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Nuclear Accidents and Their Management

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THIS CHAPTER is primarily concerned with the management of accidents resulting from peaceful uses of nuclear energy.

However, any discussion of this topic inevitably stems from and eventually leads to the myriad of problems associated with the management of radiation casualties resulting from a nuclear war. Our present knowledge of this subject stems largely from the military development and use of atomic energy. Although many of the principles discussed in this chapter are applicable to the management of radiation casualties in nuclear warfare, the conditions under which they would be used in wartime defy the imagination.

Not only can the medical profession expect mass casualties (by definition, the number of casualties that overwhelms the capabilities of the medical facility under consideration) but the overriding problem will be the associated blast and burn injuries. In peacetime, the attendant exposure during the treatment of contaminated patients is properly discussed in terms of milliroentgens. However, in wartime this exposure might well shift upwards by an order of three magnitudes (roentgens—R). Not only will fallout cause a general increase in background radiation, but it will also result in more heavily contaminated casualties. The value judgments of the medical profession will change with those of the nation. Benefits versus risk will be determined not by the absolute but by events.

Suffice it to say that the medical problems of nuclear warfare have been deliberated in many fine publications.[1] Coordinated planning on a national scale to effect optimal treatment and survival leave much to be desired. Any improvement in this regard is not foreseeable unless there is a change in public apathy, the imminency, or in direction at the top in most levels of government. Until then, further medical planning will be largely a psychologic diversion and a fearful illusion.

Radiation Accidents

Radiation accidents are unique in their infrequency and complexity. Few physicians and hospitals have had actual experience in the management of these accidents. Few fatalities have occurred.

From the beginning, the United States Atomic Energy Commission has respected the hazard inherent in the accomplishment of its mission and has established an excellent safety record. Between the years 1943 and 1966, there were only seven fatalities resulting from radiation exposure among all its employees. During that same time there were 272 fatalities as a consequence of all other accidental causes.[2]

A few major accidents have occurred in recent years in programs not related

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to AEC. Most have been the result of overexposure to electrically generated sources of x-ray in industrial and research facilities. Though few terminated in fatalities, many were associated with severe morbidity, with months of hospitalization for hematopoietic dyscrasias and radical amputations of necrotic, functionless extremities.[3,4] Between 1957 and 1966, there were five cases reported in which patients received a serious overdose of medically administered isotopes because of miscalculations.[5] Two of these resulted in the acute radiation syndrome, with severe hematopoietic depression.

Ionizing radiation is playing an increasing role in the technology of medicine, industry and research. In medicine alone, the number of isotope administrations has more than quadrupled since 1959. A Public Health Service survey in that year lists 400,000 isotope administrations throughout the United States. In 1966, 1,743,000 doses were given to patients.[6] At the present time, there are 15 nuclear power reactors operating in this country. An estimate calls for 114 nuclear power reactors by 1975. Industrial x-ray units number more than 10,000 and large particle accelerators, more than 1,000.[7] The latter are of particular concern because of their size and use in research, where technique and safety are at times overlooked in the enthusiastic pursuit of knowledge. The widespread distribution of these sources of radiation combined with the production and transportation of sealed and unsealed isotopes and of nuclear fuels means that any hospital, large or small, well-staffed or understaffed, optimally or minimally equipped, could be called upon to treat a radiation accident.

Types of Radiation Accidents

Radiation is basically a form of physical trauma. The instrument of damage is an energy transfer from source to target (patient). The vehicles of this energy are either subatomic particles (electrons, protons, neutrons) or electromagnetic waves. The latter are best depicted as "bundles" of energy which impart a "kick" upon striking matter. Neither the particles nor the electromagnetic waves can be detected by human senses. Either may be electrically generated (x-ray machines, accelerators) or may emanate from the nucleus of unstable isotopes (cobalt, iodine, radium).

The sources of energy may be external to, in contact with, or deposited in the human body.

