Effects of Ionizing Radiation and Their Importance in Anesthesiology

John B. Little, M.D., and Edward P. Radford, Jr., M.D.

As an environmental factor, ionizing radiation is of interest to the anesthesiologist not only for its effects on the patient, which may be of importance in the administration of anesthesia, but also for the hazard that radiation may offer to the anesthesiologist himself. Such hazard might arise from the use of X-ray generators in the operating room, or by accidental contamination with radioactive isotopes. In these instances radiation may become important to all operating room personnel, as well as to the patient himself.

Our plan in this review is to present first a general introduction of the nature and effects of ionizing radiation as encountered in clinical medicine, in order that the anesthesiologist may have a basic understanding to deal with the specific problems that may arise in his practice. The sources and characteristics of ionizing radiation will be reviewed, followed by an outline of its major local and systemic biological effects. Finally, a few situations are discussed in which radiation effects may be of particular importance to the anesthesiologist.

Characteristics and Sources of Ionizing Radiation

General Characteristics. Ionizing radiation may consist of either electromagnetic waves or energetic particles; both are characterized by their ability to penetrate substances and deposit energy in them by means of ionization. It is the ionization of molecules in a tissue which leads to biological damage. As the radiation penetrates and energy is absorbed by the irradiated material, the intensity and the ionizing ability of the radiation beam will be attenuated, generally in proportion to the density of the material. It is the variation in absorption with tissues of differing density that forms the basis for diagnostic radiography; this variation being greatest with radiation energies below 130,000 electron volts (130 Kev). The penetrating ability of different types of radiation in air, soft tissue and lead is shown in table 1.

Radiation quantity is expressed in terms of the energy absorbed. The dose in air is measured in "roentgens," a unit related to the number of ions produced in a cubic centimeter of air by ionizing radiation. Absorbed dose in tissue, however, is measured in "rads" (one rad representing 100 ergs of energy absorbed per gram of tissue). A third unit the "rem," used primarily for protection purposes, takes into account the relative biological effectiveness (RBE) of the specific radiation, as different degrees of biological damage may be produced by the same absorbed dose of different types of radiation (e.g., alpha particles or neutrons in contrast to X-rays). In the energy range of most diagnostic and therapeutic X-rays, one roentgen exposure will result in roughly one rad absorbed dose to soft tissues, and one rad will equal one rem for X-rays.

The absorbed radiation dose in a tissue will depend on four factors: the dose-rate measured in air at a known distance from a radiation source; the duration of exposure; the absorption characteristics of the tissue itself; and finally the absorption which occurs in any tissue or other material between the source and the point of interest. When no absorber is present, radiation intensity and therefore dose-rate will vary inversely as the square of the distance from the source, a factor particularly important in certain aspects of radiation protection. The dose-rate of X-rays in air at 20 cm. distance, for example, will be only 1/4 of that present 10 cm. away from a radiation source. This effect of distance de-
TABLE 1. Penetrating ability of various types of ionizing radiation in air, tissue, and lead. For alpha and beta rays this is expressed as the range of the particle in the material. For gamma and X-rays it is expressed as the thickness of material required to attenuate the beam to 10 per cent of its initial intensity.

<table>
<thead>
<tr>
<th>Radiation</th>
<th>Approximate Penetrating Ability</th>
<th>Air</th>
<th>Tissue</th>
<th>Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha particle (5 MeV)*</td>
<td></td>
<td>4 cm</td>
<td>0.05 mm</td>
<td>—</td>
</tr>
<tr>
<td>Low energy beta particle (0.1 MeV)*</td>
<td></td>
<td>12 cm</td>
<td>0.14 mm</td>
<td>0.01 mm</td>
</tr>
<tr>
<td>High energy beta particle (2.0 MeV)*</td>
<td></td>
<td>8 meters</td>
<td>1.0 cm</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Diagnostic X-rays (90 Kev peak)*</td>
<td></td>
<td>120 meters†</td>
<td>15 cm †</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Conventional therapy X-rays (250 Kev peak)*</td>
<td></td>
<td>240 meters†</td>
<td>30 cm †</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>&quot;Supervoltage&quot; therapy X-rays and high energy gamma rays (1-2 MeV)*</td>
<td></td>
<td>400 meters†</td>
<td>50 cm †</td>
<td>30 mm</td>
</tr>
</tbody>
</table>

* These energy units are: Mev = million electron volts; Kev = thousand electron volts.
† These figures are for a broad radiation beam where increased thickness of absorbing material is necessary due to scattered radiation in the field. Attenuation due to increasing distance from source (inverse square law) has been excluded.

