulocytes and lymphocytes, impairment of antibody production, decreased ability for phagocytosis, diminished resistance to bacterial spread and areas of hemorrhaging.

Acute Radiation Illness- this disorder develops in a small proportion of patients after radiation therapy. It begins with prodromal symptoms of a few hours to several days. This prodrome may include nausea, vomiting, anorexia, tachycardia, headache and diarrhea. This may be followed by a latent recovery period of a few days followed by a more severe illness within 2 weeks of the exposure. The higher the radiation exposure and the absorption dose, the shorter the latent period and the more rapid the onset and severe the illness. Symptoms typically subside within a few days.

Local Effects of Radiation Accidents- this may also manifest depending on the type of radiation as well as the strength of the source and the duration of the exposure or contact. Local injuries of the skin, commonly affecting the hands, may appear as swallow injuries or third degree burns depending on the source of the radiation. One should be aware that such lesions might be worse than is initially apparent. The thighs and buttocks are also commonly affected areas, especially in the industrial setting, where radioactive tools may be carried in pants' pockets.

PROGNOSIS

Radiation illness in patients receiving radiation therapy may be easily diagnosed. In these cases the prognosis will depend on the dose, dose rate, and the body distribution. Appropriate tests and procedures, such as bone marrow studies and peripheral hematologic indices may be used to gauge the severity and prognosis of the illness. In the occupational setting where a chronic radiation injury may have been overlooked, the diagnosis and subsequent prognosis may be more difficult. A possible occupational exposure should be sought if the suspicion exists. In workers involved with radiation jobs periodic examinations for cataracts may be appropriate if the eyes are habitually exposed. Chromosomal studies may be performed in order to identify possible radiation induced abnormalities, though some of these potential deficits may have preexisted the exposure or be the result of other causes. Urine should be analyzed for non- γ emitting radionuclides and radon breath analysis can be preformed if the presence of these agents is suspected. Normal hematologic values and lack ob objective clinical findings can be used to reassure workers in the event of an alleged radiation exposure.

MANAGEMENT

Radioactive skin contaminants should be removed immediately using copious water irrigation and special chelating solutions containing ethylenediaminetetraacetic acid (EDTA) and cuts and wounds should be cleaned using vigorous irrigation and debridement until the wound is free of radioactivity. Ingestion of radioactive materials should be removed by inducing vomiting or with gastric lavage. Lugol's solution or saturated solution of potassium iodide may be used for ingestion or inhalation of large quantities of radioiodine. This can be given for days or weeks to block thyroid uptake and promote diuresis.

Treatment for cerebral syndrome is usually palliative since the condition is fatal. One may be called to manage shock and anoxia as well as to relieve pain, anxiety and convulsions. In GI syndrome cases, if the exposure is minimal, the use of antiemetics, sedatives and antibiotics may suffice. A bland diet, if tolerated, fluid, plasma and electrolyte replacement may also be required. For the hematopoietic syndrome careful attention should be paid to the development of lethal infections, hemorrhaging, marrow hypoplasia and pancytopenia. Antibiotics, fresh blood and platelet transfusions are the main therapies. Protective isolation and aseptic care should be instituted to prevent exposure to pathogens. In severe cases a bone marrow transplant should be considered.

In cases of severe chronic exposures removing the affected individual is the first step. If radium, thorium, or radiostrontium are the potential contaminants, prompt administration of oral and parenteral chelating drugs (EDTA) is indicated to increase excretion of these agents. Cancers and radiation-induced ulcers require surgical intervention. Whole blood and platelet transfusions are also useful to prevent bleeding or manage anemia when parameters indicate their need.

REGULATIONS

Radiation protection programs should include source-shielding, limitations on exposure time, increasing the distance between the source and the worker, avoidance of unnecessary exposure, and exposure monitoring by environmental surveillance and personal dosimetry. Federal regulatory agencies involved in the prevention of radiation exposure include OSHA, the FDA, and the NRC. Worker exposure is subject to OSHA standard [62]. The performance of radiation equipment is regulated by the FDA's Center for Radiologic Devices and the NRC regulates the use of certain radionuclides. Individual States also have their own rules and laws pertaining to radiation protection.

Proceed to:

Radon Exposure-cases in environmental Medicine

POST-TEST