Radiation accidents are classified according to the source relationship to the patient and the clinical picture. They are:

Radiation Exposure
1. Whole-body—acute radiation syndrome
2. Local—radiation injury

Radiation Contamination
1. Internal—chronic radiation syndrome
2. External—local radiation injury, acute radiation syndrome

Combined

Whole-body exposure is defined as the condition in which the whole body or a major portion thereof has been exposed to a source of radiation apart from and usually not in contact with the body. This is exemplified by the person who

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inadvertently stands in the beam of an x-ray machine or accelerator[4] or a large radioisotopic source.[8] The clinical manifestations when present are those of the acute radiation syndrome.[9,10] The patient himself is neither radioactive nor contaminated. He does not in turn give off radiation any more than a burned patient gives off heat.

In a local exposure, the geometric relation between the source and the patient is the same as above. The difference is in the limited area of the body involved and in the ensuing clinical picture. In most accidents of this type the extremities are the affected area. The clinical picture is characterized by a local radiation injury with signs of erythema, vesiculation, and deep tissue necrosis.[11]

Internal contamination results from the accidental ingestion, inhalation, absorption or injection of radioactive isotopes. Everyone has a small amount of normally present radioactive isotopes, e.g., potassium-40, carbon-14, cesium-137. Except for the miscalculated medically administered isotopes, internally absorbed isotopes have never produced the acute radiation syndrome. If clinical manifestations develop, they are those of long-term effects, e.g., anemia and neoplasia. Though these incorporated isotopes emanate radiation from within the patient, the hazard is to the patient and not to attendants or others in his proximity.

External contamination involves the presence of radioactive isotopes on the body or clothes of a person. This contamination may be as local as a metallic sliver in a finger or as general as a fine powder or liquid spray over the entire body. In an explosion, the patient may have a spray of contaminated metallic pellets embedded in the superficial tissues[12,13] or a large, highly radioactive foreign body penetrating deep into a body cavity. For the patient, contamination poses the twofold hazard of local radiation injury and whole-body exposure. For the attendant, the primary hazard is external exposure, with the patient acting as the carrier of the source. For the medical facility, the hazard is one of secondary contamination. Since radiation cannot be changed or destroyed, the source of it must be removed.

All types of radiation accidents can create a severe demand on the staff and equipment of any hospital. However, the contaminated patient is the most difficult and urgent problem for the unsuspecting or unprepared hospital. It is not only a potential hazard to attendants, but if not handled properly, can result in both functional and economic loss to the hospital. Without prior planning and preparedness, a minor problem could be parlayed into a major disaster.

Effects of Radiation

The three types of radiation seen in contamination are alpha, beta, and gamma radiation. All three originate in the nucleus of contaminating atoms. Alpha and beta are energized particles, while gamma radiation is energy in the form of electromagnetic waves. Upon striking tissue, all three produce an identical physical effect—ionization. Ionization is the removal of one of the orbital electrons. The negatively charged electron and the remaining positively charged atoms produce chemical changes in the associated molecule. Biological damage results when the chemical changes lead to increased cell permeability, enzyme dysfunction, or mitotic inhibition. Overt clinical signs and symptoms appear

when a sufficient number of cells in an organ system are injured. Some organs and tissues are more radiosensitive than others. Bone marrow is one of the most sensitive, muscle, one of the most resistant. In general, rapidly dividing cells are more sensitive than cells which divide infrequently.

The *alpha particle* is a positively charged particle which causes ionization by attracting an electron out of orbit. Because of its size and charge, it dissipates its energy after a very short distance. Alpha is therefore the least penetrating of all radiations. It is effectively stopped by a thin sheet of paper or the cornified layer of the skin. Heavy metals such as plutonium, uranium, and radium are common alpha emitters.

As such, alpha radiation poses no external hazard to the patient or the attendant. However, the presence of alpha particles on the skin, in wounds or in the environment could lead to internal absorption. Heavy metals which emit alpha particles are primarily bone-seekers. In this configuration, the highly charged alpha particle is particularly effective in damaging bone or bone marrow cells. This combined with the long half-life of the isotope results in chronic, latent effects such as fibrosis, anemias, and neoplasia.