Pends on geometrical factors and applies to any medium through which radiation passes. Whenever absorbing materials are present, there will be a further attenuation.

Usually at least one primary ionization will occur within a cell through which an ionizing ray or particle passes, and some of these ionizing events will lead to cellular damage. An effective ionization may involve either a sensitive macromolecule directly (direct theory of radiation effect), or an adjacent small molecule leading to a rapid chain of chemical events terminating in damage to the sensitive macromolecule (indirect theory). At present there is accumulating evidence that radiation effects are to a great extent indirect, being mediated by free radicals (highly reactive molecules containing unpaired electrons) produced by the ionization of cellular water. The effects observed in tissues arise from damage to macromolecules of many cells (see below). As these changes are initiated by ionizations, the basic effect on biological systems is similar for all types of ionizing radiation varying only in the distribution and degree of damage produced.

Sources. The principal sources of ionizing radiation encountered in medical practice are X-ray generators, and radioactive isotopes including radium. More recently various atomic particles such as electrons, neutrons and protons produced in accelerators, cyclotrons or nuclear reactors have occasionally been used as an external source of therapeutic radiation in situations where a specific penetrating ability is desired that cannot be readily obtained with X-rays.

X-rays are produced by bombarding a metallic "target" with a stream of high speed electrons which have been accelerated by a high voltage across an evacuated tube. (An X-ray tube is similar to a television tube, the latter producing light rays.) When these electrons hit the atoms in the target a portion of their energy is transferred to high energy electromagnetic radiation called X-rays. These rays emanate from the target and may be collimated into a useful beam. X-rays travel in straight lines in air, but can scatter in all directions from or within matter on which they impinge. As is seen in table 1, X-rays of varying energies differ markedly in their penetrating ability both in tissue and lead. The latter is important in radiation protection, for whereas the 0.5 mm layer of lead present in the average lead apron will largely absorb diagnostic X-rays, up to 100 times this thickness of lead would be required to absorb similarly the radiation commonly employed in deep X-ray therapy.

The second source of radiation of concern to the physician arises from radioactive isotopes. These are unstable atoms which undergo spontaneous decomposition or disintegration to a stable form accompanied by the emission of ionizing particles or electromagnetic radiation, the type and energy of emission varying with the individual isotope. Radioactive isotopes may either occur naturally such as those...
of the radium series, or be artificially produced from stable atoms. Due to their varying types and energies of emission, as well as to the different physical forms in which they may be employed, isotopes have found wide use both in diagnostic and therapeutic medicine. Some of these isotopes along with their characteristics and uses are listed in table 2.

Isotopes are inherently more dangerous than X-ray generators in that they may enter directly into the body and be in or near sensitive cells. A radioactive isotope cannot be "tuned off" and will continue to radiate energy until atomic decomposition is complete. As this decomposition or decay occurs in a manner such that a constant fraction of any quantity of an isotope remaining in a sample will decay in a given time period, the rate of decomposition of an isotope is usually specified in terms of its half-life; that is, the time required for a sample to decay to 1/2 of its initial disintegration rate or activity. As is seen in table 2, these half-lives vary markedly with different isotopes. The activity of a sample of radioactive gold-198, for example, will be essentially nil after 30 days, whereas that of carbon-14 will not change significantly over 30 years. Knowledge of the half-life of an isotope is not only necessary in calculating total radiation dose to a patient, but can become very important in dealing with isotopic disposal or contamination. The quantity of an isotope is measured in "curies," a unit defining the number of atomic disintegrations occurring per unit time. Radiation dosage to tissue as a result of these disintegrations is again measured in rads.

The three major types of emission from radioactive isotopes are alpha, beta and gamma rays. Alpha rays are helium nuclei travelling at high speeds. They are densely ionizing particulate radiation, but have very limited penetrating ability in tissue, and therefore are of little concern except when they are actually emitted within the body. Internal alpha emitting isotopes are now rarely used in clinical medicine because of the great hazard they

| Table 2. Characteristics of Some Radioactive Isotopes in Current Medical Use |
|---|---|---|---|---|---|
| Element | Isotope | Half-life | Usual Form | Major Type of Emission | Average Energy of Emission (Mev) | Common Medical Uses |
| Carbon | C¹⁴ | 5,570 yrs. | Solution | Beta | 0.05 | Experimental labelling of organic compounds. |
| Chromium | Cr⁴¹ | 27.8 days | Solution | Gamma | 0.33 | Blood volume determinations. |
| Cobalt | Co⁶⁰ | 5.2 yrs. | Metal | Gamma | 1.2 | Deep external radiotherapy ("cobalt bomb"). Interstitial tumor implants. |
| Gold | Au¹⁹⁸ | 2.7 days | Colloidal solution | Beta | 0.32 | Intraperitoneal injection. |
| Gold | I¹³¹ | 8.1 days | Metal (in platinum sheath) | Gamma | 0.41 | Interstitial tumor implants ("seeds"). |
| Iodine | P⁶⁰ | 14.3 days | Solution | Beta | 0.19 | Thyroid function studies. |
| Iodine | Gamma | 0.36 | Therapy of hyperthyroidism and thyroid carcinoma. Plasma vol. determinations, renal and hepatic function, etc. |
| Radium | Ra²³⁵ | 1,620 yrs. | Encapsulated in platinum | Gamma (Alpha*) | 1.6 | Intravenous for polycythemia vera. Intraperitoneal for effusions. |
| Radon | Rn²²² | 3.82 days | | | | Interstitial and intraaerviary implants. |

* Alpha radiation is completely absorbed by platinum sheath.
present. Beta rays are particulate ionizing radiation consisting of either high speed electrons or positrons. They may penetrate up to around 1 cm. in tissue (table 1). This limited penetrating ability renders them especially useful in situations where intense superficial radiation is desired, as for intrapleural irradiation to control pleural effusions. When beta emitting isotopes are properly handled, their radiation usually offers little hazard to personnel as most beta rays are essentially completely absorbed by overlying tissue or the walls of a glass or metal container. Gamma rays, on the other hand, are very penetrating electromagnetic radiation with the characteristics of X-rays. They vary considerably in energy, depending on the specific isotope (table 2), and isotopes such as radium-226 and cobalt-60 which emit highly energetic gamma rays must be stored in very thick lead shielded containers. The thickness of lead in a lead rubber apron, for example, would have little attenuating effect on the gamma radiation from these isotopes.

A final environmental source of radiation is that arising naturally from the earth, the atmosphere, and from plant and food materials. This is called background radiation, and results mainly from cosmic rays, the naturally occurring heavy isotopes (as radium and uranium), radioactive potassium, and more recently fallout products especially radioactive strontium and cesium. These man-made isotopes at present generally contribute less than 5 per cent of the total dose from background sources.

Comparison of Sources as Environmental Hazards. X-ray generators are a hazard to personnel only while in operation, from exposure either to the X-ray beam or scattered radiation. (Irradiation with X-rays cannot produce changes in a material or tissue such that it in turn can become “radioactive” or emit any sort of ionizing radiation.) Scattered radiation will have roughly 0.1 per cent the intensity of the primary X-ray beam at one meter from the scattering material. With radioactive isotopes, however, the possibility of “contamination” becomes an important factor. Contamination may be either external or internal depending on whether the radiation source is on the outer surface or inside the exposed individual.

As long as an isotope remains in its container, or is within a patient’s body, external contamination of the environment cannot occur. If a solution is accidentally spilled, or a capsule broken, however, the isotope may be picked up on shoes, clothing, the skin, or under fingernails where it will act as a continuing radiation source until it decays or is removed. Furthermore, if significant quantities of an isotope are excreted in a patient’s urine or feces, these will act as a radiation source, and must be handled as such. Both beta and gamma emitters are important hazards in external contamination.

An isotope which is absorbed through the skin, respiratory epithelium or gastrointestinal tract, may act as an internal radiation hazard to the exposed individual. Due to their great penetrating ability, many gamma rays will escape from the body before producing much ionization; therefore, beta and alpha radiation which will be wholly absorbed within the body are usually of greater importance as internal hazards. (Alpha radiation is additionally hazardous due to its greater biological damage produced per unit of energy absorbed.) The degree of hazard will depend on the metabolic fate of the element, as well as the half-life of its isotope. Radium, for example, is a long lived alpha emitting isotope whose gamma radiation arises from its decomposition products. In a radium needle or slug the alpha radiation is wholly absorbed by the platinum sheath in which the radium is encapsulated. Radium salts absorbed into the body, however, will concentrate in bone and will remain for many years acting as a continual source of high energy alpha radiation.