The *beta particle* is an energized, negatively charged electron. As this particle passes an atom it causes ionization by repelling electrons out of orbit. The range of effect in air is a few meters and in tissue a few millimeters. Therefore, it has the capability of penetrating through the epidermis and into the dermis. Phosphorus-32 and carbon-14 are pure beta emitters.

Skin effects of beta radiation are a function of the dose, which in turn is a function of the energy of the particle, the amount of contamination, and the length of time the contaminant is in direct contact with the skin. Acute skin effects vary from mild erythema (few hundred rads) to vesiculation and skin necrosis (few thousand rads). Chronic radiation dermatitis and skin carcinogenesis in the human are rare conditions associated with exposures in the thousands of rads delivered over a period of years. Since beta radiation is substantially reduced by rubber gloves and surgical clothing, it is extremely unlikely that acute, much less chronic, effects would occur on the hands of attendants concerned with decontaminating an occasional patient. As a precaution, however, large pieces of contaminated material should be remotely handled with forceps. Like alpha radiation, beta can be particularly damaging when inhaled or ingested. Immediate and well-controlled decontamination is a necessary precautionary measure for both patient and attendant.

Gamma radiation is by far the most penetrating of the three types of contaminating radiation. These "bundles" of energy also interact with atoms to cause ionization. The range of effect in air is hundreds of meters, and in biologic tissue, as much as a few meters. Consequently, gamma radiation will penetrate deep into the body causing ionization in all tissues and organs; thus it is primarily responsible for the *acute radiation syndrome*. The manifestations of this acute radiation disease are a result of the total effect of radiation on all cellular components, particularly hematopoietic, gastrointestinal, endothelial, and central nerve tissue. Most radiocontaminants, particularly fission products, emit both beta and gamma radiation.

Table 1 is a guideline for relating dose and effects. It is useful in *planning*

TABLE 1.—*Dose-effect Guidelines* *

5 rad	No observable effects
25 rad	Blood threshold effects
100 rad	Symptom threshold effects
350 rad	50% lethality
600 rad	100% lethality (approaching)

* Penetrating gamma radiation received within the previous 24 to 48 hours.

an approach to a highly contaminated patient where potential attendant exposure can be measured *before* the fact. It is also helpful in evaluating exposed patients if the exposure conditions and doses are known. This is not always the case. There is nothing magical about the numbers. They must be prudently considered within a context of biologic variation and clinical judgment.

For protection against gamma radiation during the treatment of a highly contaminated patient, the attendant must rely on shielding, time and distance. The amount of shielding required is a function of the dose emitted from the patient and the dose acceptable to the attendant. As a working guide, every attempt should be made to keep the dose to the attendant below 5 rads. In an extreme emergency, exposure to 25 or even 100 rads would be acceptable to save a life. Having to treat patients emitting more than a few R/hr should be a rare event. Shielding (a few centimeters of lead or a few inches of steel), remotely operated devices (long-handled brushes, hoses with spray nozzles), and platoon rotation of attendants should be adequate to meet the 5- to 25-rad exposure criteria encountered in handling contaminated patients under most circumstances.

REGIONAL APPROACH

Since it is economically unsound and virtually impossible for all hospitals to be prepared to manage every conceivable radiation accident, the only reasonable course of action is to develop a regional approach to this problem. This would mean that one medical center would assume the responsibility for the total evaluation and care of any radiation accident. Other hospitals in the region would develop their plans in accordance with their capability, interest and proximity to sources of potential accidents. A closely coordinated regional master plan would ensure that the radiation accident patient receives care in the closest hospital best equipped for his treatment. Individual hospitals would not be responsible for radiation accidents beyond their capability, and mass casualties from an individual accident would be properly distributed according to the work load.

This approach would have a central control point, the medical center, from which the operational aspects of the master plan would be directed. From this center, medical consultation and advice could be sought and radiological emergency teams dispatched. A reliable hot-line communications system connecting all participating parties would be an obvious necessity. A helicopter and ambulance evacuation system, designed specifically to handle contaminated patients, would ensure the expeditious movement of patients within the region. Ideally all public relations affairs, after being coordinated with authorities responsible for the accident, should emanate from the control point.

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Radiation Medicine Center

The development of a radiation medicine center to manage any type of accident is a complicated and costly process. Outside of government installations few of these exist in the United States today. This center must have not only knowledgeable and trained staff, but also very specialized instrumentation, equipment, and facilities. These include a radiosurgery decontamination suite to perform major surgery on contaminated patients, a radiation exposure treatment suite with bone-marrow transplant capabilities and reverse isolation to treat the overexposed patient, and a radiation evaluation laboratory with a whole-body counter to evaluate internal contamination. A list of existing government and civilian radiation medicine centers is seen in Table 2. The details of such a center is beyond the scope of this volume. However, the emergency management of radiation accidents is distinctly the problem of all other hospitals within the region. The chances of any one hospital handling a radiation accident are small. The most severe problem for this hospital would be receiving the radioactively contaminated patient. A likely situation is a transportation accident involving radioactive materials.

Radiation Emergency Plan

The radiation emergency plan for the supporting hospital should be designed for simplicity, developed around existing facilities and equipment, and understood with little training. The requirements of the plan are minimal. They are: (1) identification of the contaminated patient; (2) determination of the extent of the radiation hazard; (3) treatment of the medical condition; (4) call for assistance; (5) decontamination; (6) evacuation of the patient; and (7) confinement of subsequent facility contamination.

It is extremely unlikely that a hospital will unknowingly receive a contaminated patient. All nuclear facilities handling potentially contaminating radioactive materials are identified by law and must have proper markings and emergency plans. All patients from these facilities should be treated as contaminated until proved otherwise. For this the hospital needs some kind of radiation detection instrument. Most x-ray departments have portable radiation detection survey meters. If not, a radiation detector can be obtained from the local civil defense, fire department or police department. All personnel in the emergency room and x-ray department should learn how to use this instrument. This requires about 15 minutes of instruction per year. Slowly passing the probe of the instrument

Table 2.—*Radiation Medicine Centers*

Hospital of the University of Pennsylvania, Philadelphia, Pennsylvania
University of Michigan Hospital, Ann Arbor, Michigan
Presbyterian University Hospital, Pittsburgh, Pennsylvania
Argonne Cancer Hospital, Chicago, Illinois
Hospital of the Medical Research Center, Brookhaven National Laboratory, Upton, Long Island, New York
Donner Pavilion, Cowell Memorial Hospital, Berkeley, California
Oak Ridge Associated Universities Hospital, Oak Ridge, Tennessee
Los Alamos Medical Center, Los Alamos, New Mexico
Kadlec Hospital, Richland, Washington

approximately 6 inches above the patient from head to foot will determine whether a gamma hazard exists for the attendant and the extent of this hazard. Since the instrument reads in roentgens per hour (R/hr), it is a simple matter to determine how long an attendant should be as close as six inches to the patient before he receives a dose of 5, 25, or even 100 roentgens. It is important to remember that radiation intensity falls off rapidly with distance. Anyone standing a few feet or more from the patient receives a small fraction of the 6-inch dose.

As is consonant with good emergency medical care, the contaminated patient should be received in a remote and easily controlled part of the hospital. This could be any area with a separate entrance that requires as little movement of the patient as possible through the hospital. This could include a hospital room or rooms, physical therapy, morgue, conference room, or even a section of the emergency room. The hospital should consider that the area must be able to support an emergency medical capability, will be immediately isolated (roped off) and will remain unusable until a radiological emergency team arrives to decontaminate the area and declare it clean for ordinary use. All unnecessary personnel should be removed from the area, and those entering to treat the patient, as well as all equipment and supplies, should remain until they are checked by the radiological emergency team. It may be a few hours before this team arrives. This is the only way to prevent the spread of even a small amount of contamination throughout the entire hospital. Though this confinement may be an extremely severe restriction, the chances of any one hospital having to treat a contaminated patient are so small as to be infinitesimal. The medical community must continue its responsibility for accepting and treating any emergency. For the supporting hospital, the above approach in the long run is much more simple and economical than establishing a costly, perhaps never used, radiosurgery decontamination suite and time-consuming periodic training programs that disintegrate from disuse.