Biological Effects of Radiation

Cellular Effects. Observed changes in irradiated cells include delay and inhibition of mitosis, the latter leading to cell death, and genetic changes such as chromosome aberrations and fragmentation. It is well known that ionizing radiation in vitro may chemically alter molecular structure, and the initial biological damage caused by irradiation probably results from chemical derangement of sensitive macromolecules in the cell. While the specific biochemical pathway by which radiation dam-

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Table 3. Comparison of Radiation Exposure from Various Environmental Sources with Permissible Levels

<table>
<thead>
<tr>
<th>Source</th>
<th>Dose (rem)†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly whole body dose received from background radiation.</td>
<td>0.15</td>
</tr>
<tr>
<td>Average yearly dose (including some background) to anesthesiologists in a large hospital. (No lead aprons or other protective devices employed.)</td>
<td>0.2</td>
</tr>
<tr>
<td>Maximum permissible yearly dose for general population from other than background radiation and medical X-rays.</td>
<td>0.5</td>
</tr>
<tr>
<td>Skin dose to patient from single radiograph (P-A chest—Lat. lumbar spine).</td>
<td>0.02–2.0</td>
</tr>
<tr>
<td>Maximum permissible yearly dose for radiation workers to gonads and blood forming organs.</td>
<td>5.0</td>
</tr>
<tr>
<td>Maximum permissible yearly dose for radiation workers, localized to hands.</td>
<td>75.0</td>
</tr>
<tr>
<td>LD₉₀ dose for whole body exposure in man.</td>
<td>Ca. 500</td>
</tr>
<tr>
<td>Dose to malignant tumor in curative radiotherapy.</td>
<td>5,000–7,000</td>
</tr>
<tr>
<td>Dose to functional thyroid carcinoma metastasis treated with ¹³¹I.</td>
<td>10,000–25,000</td>
</tr>
</tbody>
</table>

* This permissible dose level applies to individuals outside a radiation area and has been recommended primarily to keep the average dose to the whole population as low as reasonably possible. Medical X-rays refer only to those procedures performed specifically on the individual concerned.
† Dose in rems equals absorbed dose in rads multiplied by the RBE (relative biological effectiveness) of the type of radiation to which individual is exposed. (RBE = 1 for most beta, gamma and X-rays, up to about 10 for alpha particles and neutrons.)

age is produced remains uncertain, it appears related to the macromolecule deoxyribonucleic acid (DNA), which is found in the nucleus of the cell and is the constituent of the chromosomes believed to convey genetic information. If cellular death does not occur following irradiation and the cell is able to divide, chromosome abnormalities and mutations may be passed on in subsequent generations. Thus, radiation has two major effects: a direct or somatic effect on cell viability, and a genetic effect on future cell populations. If the gonadal cells of mammals are exposed, genetic changes may be passed on to the subsequent offspring.

From their study of irradiated tissues, Bergonié and Tribondeau in 1966 formulated their well known “law” which states that radiation is more effective in cells with high reproductive activity, with a long dividing future, and in cells whose morphology and functions are less differentiated. This observation that increased radiosensitivity occurred in rapidly dividing undifferentiated cells has held true with few exceptions and has formed the basis for cancer radiotherapy. Of normal tissues, for example, the gastrointestinal tract epithelium, blood forming and reproductive organs whose reproductive activity is great will be relatively sensitive to irradiation.

The effects of radiation will also depend on the volume of tissue irradiated and the duration of irradiation. A small volume of tissue, for example, will tolerate a much larger dose than the whole body (see table 3); and as a certain degree of recovery follows an acute dose of radiation, a greater total dose can be tolerated if given either in increments over a long period of time, or if exposure is continuous but at a low dose-rate. The fact that recovery between exposures appears slightly faster for normal tissues than for cancer cells, has provided the rationale for extended fractionation of radiation dose as it is almost uniformly practiced in clinical radiotherapy.

Effects of Whole Body Irradiation. These effects may be divided into two main groups: first, acute somatic effects observed following high radiation dosage such as might occur with a nuclear reactor accident or with therapeutic whole body irradiation for widespread malignant disease; and, secondly, long-term effects which may result from low doses such as might occur with chronic occupational exposure.