Having identified the contaminated patient and the degree of contamination, the hospital attendants should immediately turn their attention to emergency medical treatment. The equipment and supplies necessary to handle a radiation accident are seen in Tables 3 and 4. The object of treatment should be resusci-

Table 3.—*Stored Supplies* *

Facility Protection
1. 500 feet of rope
2. "Radiation Area" placards
Patient Evaluation and Treatment
1. Plastic bags, assorted sizes
2. Detergent soap
3. Specimen containers, assorted sizes
4. Paper cups, assorted sizes
5. Identification and information tags
6. Cotton-tipped applicators
7. Cotton balls
8. Hand brushes

* These supplies are easily stored in a foot-locker marked "Radiation Accidents Only." This foot-locker should remain in the area designated to receive an externally contaminated patient.

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TABLE 4.—*Earmarked Supplies and Equipment*

Personnel Protection
1. Surgical scrub suits, masks, booties and hats
2. Lead aprons
3. Surgical gloves
4. Surgical gowns

Patient Handling
1. Hospital gowns
2. Sheets and blankets
3. Restraint straps

Patient Evaluation and Treatment
1. Geiger-Mueller portable survey meter with alpha probe
2. Film badges
3. Pocket dosimeters
4. High-level portable survey meter
5. Hair clipper
6. Bath towels
7. Washcloths
8. Suction machine
9. Anesthesia-dispensing equipment
10. Oxygen
11. Surgical lamp
12. Surgical equipment stand
13. Surgical drapes and towels
14. Surgical instruments
15. Instrument cart
16. Double basin stand
17. Tracheotomy tray
18. Cut-down tray
19. Physical examination equipment
20. Tourniquets
21. Nasal irrigation set
22. Metabolic wound monitor
23. Emergency drug tray
24. Waste disposal pails
25. Intravenous equipment stands
26. Patient transportation cart
27. Saline
28. Sterile water
29. Ophthalmic ointment
30. Neosynephrine 1/4%
31. Bulb syringes
32. Assorted syringes and needles

tation and stabilization procedures to prepare the patient for evacuation to a center equipped to give definitive evaluation and treatment of the radiation injuries. As few attendants as possible to treat and prepare the patient for evacuation should enter the controlled area. Donning the complete surgical scrub suit (gowns, booties, gloves, mask, and hat), they should work next to the patient only as long as necessary to perform emergency procedures. As with operating room technique, all equipment and supplies should be passed through a control point, and once in the area, should remain there until properly monitored and decontaminated by the radiological emergency team.

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Decontamination can proceed simultaneously with medical treatment. In most cases, the removal of all clothing will remove better than 90 per cent of the radiation hazard. This clothing as well as other contaminated material can be placed in plastic bags in a far corner of the control area. The patient is then given a thorough bath with warm water and a detergent soap, e.g., Tide. pHisoHex may also be used. Body orifices, the eyes, and wounds should be flushed with copious amounts of sterile water.

At this point, the hospital has the choice of either holding the patient *in this area* and awaiting the arrival of the radiological emergency team or evacuating the patient to a radiation medicine center. For evacuation the patient is wrapped in a hospital gown, and cocooned in sheets and blankets. A large plastic sheet as an outer covering is also desirable.

Once the patient has left, the hospital is faced with the problem of a contaminated area. For the untrained hospital personnel this is best handled by strict confinement and isolation. The entire area should be roped off; *absolutely nothing* should pass in or out. All personnel who were in the area should immediately and thoroughly shower and put on clean scrub suits. They can then proceed to an adjoining room (part of the control area) and await the arrival of the radiological emergency team. This team will conduct a detailed survey to determine the effectiveness of the initial showering. Though the likelihood that any significant amount of contamination will remain after a shower is extremely small, such personnel should not leave this area until this team has cleared them.