In the acute phase (up to 2 months) fol-
lowing a sub-lethal dose of total body radiation (roughly 100–400 rads) effects produced appear to depend on the ability of radiation to cause cessation of mitosis in dividing cells. The most important manifestations are therefore in tissues undergoing rapid cell division, and the blood forming organs and gastrointestinal tract are the principal organ systems affected. Depression of all blood elements occurs but primarily of platelets and leukocytes. As a result, hemorrhagic tendencies and susceptibility to infection are important acute complications of such systemic irradiation, which are most pronounced in the period from 2–6 weeks following acute radiation exposure. Anemia may be prominent at the higher dose levels. Nausea and vomiting are common symptoms of general radiation sickness in the first few days (see below), but may persist due to the inflammation and ulceration of the epithelium of the gastrointestinal tract occurring with higher exposure.

Long-term effects of acute or chronic systemic irradiation include sterility, cataract formation, life shortening, cancer induction (especially leukemia), and genetic changes in the gonads. Although sterility and perhaps cataract formation may be related to cell death, the remaining effects are probably associated with chromosomal changes in cells modified by radiation exposure. These latter effects are of importance to the anesthesiologist with respect to his personal exposure, as they are observed with radiation dose-rates considerably below those required to produce any acute somatic changes. Nonspecific life shortening has been observed thus far only in animals. This is also true as regards genetic abnormalities in offspring. Genetic changes following chronic exposure in man, however, may eventually prove to be important as they affect the mutation rate in human populations.

Carcinogenesis is a well known effect of occupational radiation exposure above permissible levels, and the carcinogenic effect of radiation in man has been demonstrated for a wide variety of malignant diseases. These include the higher incidence of leukemia in radiologists, lung cancer in uranium mine workers, and osteogenic sarcomas in radium dial painters. It is the possible carcinogenic action of radiation that largely determines the permissible levels of human exposure. In the past it has been generally thought that a threshold dose existed for radiation effects; that is, that radiation in doses below a certain level produced no biological damage of consequence in man. A recent analysis of the occurrence of cancer in children who received prenatal diagnostic X-rays, however, suggests that if such a threshold exists for radiation-induced childhood cancer it must be extremely low (below 1 rad); and in general there is considerable question as to the existence of a threshold dose for radiation-induced genetic changes. If no threshold indeed exists, then any additional exposure above background radiation could be potentially harmful.

Maximum Permissible Radiation Exposure to Man. Because of the increasing evidence that radiation may produce significant effects at low dose levels, maximum permissible doses to individuals occupationally exposed to ionizing radiation from external sources have been recommended by the National Committee on Radiation Protection. These recommendations are published in detail in handbook form by the National Bureau of Standards. The level at which permissible doses are set is somewhat arbitrary, but is based on the concept of an acceptable risk of radiation effects; that is, doses below a certain level are estimated to incur risks which are small compared with other hazards of living. As is seen in table 3, the maximum recommended dose for radiation workers to the whole body, or to the gonads and blood forming organs, is 3 rems per three month period, and an average annual dose not exceeding 5 rem per year. A greater dose to certain localized areas such as the hands is permitted. Provision is also made for emergency doses up to 25 rem beyond the normal occupational limits. For individuals whose employment does not involve radiation, however, maximum permissible doses have been set at 10 per cent of those for radiation workers (table 3).

Effects of Local Irradiation. The somatic effects of radiation exposure to a small volume of tissue are significant because of the high local doses employed in clinical radiotherapy. Many patients undergoing radiotherapy to a particular area will experience some degree of "radiation sickness," a syndrome associated
with acute or chronic radiation exposure and consisting of anorexia, nausea and vomiting, and generalized fatigue and debilitation. These systemic effects of local irradiation are thought to be due to release into the bloodstream of enzymes and toxic molecular breakdown products from irradiated cells. Furthermore, when the radiation field includes significant amounts of bone marrow or intestine, symptoms referable to these systems may arise similar to those observed following acute whole body exposure. Effects observed in the field of irradiation itself will depend on the specific tissues involved, and several particular organ systems are affected by radiation in a manner which may be of specific concern to the anesthesiologist. These include the mucous membranes, lungs and kidneys; the changes in these organs will be discussed in detail in a subsequent section. In general, tissues subjected to intense local irradiation react with congestion, edema and degeneration of cells and intercellular substances, often with the absence of inflammation and cellular reaction commensurate with the degree of tissue necrosis, edema and degenerative changes.

**Radiation Modifiers.** Considerable study has been devoted to systemically administered compounds which alter radiation effects, and extensive lists are available of chemicals including anesthetic agents which produce either protection or sensitization to radiation in animals when employed either just before or during irradiation. Oxygen is perhaps the best known substance which increases tissue radiosensitivity, but an increase in oxygen pressure of several atmospheres in the inspired air is required to significantly enhance tumor oxygenation.

It is well known that anesthesia during whole body irradiation in animals will affect survival. Experience with anesthetic agents given after completion of irradiation, however, is limited, although some recent work suggests that common anesthetic agents, administered up to four weeks following whole body exposure in small animals, may influence radiation mortality. Specifically, cyclopropane and halothane were associated with a low incidence of mortality, and thiopental, sodium and divinyl ether with relatively high mortality.

**Some Specific Problems in Anesthesiology**

The problems that ionizing radiation may pose lie in two main areas: those pertaining to the environmental hazard to the anesthesiologist himself, and those arising from the effects of radiation in his patient. In the latter case we are concerned primarily with the acute somatic effects of radiation, whereas in the first genetic and carcinogenic effects play an important role.

**Radiation as an Environmental Hazard to Personnel.** If proper precautions are taken, it is very unlikely that operating room personnel will be exposed to radiation in excess of the current maximum permissible levels. Recent measurements of radiation exposure over a prolonged period of time to members of anesthesiology departments in three different hospitals showed doses received in all cases to be well within allowable limits (table 3).

Several specific situations exist, however, where care should be exercised. The first involves the use of diagnostic X-rays in the operating room, especially when multiple radiographs are made as in cystoscopy or operative reduction of a hip fracture. The anesthesiologist, who must remain with the patient during exposure, should be aware of the possible hazard to operating room personnel. Obviously, no one should be even partially in the direct radiation beam while a radiograph is being taken. The dose to the patient's skin from a single hip radiograph, for example, will be in the order of 1-2 rads, and a male individual standing three feet behind the patient might receive 25 per cent of this dose to his gonads. Fortunately, the ovaries in the female receive some protection from direct exposure, due to surrounding tissue. Tables of exposure doses from various radiograph examinations are readily available. Individuals who must remain in the room during radiography should keep as far away as possible from the X-ray tube. Use should be made of high speed films to reduce exposure time, and collimators to decrease field size and minimize scattered radiation. A lead rubber apron will provide additional protection against scattered radiation and should be worn whenever possible by individuals who are frequently in-
volved in radiographic procedures. Working behind a special shield is sometimes feasible, and such a shield has recently been designed for operating room use during cystoscopy. As with any piece of electrical equipment, a hazard exists from X-ray equipment near potentially explosive anesthetic agents. Most modern operating room radiographic equipment is "explosion proof."

Fluoroscopy is a potent source of scattered radiation, and its indiscriminate use accounted for much overexposure in the near past when machines generating as much as 25-100 roentgens per minute at the table top were sometimes employed. At the present time, the use of fluoroscopy in the operating room is rarely indicated. All individuals in the room should wear lead aprons, even when image intensification or television monitors are used.

Occasionally the need may arise for an anesthesiologist to be present during some form of external radiation therapy where it would be unsafe to remain in the room with the patient during treatment. Recently a problem of this nature arose in connection with the treatment of brain tumors by neutrons, and an ingenious remote control anesthetic apparatus was devised. With the use of energetic gamma emitting isotopes such as radium-226 or cobalt-60 in intracavitary or interstitial treatment of cancer, the lead shielding required during actual implantation would be so heavy as to be impractical (table 1), and the only protection available is speed in implantation and distance from the source. The average radium implant for carcinoma of the uterine cervix contains about 100 mg. (100 millicuries) of radium. Such a source would provide a dose rate of 0.1 roentgen per hour in air at a point 36 inches from the source, allowing for no absorption in tissue. A very high intensity interstitial implant might contain 60 mg. of radium, although the usual implant such as is currently used for carcinoma of the oral cavity or skin will contain around 10-15 mg. Dose rates in air 36 inches from these sources would be 0.06 roentgen/hour and 0.01-0.015 roentgen/hour, respectively. Since the usual implantation takes considerably less than one hour, and the dose-rate falls off according to the inverse square law as one moves away from the source, it is evident that except under most unusual circumstances the maximum permissible dose is hardly likely to be exceeded for the anesthesiologist. He should not, however, remain close to the patient any longer than is necessary during the postoperative period, particularly if he is frequently associated with radium implants.