Finally, the radiological emergency team will monitor and survey the entire area and conduct clean-up operations. They are experienced in these matters and will dispose of contaminated material according to federal and state regulations. Usable equipment and supplies will be decontaminated and returned to hospital.

The emergency treatment of radiation accidents not involving external contamination poses no severe problem for a hospital. As discussed earlier, the overexposed patient, the local radiation injury, and the internally contaminated patient are not a hazard to attending personnel. They should be admitted directly to the emergency room and emergency treatment instituted.

The heavily overexposed patient will be extremely apprehensive. He may have severe nausea, vomiting, and diarrhea. Erythema of the skin may be associated with a tingling and burning sensation. Emergency treatment is entirely symptomatic.

Depending on the dose received, within a few days to a few weeks this patient could become severely ill because of complications resulting from intestinal denudation, hematopoietic depression, and central nervous system disturbances. He will be a problem in management of fluid imbalances, infections, and bleeding. The evaluation and treatment of this type of patient is a long, costly, and complicated process. To assist the physician in determining the dose received a physicist is needed who can mock up an accident and laboratory with a radiochemistry, bioassay, and chromosome karyotyping capability. Treatment may include a reverse isolation facility and bone-marrow transplant. Unless a hospital has a particular interest and expertise in these areas, the patients are best evacuated to a radiation medicine center.

The patient with local radiation injury due to overexposure is primarily a problem in long-term management of continuing tissue necrosis. Initial signs and symptoms may be absent or be manifested by erythema and a tingling, burning sensation. Depending on the dose received, this can progress rapidly to swelling, bullous formation, severe pain, and skin breakdown. Emergency treatment is symptomatic with relief of pain and keeping the patient comfortable. Since these cases are usually complicated by associated whole-body exposure, they are best treated at the radiation medicine center.

The management of the internally contaminated patient is an exercise in detailed bioassay evaluation and long-term sophisticated treatment, in many cases with experimental drugs. These patients are usually asymptomatic. They should be transferred to a center equipped to handle them. Treatment is very specific and depends on the metabolic pathway of the isotope involved. On an emergency basis, the hospital first seeing this type of patient should obtain a detailed history to include the information in Table 5. All excreta should be carefully collected and labeled with this information. If tritium is involved or even suspected and the patient's medical condition warrants, the patient should be immediately encouraged to drink large quantities of water up to a maximum of 5 liters per day. If the accident was very recent, cathartics and emetics to enhance elimination from the gastrointestinal tract should be given. If radioactive iodine is involved or suspected, the thyroid gland can be blocked with Lugol's solution. Other contaminating isotopes require qualification and quantification before any treatment is instituted.

Summary and Conclusions

The increasing use of nuclear energy in industry, medicine and research invites the medical profession to take another look at its preparedness to handle radiation accidents. The infrequency of accidents and extensive requirements for definitive evaluation and treatment dictate a regional approach to the problem. A single radiation medicine center with an entire accident treatment capability could support all other hospitals in the region. The latter would concentrate on a primary emergency response. This requires minimal radiation knowledge directed toward alleviating fear and preventing gross error.

Through the immediate employment of basic medical and surgical principles for resuscitation and stabilization and the exercise of respect for the problem of the externally contaminated patient, any hospital with prior planning will be able to communicate quickly with a radiological emergency team and evacuate the radiation casualty to a regional radiation medical center.

Table 5.—*Bioassay Information*

Accident:
Date:
Location: Time:
Type:
Patient:
Name:
Address:
Age:
Isotopes Involved:
Type:
Amount (Estimated):
Chemical Form:
Physical Form:
Sample:
Type and Amount:
Date and Time of Collection:
Remarks:
Requested by: _____

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