The patient containing other gamma and beta emitting isotopes in current clinical usage usually will not act as a significant radiation source to operating room personnel. This situation may well change in the future with the advent of new isotope techniques, such as the use of large amounts of internally administered isotopes to depress the antibody response prior to organ transplantation. For example, the recent experimental use of massive intravenous doses of chelated yttrium-90 for selective destruction of lymphatic tissue in man has produced radiation fields up to 20 rads/hour outside the patient's body. Isotopes used in implantation are employed either in sheathed metallic form (as gold-198) or in sealed containers (as radium or cobalt slugs or needles). As a result they offer no contamination hazard except in the rare event that a sealed source such as a radium needle should be broken. This would allow escape of radioactive radon gas as well as the radium salts themselves. Isotopes used as colloids or in solution (such as radioactive gold, phosphorus and iodine), on the other hand, offer a real contamination hazard if accidentally spilled. Of importance in cases of radioactive contamination is a knowledge of the energy and type of emission of the isotope, as well as its half-life and some idea of the quantity spilled. Isotopic solutions can impregnate clothing and cling to the skin unless very carefully removed, and may easily be transferred to food and cigarettes. If badly contaminated, clothing or shoes must be discarded, or put aside until sufficient isotopic decay has occurred. Any physician involved regularly in the use of radioactive isotopes should be aware of the essentials of decontamination and radioactive waste disposal. He should also be informed about potential hazards arising from any new or experimental isotopic procedures, such as the administration of a radioactive gas which might contaminate the anesthetic apparatus.
IONIZING RADIATION

Radiation Effects in the Patient. The systemic effects of radiation may pose certain problems in the administration of anesthesia irrespective of the source or field of irradiation. Problems in maintaining a proper nutritional status often follow irradiation, and electrolyte imbalance may ensue due to vomiting, diarrhea and inanition.24 In cancer patients, greater anesthetic risk may result from a patient's debilitated state due to a combination of radiation sickness and malignant disease. It has been recommended from studies in animals that light anesthesia balanced with relaxants may be of value in the irradiated human being.22 If leukopenia is present, susceptibility to infection may be high, and in addition any drugs or agents should be avoided which in themselves have a depressant effect on the bone marrow. In general, after a recovery period of 6–8 weeks following either acute or chronic irradiation the systemic factors related to radiation itself should play little role in anesthetic risk. This recovery period is quite likely much shorter in many radiotherapeutic situations involving irradiation of localized areas.

The radiation effects which may be of concern to the anesthesiologist will probably occur following external radiotherapy or accidental whole body exposure. In most instances, such effects do not result from the medical use of isotopes which are employed either in localized regions, or systemically in very low dosage. One exception is radioactive iodine-131. The doses used to treat metastatic thyroid carcinoma are sometimes high enough to result in up to 200 rads or more total body exposure to the patient.23 Radiation sickness, leukopenia and anemia may be observed in such cases.

Acute radiation pneumonitis is a local effect of radiation which could be of importance in the administration of anesthesia due to marked alterations in pulmonary function. This condition may occur if 4,000–5,000 rads are absorbed by a significant mass of lung tissue. It is usually seen 1–4 months after curative external radiation therapy for carcinoma of the breast or lung where it has not been possible to shield adequately normal lung tissue. Severe radiation pneumonitis has also been reported following treatment of pulmonary metastases from thyroid carcinoma with intravenous radioactive iodine-131.23 Acute changes in the lungs are characterized histologically by marked interstitial edema with swelling and destruction of alveolar lining cells. There is deposition of fibrin-like material in the alveoli, which may lead to hyaline membrane formation in severe cases.28 Recently, an associated defect in lung plasminogen activation has been demonstrated.27 Acute radiation pneumonitis may subside after several months with no sequelae, or develop into chronic radiation fibrosis persisting many years after irradiation. In the latter case, changes in the lung consist mainly of fibrosis with loss of effective alveolar membrane.

Pulmonary function studies in patients after both unilateral and bilateral chest irradiation have shown a decrease in lung volumes, associated with an increase in the work of breathing, and an impairment of the diffusing capacity. These changes may develop even before radiographic signs of lung damage.28 There is early reduction of inspiratory capacity, residual volume, and total lung capacity; and maximal breathing capacity is reduced mainly as a result of decreased pulmonary compliance, though increased air-flow resistance is occasionally observed. These changes in lung volumes and in the mechanics of breathing are generally not reversible when the acute stage subsides. Impairment of diffusion of oxygen from the alveoli into the pulmonary capillary bed is an important facet of acute radiation pneumonitis which appears later than the mechanical changes, and usually returns to normal except when severe bilateral fibrosis is present. Other anesthetic complications reported to be associated with radiation pneumonitis are severe coughing, laryngospasm and bronchospasm which are difficult to control and unresponsive to bronchodilatory therapy.29

Radiation nephritis follows acute exposure of the kidneys usually during the course of abdominal radiation, and symptoms develop from several months up to several years after radiotherapy. It will occur frequently if more than 2,500 rads absorbed dose is given to both kidneys in their entirety, and is characterized histologically by diffuse interstitial fibrosis and large numbers of fibrohyaline glomeruli.20, 21 Two biological effects may result: interstitial fibrosis and hypertension. Acute radiation nephritis may manifest itself
as malignant hypertension alone, though more commonly progressive renal failure with uremia occurs. Patients with chronic radiation nephritis, however, may live many years after irradiation. Anesthetic problems would be similar to those present in patients with chronic nephritis and progressive renal failure due to other causes.

Since one of the most common areas of clinical radiotherapy is in the treatment of cancer of the oral cavity, pharynx and larynx, occasionally general anesthesia may be required in a patient during or soon after completion of irradiation to one of these regions. The mucous membranes react to irradiation with congestion, edema and degenerative changes in the epithelium which may lead to ulceration when the radiation reaction is especially severe. These changes render these areas easily traumatized and vulnerable to bleeding, necrosis and secondary infection. Radiation edema of the laryngeal tissues is seen to some degree in most patients receiving cancerocidal irradiation to the glottic region. This glottic edema may persist for several months following therapy, and in extreme cases can lead to acute obstruction. Furthermore, irradiated teeth may loosen or undergo loss of structural strength and be easily broken off; metal fillings will also be easily dislodged from such teeth. All of these factors could present problems during intubation of such patients. The best course of action would be a careful examination of the pharynx and the larynx with the radiotherapist concerned, in order to decide what risks intubation might offer in the individual patient. In the case of oral radium implants requiring general anesthesia during implantation, an agent should be selected which causes minimal postanesthetic nausea and vomiting which might disrupt the implant.

Accidental Whole Body Irradiation and Atomic Disaster. With the increased use of nuclear reactors, accidental exposure to whole body irradiation may become a more frequent occurrence. The problems involved in these accidents are primarily those of the systemic effects of radiation with symptoms depending on the exposure dose. In such cases, however, the medical profession may be faced with the dual problem of dealing both with radiation effects in the individual and radioactive contamination simultaneously. In atomic disaster physical injury will probably be a third factor which may well require emergency surgical intervention. In this event, the anesthesiologist in common with other members of the medical team may be subject to massive contamination both external and internal. It is beyond the scope of this review to discuss the role the anesthesiologist may play in such complex circumstances, but, hopefully, the likelihood of such a possibility is small.

Conclusions

The anesthesiologist should be aware of the fundamental characteristics, sources and biological effects of ionizing radiation, as exposure of both patients and physicians is likely to increase with greater use of diagnostic and therapeutic X-rays and radioactive isotopes. Furthermore, environmental contamination by radioisotopes is becoming increasingly important as a potential hazard to the population in general as well as to hospital personnel.

Acute somatic effects of radiation may be either systemic or local, and generally are observed with high doses. These effects are of concern in patients as they may influence the administration of anesthesia. Systemic changes usually occur during or shortly after a course of radiation treatment and may be modified by some anesthetic agents. In contrast, local tissue effects can occur with delays up to several years in certain organ systems, notably the kidneys and lungs. Only occasionally, however, are either local or systemic radiation effects in the patient likely to be a significant factor in the practice of anesthesiology.

Genetic and carcinogenic effects of radiation may occur with relatively low doses to susceptible tissues, and therefore are of particular importance as regards exposure of the anesthesiologist himself. If proper precautions are carefully observed, however, radiation exposure from sources used in clinical medicine should offer little environmental hazard to the anesthesiologist. He should be informed about potential hazards arising from procedures with which he is regularly associated, particularly those involving radioactive isotopes.
References


General References:

