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● *Special Feature*

INTRAOPERATIVE ELECTRON BEAM RADIATION THERAPY: TECHNIQUE, DOSIMETRY, AND DOSE SPECIFICATION: REPORT OF TASK FORCE 48 OF THE RADIATION THERAPY COMMITTEE, AMERICAN ASSOCIATION OF PHYSICISTS IN MEDICINE

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Intraoperative radiation therapy (IORT) is a treatment modality whereby a large single dose of radiation is delivered to a surgically open, exposed cancer site. Typically, a beam of megavoltage electrons is directed at an exposed tumor or tumor bed through a specially designed applicator system. In the last few years, IORT facilities have proliferated around the world. The IORT technique and the applicator systems used at these facilities vary greatly in sophistication and design philosophy. The IORT beam characteristics vary for different designs of applicator systems. It is necessary to document the existing techniques of IORT, to detail the dosimetry data required for accurate delivery of the prescribed dose, and to have a uniform method of dose specification for cooperative clinical trials. The specific charge to the task group includes the following: (a) identify the multidisciplinary IORT team, (b) outline special considerations that must be addressed by an IORT program, (c) review currently available IORT techniques, (d) describe dosimetric measurements necessary for accurate delivery of prescribed dose, (e) describe dosimetric measurements necessary in documenting doses to the surrounding normal tissues, (f) recommend quality assurance procedures for IORT, (g) review methods of treatment documentation and verification, and (h) recommend methods of dose specification and recording for cooperative clinical trials.

Radiotherapy, Surgery, Intraoperative care, Electrons, Neoplasms.

INTRODUCTION

Intraoperative radiation therapy (IORT) is a treatment modality in radiation therapy widely used as an adjuvant to surgery and/or fractionated external beam radiation for locally advanced cancers of the abdomen, pelvis, neck, cranium, thorax, and extremities (2–5, 7, 16, 17, 26–32, 38, 44, 52, 55, 57, 58, 61, 60, 63, 65, 66). Intraoperative radiation therapy involves the delivery of a single large radiation dose to the exposed tumor at the time of surgical exploration or to the bed of a resected tumor. As a multidisciplinary procedure, it requires a well-coordinated team approach by anesthesia, surgery, and radiation therapy staffs (10). All personnel involved in the procedure should be made intimately familiar with each aspect of the operation, which may require many dry runs and reviews of written procedures before an IORT program is started. In the last few years, IORT facilities have proliferated around the world, but the number of facilities in the United States has decreased. The IORT techniques used at these facilities vary greatly in sophistication and design philosophy (8, 14, 21, 25, 35, 39, 40, 46, 51, 53, 54). Intraoperative radiation therapy is a labor-intensive modality requiring significant amounts of preparation time

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and use of clinical resources. For example, the physicist needs to commission IORT applicators at all available energies before they are needed clinically. It can take hours of beam-on time to measure the required beam parameters. Many more hours are required to summarize the dosimetry data so that they can be readily used in the operating room (OR).

A thorough understanding of the technical aspects of IORT is essential to realize the full potential of this treatment modality (15, 18, 47, 48). The clinical circumstances of IORT are unique compared with conventional radiation therapy in that the treatment is a single fraction, and very little is known about the target volume that needs to be treated until immediately before the actual treatment.

This report specifically addresses the technical and dosimetric aspects of IORT with megavoltage electron beams. Electron beams are universally accepted as the standard modality for IORT, though orthovoltage x-ray beams have been used (56). A comprehensive overview of the physical aspects of IORT, the role and responsibilities of each IORT team member, and the major considerations in designing a facility for IORT is presented. Dosimetric parameters and guidelines for the delivery and documentation of the procedure are defined. Additionally, the quality assurance requirements and dose specifications for reporting are outlined.

Background of IORT

The first documented use of IORT dates back to 1909, fewer than 20 years after the discovery of x-rays (12, 23). The rationale for IORT was that radiosensitive normal tissues could be excluded from the treatment volume and that an improved therapeutic ratio of local control to major complications could be achieved for deep-seated tumors, which could not be adequately treated with then-available x-ray beams of limited penetration. The interest in IORT waned with the introduction of megavoltage x-rays for radiation therapy in the 1950s. The x-ray beams from these machines could deliver high doses of radiation to deep-seated tumors without the necessity of surgical exposure and without the limitation of skin-dose tolerance.

Renewed interest in IORT began in the 1960s with Abe *et al.* (1–3), who rationalized that IORT offered a definite advantage compared with conventional megavoltage radiation therapy for tumors adjacent to critical radiosensitive structures. In addition, cancericidal doses of radiation could be delivered at the time of surgery to the potential areas of local microscopic spread. Consequently, they reported the use of IORT techniques in the treatment of locally advanced intraabdominal, retroperitoneal, pelvic, thoracic, and soft tissue tumors that were not likely to be controlled by surgery and/or radiotherapy alone (2, 4–6). Almost all of their experience in IORT was with high-energy electron beams given as a single dose without conventional external beam therapy.

Intraoperative radiation therapy was introduced in the US in the mid-1970s. Initially, IORT clinical trials were limited to four major institutions: the National Cancer Institute (NCI), the Massachusetts General Hospital, Howard University, and the Mayo Clinic (26, 30–32, 42, 43, 63, 64). More recently, a large number of institutions have started to use IORT as an adjunct to surgery and/or conventional radiotherapy. As a result of increasing interest in IORT, the Radiation Therapy Oncology Group (RTOG) has developed several ongoing clinical trials with this modality. A burgeoning interest in IORT is evident in Europe as well. The primary interest in IORT is as a "boost" to a course of preoperative or postoperative fractionated external beam photon treatment.

A multidisciplinary approach

Intraoperative radiation therapy combines two conventional methods of cancer treatment: surgery and radiation therapy. In concept, IORT is a very simple procedure in which the tumor or tumor bed is surgically exposed to a collimated radiation beam. In practice, however, IORT can be complex because professionals from different disciplines need to understand one another's requirements explicitly (36). One way to accomplish this is to have extensive discussions during the planning stages of the program among individuals of all disciplines who are identified as IORT team members. The team should develop written procedures and protocols that meet the approval of all members before initiating IORT procedures. It is important to recognize that these procedures can vary from institution to institution because of differences in the physical layouts of the facilities and institutional preferences. The written procedures should be reviewed periodically by the IORT team.

The IORT team

Key members of the IORT team include the surgeon, radiation oncologist, radiation physicist, anesthesiologist, nursing staff, pathologist, and radiation therapist (i.e., the radiotherapy technologist). Other team members include transport, housekeeping, engineering, and security support personnel. Because IORT requires a well-coordinated team approach, each team member should clearly understand his or her responsibilities.

Surgeon. The surgeon, who plays a key role in IORT, holds the overall responsibility for the procedure and needs to discuss the surgical procedure with the radiation therapy staff before the case is started. Often, the size of the incision required for IORT is more generous than that for conventional surgery. Also, the surgical approach may have to be altered to accommodate the IORT hardware and the radiation machine. Sometimes it may be necessary for the surgeon to use special retractors to accommodate IORT hardware optimally. The surgeon works closely with the radiation oncologist in setting up the patient for radiation treatment and, along with the anesthesiologist, is responsible for assuring that it is safe to leave the

patient totally unattended for a few minutes while radiation is being delivered.

Radiation oncologist. The radiation oncologist is responsible for evaluating the patient for IORT, reviewing the surgical approach with the surgeon before the IORT procedure, and presenting the IORT case for discussion at the treatment-planning conference in the radiation therapy department. During surgery, the radiation oncologist reviews the surgical and pathologic findings with the surgeon; then they make a joint decision about whether to proceed with IORT or not. If the decision is to proceed, then it is important for the radiation oncologist to communicate at this point with the radiation physicist and decide on the size of the IORT field, energy of the beam, percent depth dose, IORT dose, and the technical approach for the treatment. These decisions should be based on the extent of the disease and proximity of radiosensitive structures to the treatment area found at the time of surgery. The radiation oncologist is responsible for positioning the IORT hardware and setting up the patient for radiation treatment. The radiation physicist or the radiation therapist and appropriate OR and anesthesia staff assist in positioning the patient under the machine.

Radiation physicist. The radiation physicist is a key individual in IORT, being responsible for acquiring all dosimetry data required to deliver the prescribed dose of radiation, for quality control of the machine, and for supervising delivery of the radiation treatment. Also, the radiation physicist must advise the radiation oncologist about appropriate positioning of the patient for radiation treatment, the size of the applicator, and the energy of the radiation beam. These decisions should be based on the size of the target volume and the normal radiosensitive structures surrounding the target volume. It is important that the radiation physicist have dosimetry data readily available to calculate the monitor units required to deliver the prescribed dose accurately. Examples of data needed to make these decisions are described later in this report.

Anesthesiologist. The anesthesiologist is responsible for ensuring that the patient is stable during surgery, transport, and irradiation (11). The anesthesiologist must maintain adequate ventilation for the patient during transport. During IORT, the patient's vital signs must be closely monitored, either through a remote system or by closed-circuit television. The anesthesiologist should always be satisfied with the hardware for monitoring the patient's life-support systems (particularly as the patient is totally unattended for several minutes during IORT) and should have rapid access into the treatment room to attend to the patient in any instance by interrupting IORT delivery. It is important for anesthesiology staff to realize that IORT is very different from the surgical procedures to which they are accustomed in their daily practices. They need to resolve all issues regarding the patient's safety while unattended and keep the whole IORT team informed of potential problems.

Nursing staff. The OR nursing staff has responsibilities before, during, and after the IORT procedure. The preoperative responsibilities include coordinating the date and time of surgery and arranging for the patient's transfer, if treatment is delivered at a site remote from the OR suite. The OR nurse coordinator also assures that the OR and treatment room supplies are properly prepared before the case is started and that the necessary emergency equipment as required by the hospital "crash team" is readily available near the treatment area. During the surgical procedure, the circulating staff nurse is responsible for providing support services to the surgeon, assuring appropriate scrubbing, gowning, and gloving procedures, maintaining awareness of potential surgical emergencies in the treatment room, and maintaining maximum aseptic technique during transportation and radiation treatment of the patient. After the IORT is delivered, the nursing staff is responsible for assuring sterile and aseptic transfer of the patient to the OR suite for completion of the surgical procedure, if the procedure is not being done in a dedicated facility (34). The nursing staff is also responsible for keeping inventory of all IORT hardware used in the procedure and returning it for sterilization.

Pathologist. Sometimes the decision regarding IORT dose (or even whether IORT is indicated) must await pathologic confirmation of the disease during the surgical procedure. The pathologist should be made aware of the urgency of the diagnosis during IORT procedures. The results of the pathology should be quickly communicated to the surgeon and the radiation oncologist.

Radiation therapy staff. The radiation therapist (technologist) is responsible for delivery and documentation of IORT to the patient and for making sure that a written dose prescription is available before the treatment is delivered. If therapists are involved in setting up the patient for treatment, they should be familiar with OR procedures and the importance of sterile technique.

Engineering support personnel. Engineering support personnel should make sure that the machine is in proper working order before the IORT patient is brought for radiation treatment, and they should be immediately available to attend to potential radiation machine problems during the treatment. Engineering personnel should work closely with the radiation physicist during IORT procedures and should also be conversant with OR procedures and sterile technique. In addition, they should make sure that the television cameras and other support equipment are completely functional before and during the procedure. A contingency procedure plan should be developed for implementation in the event of a machine malfunction during a patient treatment.

Other support personnel. Sometimes, depending on the design of the facility, other support personnel may be involved in the IORT procedure, such as housekeeping, security staff, transport personnel, and elevator operators.

They all need to be familiar with OR procedures and sterile technique.

FACILITY CONSIDERATIONS

Intraoperative radiation therapy requires a surgical suite and a medical linear accelerator. The simplest way to provide IORT is to modify an existing radiation treatment room to accept the patient from a remote OR. A major drawback to this approach is transferring the patient from the OR to the radiotherapy department. Although mishaps during patient relocation or consequent serious infectious complications have not been reported, the potential is always there. The ideal setup for IORT is to have a dedicated radiation machine in the OR. The OR location is highly desirable from the standpoint of scheduling and maintenance of sterile conditions. It avoids disruption of daily routine in the radiation therapy department as well. The only disadvantage of having a dedicated IORT machine in an OR is cost, if the IORT workload cannot justify it. Sometimes, a refurbished older machine can be a viable alternative, provided the reliability and stability of beam characteristics can be assured. An alternative to the ideal setup is to have an OR suite adjoining the radiation treatment room. Each of these setups requires special considerations, which are described in the next section. Recently, the use of specially designed mobile linear accelerators for IORT is being explored. Such systems may become available in the future.

Dedicated facilities

The rationale for a dedicated IORT facility is multifaceted. An IORT machine located in the OR does away with the need to transport the patient from surgery to the radiotherapy department, thus greatly reducing the total IORT procedure time. The location of the OR is also highly desirable from the standpoint of surgical support, scheduling, and maintenance of sterile conditions. Other advantages include not having to disrupt daily routine in the radiation therapy department and experiencing fewer delays in delivering IORT because of restrictions sometimes imposed by non-OR locations.

Many features of a dedicated unit make it particularly attractive for use in IORT, among them (a) electron-only operation with a fixed circular precollimation, eliminating the need for adjustable photon collimation and monitoring; (b) use of a magnetron-driven power unit vs. the more expensive Klystron; (c) use of thin scattering foils that reduce the bremsstrahlung background; (d) a reduction in gantry size and weight with a mounting mechanism that is suitable for a given OR suite. Nyerick *et al.* (53) compared results from a 12 cm straight applicator at $E_{p,0}$ = 16.1 MeV; the IORT linear accelerator had a bremsstrahlung tail of 2.1%, and the conventional linear accelerator had a tail of 3.1%. In general, the bremsstrahlung tail for a dedicated unit was decreased by about 0.5–1% from that of a conventional linear accelerator. Reducing bremsstrahlung reduces the need for room shielding. Furthermore, the reduced thickness of the scattering foil helps improve the quality of the electron beam by increasing the depth of the 90% isodose level slightly for a fixed electron energy (35); the typical increase in the 90% isodose is about 2 mm for the IORT linear accelerator compared with that obtained using a conventional linear accelerator. Whether an existing linear accelerator is adapted for IORT treatment or a dedicated unit is placed in an OR, the treatment room must meet all shielding requirements (50).

In a dedicated facility, the treatment machine can be placed directly inside the OR or in an adjoining room. The considerations for placing a machine directly in the OR are different from those for placing the machine in an adjoining room.

Treatment machine in OR. Having an accelerator in the OR has its pros and cons. The advantages of this location are alluded to in the previous section. Among potential disadvantages of this location are that (a) the machine use is limited to IORT only and (b) an OR is a sterile environment, limiting uncontrolled access to the machine, so all physics measurements and machine-related maintenance would require personnel to take precautionary measures to maintain the sterility of the environment. Moreover, access to the machine for dosimetric measurements could be greatly restricted by use of the OR for non-IORT procedures or because of the limits imposed by the shielding design in relation to radiation exposure. Unnecessary problems relating to machine maintenance can be avoided by appropriate design of the facility. For example, one can design an accelerator such that all system functions that require service are outside the OR.

Treatment machine in room adjoining OR. Having a functional OR in the radiotherapy department adjacent to the radiation treatment vault allows the accelerator to be used for regular treatments, as well as the IORT procedure (54). The disadvantages of this are the institutional logistics of running a satellite OR. Areas to consider in this setup are the location of OR support staff, sterile supplies, and anesthesia equipment, and the time required to prepare the treatment vault for IORT.

If the treatment machine is placed in a room adjoining the OR, appropriate sterility of the treatment room can be achieved by cleaning the room the night before the IORT procedure and then terminally cleaning the room before the patient is brought in for IORT. In this arrangement, normal treatment of patients can continue until a decision about the need for IORT is made. The treatment room should be designed such that it meets all the requirements of an OR and minimal time is spent to prepare the room before it can accept the IORT patient.

A complete set of anesthesia and monitoring equipment should be kept in the treatment room at all times, so that a patient who is brought to the treatment room can be

hooked up to the appropriate anesthetic and monitoring equipment. Appropriate viewing arrangements should be made to enable remote monitoring both by anesthesia personnel and the radiation therapists at the main console. There should be at least two independent camera and television monitoring systems, one for visual monitoring of the patient and the other for visual monitoring of anesthesia equipment. The patient support system should permit easy transport of the patient to the treatment room. An effective communication system between the therapists and the person designated to signal the beginning of the IORT treatment must be established. At the end of the IORT, the room should be cleaned again before resuming normal treatment procedures.

Shielding. Shielding of the facility is important. Because high doses (10–25 Gy) could be given in a single treatment, the room should be shielded for weekly exposure rates, as well as hourly exposure rates. X-Rays generated by electron energies of 15 MeV and higher exceed the threshold energy for the production of photoneutrons (50). Thus, shielding of an IORT facility must be designed for neutrons as well as x-rays.

Calculations on room shielding must be made with regard to the various sources of relevant radiation identified. The source and magnitude of leakage radiation (both x-ray and/or neutron) depend on the design of the machine. Also, x-ray contamination present in an electron beam is an important consideration. These x-rays are produced by bremsstrahlung interactions of the electron beam in the scattering foils, in the primary collimators, in the beam-defining collimating system, and in the patient. The x-ray leakage outside the treatment field arises from the bending magnet assembly, the scattering foils, the primary collimators, and the beam-defining collimating system. If the electron beams produced by the machine have an energy that exceeds the threshold for photoneutron production, then the machine head must be shielded against excessive neutron leakage. These neutrons could be produced in the bending magnet assembly and in the primary collimators of the accelerator. Although the electron-beam current required for IORT in electron-only linear accelerators is orders of magnitude smaller than that required for conventional x-ray therapy, the magnitude of photoneutrons produced in these accelerators is significant enough to warrant their inclusion in radiation shielding design.

Typically, x-ray and neutron leakage components for 15–20 MeV electrons are of the order of 0.002% at 1 m (50). Assuming an intraoperative workload of 200 Gy/week, including warm-up time, for an exposure level of 0.1 mSv/week and 100% occupancy at a distance of 3 m, approximately 2 half-value-layers (HVLs) are required for shielding. This is translated into walls of 20–30 cm-thick concrete, and a door of 7.5 cm steel backed with 5.0–7.5 cm of polyethylene (for neutrons). X-Ray contamination produced by the electron beams incident on scattering foils and the patient presents a different scenario because its magnitude is 2 to 5% of the total workload. A weekly exposure at a distance of 2 m at the floor is expected to be 2.5 Gy. Reduction to 0.02 mSv/week requires 5.5 TVLs (approximately 2.5 m of concrete or 25 cm of lead for 20-MV x-rays). These examples illustrate the need for careful evaluation of the shielding requirements for a dedicated electron-beam IORT machine. Procedures for monitoring and protecting personnel in uncontrolled areas surrounding the IORT facility should be developed prior to the start-up of the machine, as well. Particular attention must be paid to monitoring beam-on time during commissioning of the machine and subsequent long exposures for quality-assurance measurements.

Nondedicated facilities

Use of existing facilities can be the most economical choice for providing IORT to selected patients. In using existing OR and radiation therapy facilities, two problems must be surmounted: round-trip transportation of the patient between the OR suite and the radiation therapy suite, and preparation of the radiation therapy suite to handle a surgical patient.

Patient transportation to the treatment room. A number of difficulties must be considered in the safe transportation of a patient to and from the radiation therapy suite. These problems are not insurmountable, given a good IORT team to address them.

Wound sterility during transport: this problem, handled routinely in most surgical suites, is solved by appropriately draping the surgical site and the patient with several sterile covers. These covers are discarded in the radiation therapy facility and new ones are added for transport back to the OR.

Patient table for transport: the choice of table for transport is critical. Many facilities have chosen to use the same table for surgery, transport, and radiation therapy. Because these tables have numerous accessories for positioning patients, they are extremely heavy—400 lbs or more. Several dry runs with a table can help to address problems that might arise and discover adaptations that may be necessary to facilitate the table's use.

Equipment necessary during transport: in case of possible emergencies, such as power failure or an abrupt change in the patient's medical status, a minimal set of equipment should go with the transport team: a manual ventilator, oxygen, patient monitor, defibrillator, and some additional IV fluids. Sometimes ramps may be needed to overcome barriers or floor gaps.

Route of transport: the route should be chosen with consideration for the shortest distance and minimum obstacles, while permitting maintenance of security and avoiding crowds. Transportation between buildings has been accomplished routinely; however, this presents greater difficulties with respect to security, sterility, and protecting the patient

from weather conditions. An alternate route should be considered in case of unforeseen events.

Security during transport between OR and radiotherapy facility: security personnel are responsible for dedicating elevators, clearing hallways, limiting access, and expediting passage of the patient and team between the facilities.

Maintenance of sterile conditions for the surgical team: generally, staff members attending the patient are double-gowned before transport of the patient and then regowned, if necessary, in the radiation therapy suite, to avoid the necessity for the entire team to rescrub in the radiation therapy suite before proceeding with the radiation therapy portion of the treatment. The same is true on returning to the OR.

Communication between OR and radiotherapy facility: generally, communication is accomplished by telephone. A checklist of information should be communicated for each procedure so that all pertinent information is communicated each time the procedure is performed. Radio communication, which can be used as a backup for phone-line failure and/or when transporting patients between the OR and radiation therapy suites, should be provided. Members of both the OR and the radiation therapy teams should be stationed at both facilities to assist in following routines and overcoming unforeseen obstacles.

Transport of patient back to OR: after IORT, the patient can be transported back to the OR suite for additional surgery and/or closure of the wound site in the same manner as described above.

Preparation of the treatment room. The treatment room must serve as a minimal operating suite to handle any emergency surgical procedure that might be required. Very often, final preparation of the surgical site and placement of the electron-beam applicator are done in the radiation therapy facility. The surgeon and anesthesiologist must have essential equipment, much of which is mobile and need only be brought in for the specific procedure. Some items should be considered for permanent placement in the radiation therapy suite before implementation of IORT, so that appropriate structural modifications can be made if necessary; such items include air flow, oxygen, and vacuum equipment, a remote patient-monitoring system, additional power outlets, emergency power and lighting equipment, and an emergency communication system.

The following items can be installed permanently or brought in only temporarily: anesthesia gases, surgical lighting, surgical-treatment-site video monitoring, battery backup for patient monitors, i.v. poles, surgical instruments, scrub gowns, drapes and other sterile supplies, and cauterizing equipment.

In addition to the equipment that must be either installed or brought in, a certain amount of room preparation is necessary. This may involve cleaning the radiation therapy suite, removing or docking the treatment table, providing access for the treatment surgical table, and moving or adjusting monitoring cameras.

Air-handling systems: while these can be provided by bottled gases and vacuum pumps, they can also be placed permanently at a convenient location in the room for reliable ready access. Bottled gases and vacuum pumps would then be supplied as backups for primary system failures.

Remote patient monitoring: for the short period of time (5–10 min) in which the patient is alone in the treatment room, essential monitoring can be maintained by the physician team through several means. Because most radiation treatment rooms have two TV cameras, one camera can be used to view the patient-monitoring systems, while the other is being used to view the patient directly. Alternatively, an access cable relaying information from patient sensors to physicians may be used. Finally, there are manual methods to monitor patient sounds through a plastic hose and stethoscope.

Emergency power and lighting: these are essential, if only to extricate and rush the patient from the treatment unit back to the OR facility. Emergency lighting in most facilities tends to be minimal, but this can be increased by having battery-powered lighting available.

IORT TECHNIQUES

Accelerator

The megavoltage electron beam, the most common radiation modality used to date for IORT, is an excellent choice for treatment because the beam may be collimated to the desired shape, a suitable penetrating energy may be chosen to take advantage of the finite range of a given electron energy, and, unlike orthovoltage photons, there is no differential absorption for bone over that of soft tissues. Existing linear accelerators can easily be adapted for IORT treatment, which does not require any modification of the accelerator head, gantry, dose rate, or the mechanism for the production of electron beams; however, the system for collimating the electrons must be modified for IORT, which can be done by designing an applicator plus adapter system and then adapting this unit to the treatment machine. The adapter system may consist of two parts, a main adapter that is interfaced to the collimator head and a docking adapter that fits into the main adapter. Both the docking adapter and the main adapter are rigidly attached to the collimator head. An applicator is a tube (made of either Plexiglas or metal), which can be circular, rectangular, or any other geometric shape in cross section, through which electrons pass before irradiating the target volume. The applicator may attach rigidly to the IORT adapter (hard docking) or may not attach (soft docking). The entire applicator plus adapter system should be designed such that the dose outside the clinical treatment field is within acceptable limits.

Accelerators specifically designed for IORT are now commercially available (53). These accelerators offer optimized beam characteristics and radiation delivery sys-

tems for IORT and are electron-only machines. There is less danger of overdose on these machines in that the design precludes high beam currents.

Patient support system

Precise alignment of the treatment field with the radiation field requires gantry and table motion. Standard tables supplied by the manufacturers for use in external-beam radiotherapy have provisions for fine vertical, longitudinal, and lateral motions, but not for tilt motion, which is highly desirable for the IORT alignment procedure. Standard surgical tables also do not have provisions for the above motions. Therefore, various institutions have designed new tables solely for the purpose of IORT (53, 54).

The unique features of these modified tables are precision lateral, longitudinal, and tilt drives for fine positioning; slow vertical motion for safe and precise alignment; and large casters for ease in transportation of the patient from the OR to the treatment room.

Collimation and docking system

To date, two different techniques have been developed for IORT treatment: a "hard-docking system" and an "air-docking system," sometimes also called a "soft-docking system." In the hard-docking system, an applicator placed within the patient is rigidly attached to the collimator head of the accelerator. In contrast to this, in the air-docking system, the applicator is placed within the patient and rigidly attached to the patient support assembly with no rigid attachment to the collimator head of the accelerator.

Hard-docking system. Almost all of the hard-docking IORT systems built to date consist of four major components: (a) a main adaptor that attaches to the front surface of the accelerator collimator assembly; (b) a set of docking adaptors that fit into the main adaptor; (c) a series of applicators made of methyl methacrylate plastic or brass (sometimes referred to as applicators) in various sizes and shapes that fit into the docking adaptor; and (d) a system for viewing and verification of the treatment field. An example of the Mayo Clinic IORT system (46), which incorporates all of the above features in a linear accelerator,[1] is shown in Fig. 1. Typically, the main adaptor, made of aluminum or stainless steel, fits in the standard accessory holder. Also, it is fitted with a specially coded electron tab to set interlocks for electron beams. The docking adaptor, also made of aluminum, is attached to the accelerator head through the main adaptor. Circular methyl methacrylate plastic applicators of various diameters are made to fit into the aluminum docking adaptor by use of an appropriate-sized annulus. A retractable mirror-telescope-light system is used to look down on the area to be treated. The mirror is made of metal to prevent breakage and is positioned in such a way that pressure must be applied to position it into the docking adaptor system. A 0.003–0.005 inch-thick piece of strong polyester film is placed over the upper end of the docking adaptor to prevent small objects from dropping down into the patient from the accelerator head. This polyester film does not degrade the electron beam energy significantly, but it can affect the dosimetry of the electron beam. It is, therefore, recommended that a broken piece of polyester film be replaced with another piece of the same thickness.

Although most of the hard-docking IORT systems built to date have many similarities, they also differ from each other in many ways. For example, the viewing arrangement in the Medical College of Ohio IORT system (9) consists of a 90° rigid fiberoptic telescope with a variable intensity light source that allows a "beam's-eye view" of the treatment region with minimal optical distortion. For documentation of the treatment field, a 35 mm camera is attached to the viewing end of the telescope and photographs of the treatment area are taken. In the National Cancer Institute IORT system (24), the verification and documentation of the treatment area are done by using a television camera system. Some machines are designed such that a predefined photon collimator jaw setting is automatically selected when the main adaptor is attached to the machine head and an appropriate electron beam energy is chosen (54). Other accelerators, however, require that the photon jaws are adjusted manually to pre-

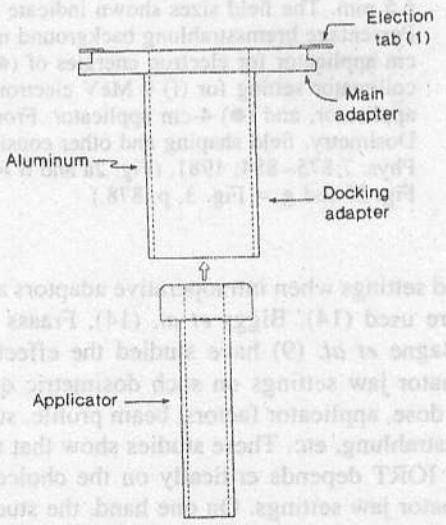

Fig. 1. Schematic of the IORT applicator system developed at the Mayo Clinic. Methyl methacrylate plastic applicators "dock" into an aluminum jacket that attaches to the head of the accelerator. Redrawn from McCullough, E. C.; Anderson, J. A. The dosimetric properties of an applicator system for intraoperative electron-beam therapy utilizing a Clinac®18 accelerator. Med. Phys. 9:261–268; 1982. (Fig. 1, p. 261).

[1] Varian Clinac 18, Varian Medical Equipment, Palo Alto, CA.

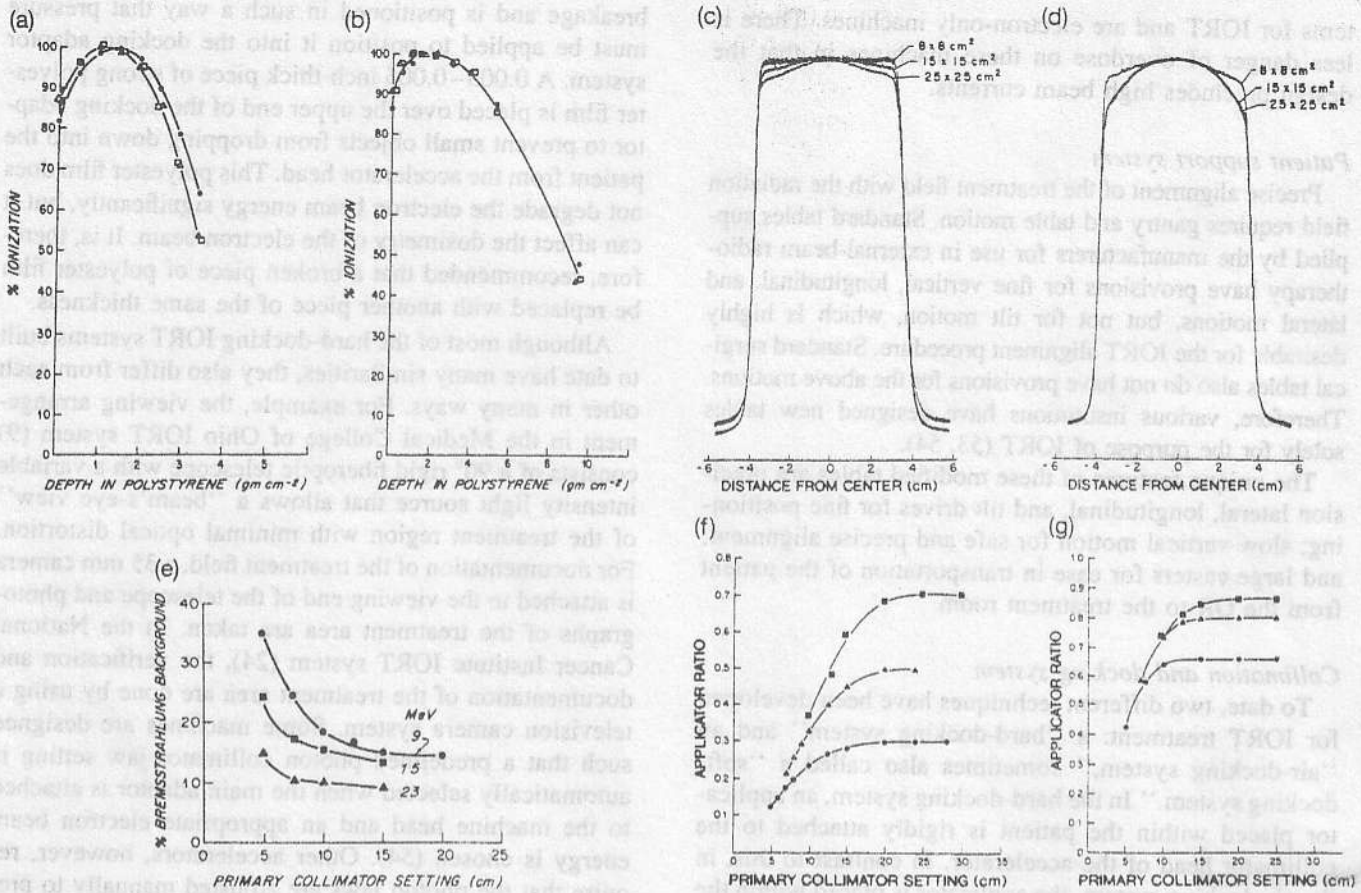

Fig. 2. Percentage ionization curves for primary collimator settings of (○) 5 × 5 cm² (△) 15 × 15 cm² (□) 35 × 35 cm² for a 4-cm applicator at (a) 9 MeV and (b) 29 MeV. Beam profiles for a 7 cm applicator at a depth of 6.5 mm. The field sizes shown indicate the settings of the primary collimators (c) 9 MeV and (d) 23 MeV. (e) Percentage bremsstrahlung background measured in water as a function of the primary collimator setting for a 4-cm applicator for electron energies of (●) 9 MeV, (□) 15 MeV, and (△) 23 MeV. Applicator ratio vs. primary collimator setting for (f) 9 MeV electron beam and (g) 23 MeV electron beam. (■) 9-cm applicator, (△) 6-cm applicator, and (●) 4-cm applicator. From Biggs, P. J.; Epp, E. R.; Ling, C. C.; Novack, D. H.; Michaels, J. B. Dosimetry, field shaping and other considerations for intraoperative electron therapy. Int. J. Radiat. Oncol. Biol. Phys. 7:875–884; 1981. (Fig. 2a and b = Fig. 4, p. 879; Fig. 2c and d = Fig. 5, p. 880; Fig. 2e = Fig. 6, p. 880; Fig. 2f and g = Fig. 3, p. 878.)

scribed settings when intraoperative adaptors and applicators are used (14). Biggs *et al.* (14), Fraass *et al.* (25), and Bagne *et al.* (9) have studied the effect of photon collimator jaw settings on such dosimetric quantities as depth dose, applicator factors, beam profile, surface dose, bremsstrahlung, etc. These studies show that the dosimetry of IORT depends critically on the choice of photon collimator jaw settings. On one hand, the study of Biggs *et al.* (14) shows that a collimator jaw setting just greater than the chosen field size gives the best depth-dose distribution (Fig. 2a and b) and flattest beam profiles (Fig. 2c and d). On the other hand, such a collimator jaw setting results in a large bremsstrahlung tail (Fig. 2e) and undesirably low applicator factors (Fig. 2f and g). Applicator factors are defined as the ratio of dose for the IORT applicator to the dose for the standard calibration electron applicator, both measured at the depth of maximum dose. If the collimator jaw setting is made too large, then the applicator factors approach a constant value, resulting in no further increase in effective electron dose rate. Biggs *et al.* (14) used a fixed collimator setting of 15 × 15 cm² that was a compromise between the advantages and disadvantages outlined above. It should be pointed out that data reported by Biggs *et al.* (14) were measured on a linear accelerator[2] that used 0.3 to 0.6 mm lead scattering foils. Most accelerators now have a bremsstrahlung tail that is less than 5% for all clinically used electron energies.

Applicators used in IORT are typically circular or rect-

[2] Varian Clinac 35, Varian Medical Equipment, Palo Alto, CA.

angular in cross-section and collimate the electron beam to the target volume. The walls of these applicators shield normal tissue outside of the applicator from primary radiation. Homogeneity of dose inside the applicators and leakage outside the applicators depend on the thickness, material, and design of the applicators and on how they are interfaced to the machine. Both brass and methyl methacrylate plastic have been used as applicator materials in IORT. Methyl methacrylate plastic has the advantage of being transparent, which renders easy visualization of the target volume; however, depending on the size (length, inner diameter, etc.), treatment source-to-skin distance (SSD), and energy of the beam, an applicator wall thickness of 5–8 mm may be necessary to achieve an acceptable level of leakage through the side walls of the applicator. Such applicators may be too thick to access tight-fitting anatomical situations. Brass, on the other hand, is not transparent, so a special arrangement is necessary for viewing the treatment field. However, brass has the advantage of being durable, it can be chrome plated and flash sterilized, and its walls can be made thinner than methyl methacrylate plastic, permitting better tumor coverage in tight-fitting anatomical situations. Irrespective of which material is chosen, it is important to design the applicators in such a way that radiation leakage through the wall is minimized.

The lengths of the applicators used in IORT are designed such that the ends of the applicators lie on the surface of the lesion and are often at the isocentric distance. Clinical experience suggests that the lengths of the applicators be about 25–30 cm to reach tumors deep within the abdomen. Although the design criteria of accelerators put a constraint on how long an applicator can be, whenever possible, a standard length of at least 25 cm is recommended for all applicators. Having a standard applicator length makes it possible to generate all relevant dosimetric data only once, and no source-to-skin distance (SSD) corrections are necessary. Of course, dosimetry of applicator of different lengths will differ; thus, if applicators of varying lengths are used for IORT treatment, it will be necessary to assess the beam characteristics of each and generate relevant dosimetric data accordingly. Because data acquisition for IORT is very labor intensive, any additional work in calibrating applicators of different lengths may cause a significant strain on the initiation of any new IORT program.

A hard-docking system requires direct patient contact with a fixed applicator attached to a linear accelerator; potentially, an increased risk of crush injury exists, if the applicator will not give way on contact. Special attention must be given during the docking procedure to avoid accidental or extreme movement.

Air-docking system. In the air-docking system, the applicators are held rigidly to the OR table and are not in direct contact with the collimator head. A clamp-and-post assembly (35, 39, 54) attached to the OR table holds the

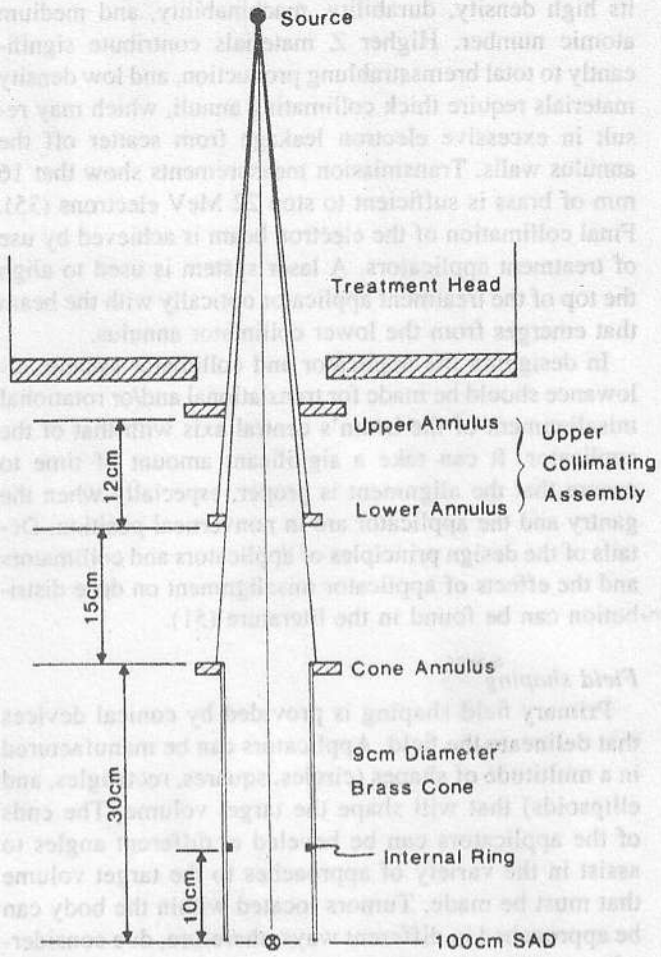

Fig. 3. Schematic of collimation system developed at M. D. Anderson Hospital. The two annuli are attached to the treatment head and provide electron collimation. A 15-cm air gap is maintained between the lower annulus and the IORT applicator. From Hogstrom, K. R.; Boyer, A. L.; Shiu, A. S.; Ochran, T. G.; Kirsner, S. M.; Krispel, R, Rich, T. A. Design of metallic electron beam cones for an intraoperative therapy linear accelerator. Int. J. Radiat. Oncol. Biol. Phys. 18:1223–1232; 1990 (Fig. 1, p. 1224.)

applicators in the patient. Collimation of the electron beam can be accomplished in various ways. Figure 3 shows a schematic diagram of the collimating system of the electron beam used at the M. D. Anderson Hospital. The collimation system consists of three major components: an upper collimator assembly, an applicator annulus, and the treatment applicators. The upper collimator assembly consists of upper and lower brass annuli that are fixed to the head of the machine and act as an initial collimation system for the electron beam. A brass annulus (applicator annulus), which is placed on top of the treatment applicators, further defines the clinical beam and minimizes leakage outside the treatment area caused by the lateral scatter of the electrons. The applicator annulus and treatment applicators are mechanically attached not to the upper collimator assembly but rather to the treatment couch. Usually, brass is used for collimation because of

its high density, durability, machinability, and medium atomic number. Higher Z materials contribute significantly to total bremsstrahlung production, and low density materials require thick collimating annuli, which may result in excessive electron leakage from scatter off the annulus walls. Transmission measurements show that 16 mm of brass is sufficient to stop 22 MeV electrons (35). Final collimation of the electron beam is achieved by use of treatment applicators. A laser system is used to align the top of the treatment applicator optically with the beam that emerges from the lower collimator annulus.

In designing the applicator and collimator system, allowance should be made for translational and/or rotational misalignment of the beam's central axis with that of the applicator. It can take a significant amount of time to ensure that the alignment is proper, especially when the gantry and the applicator are in nonvertical position. Details of the design principles of applicators and collimators and the effects of applicator misalignment on dose distribution can be found in the literature (51).

Field shaping

Primary field shaping is provided by conical devices that delineate the field. Applicators can be manufactured in a multitude of shapes (circles, squares, rectangles, and ellipsoids) that will shape the target volume. The ends of the applicators can be beveled at different angles to assist in the variety of approaches to the target volume that must be made. Tumors located within the body can be approached in different ways; therefore, due consideration must be given to selection of the applicators. Most manufactured docking systems provide that the end of the applicator is at the isocenter of the accelerator. However, consideration should also be given to acquiring several applicators of extended length for approaches that are different from the norm—for example, for a perineal approach.

Additional field shaping can be achieved through surgical displacement of critical organs for the sake of treating the target volume. When that is not possible, sterile lead pieces wrapped in sterile gauze placed adjacent to the target volume within the applicator can provide additional custom shaping of the field. Enough thickness of lead should be used to reduce the dose by 95%.

Acquiring a large number of applicators increases the time required to evaluate dosimetry, because good physics practice requires evaluation and documentation of each applicator acquired.

Treatment-viewing arrangements

Viewing of the area to be treated before starting treatment is an absolute necessity for the physician and the physicist, because many extenuating factors could change the site of treatment. At least four types of viewing systems (direct, periscopic, fiberoptic camera, and remote camera with mirror optics) are readily available.

Direct view. This mode, applicable primarily to air-docking systems, permits viewing of the treatment site directly down through the applicator, with some light assistance, if necessary. A photograph can be made, also, for a permanent record.

Periscopic view. In this mode, applicable primarily to hard but also to air-docking systems, a periscope with a removable mirror is attached to the adapter system, which permits viewing by either the naked eye or video camera. Viewing (often from a stepstool or ladder) through the periscope can put the viewer in an awkward position, depending on his or her height. Also, periscopic viewing requires removal of the mirror optics before treatment. Most mirror optics should be interlocked to prevent operation of the accelerator if the mirror is left in place. An attached video camera will provide for remote viewing and easy documentation of the treatment site.

Fiberoptic camera. A flexible fiber can be placed through any available access and the treatment area can be viewed directly or recorded by video camera. This provides a relatively simple solution to the problem of viewing the treatment site.

Camera with mirror optics. Video cameras can be used in any of the above situations, but generally the field of view will be limited to the optics of the periscope or the fiberoptic camera. Several facilities now use a camera, mounted with a motorized mirror optic system, that permits adjustment of focus, field of view, and light levels necessary for a very clear, accurate view of the treatment site. Viewing could be accomplished even during treatment by using a sheet of very thin, strong aluminized polyester film for the mirror. Such a mirror would complicate dosimetry, however, and might not be of any real benefit. As in the periscopic system, a normal mirror would have to be withdrawn during treatment.

Suction for blood accumulation

During the IORT procedure, the treated volume will tend to adhere to the applicator edges, creating a seal in which blood and other fluid can accumulate. Accumulation of too much fluid in the treated volume will significantly change the dosimetry in the target volume. Several options exist for the removal of fluid and should be considered. Usually, serious blood or fluid accumulation is an indication that the surgeon should be permitted to do some additional work. If fluid accumulation persists, a drain or suction can be provided at the base of the applicator for continuous removal of fluid. With less serious accumulation, the blood or fluid can be removed by suction through an access port just before treatment. If fluid suction is a matter of concern, the IORT can be interrupted to check for fluid accumulation within the applicator.

IORT hardware sterilization

The importance of correct sterilization for the various pieces of hardware used in IORT cannot be overstated.

Every institution must establish a protocol for correct sterilization procedures before initiating an IORT program. Treatment accessories made of brass or steel can be steam sterilized, whereas those made of methyl methacrylate plastic or aluminum require gas sterilization, a procedure typically consisting of a humidification stage during which steam is allowed to penetrate into the items to be sterilized, followed by an exposure stage during which the items are exposed to ethylene oxide gas at a temperature of approximately 132–134°F. At the end of this cycle, the items are placed inside an aeration cabinet and exposed to warm air to remove the residual ethylene oxide gas from the items. Sterilized items can then be sealed and stored for as long as about 2 years.

It has been the experience of various institutions that methyl methacrylate plastic suffers from distortion and cracking after years of repeated gas sterilization. This can affect the dosimetry significantly, so frequent checks on the integrity of methyl methacrylate plastic equipment should be made. The commercial providers of IORT hardware or of materials used to manufacture it within the institution can be consulted regarding recommendations for establishing a correct standard sterilization procedure.

DOSIMETRY PARAMETERS AND MEASUREMENTS

The dosimetry of the IORT system is unique and requires a complete set of measurements (to be defined in this section). As discussed previously in the section on techniques, many choices need to be considered before measurements are made. Careful planning beforehand will ease the task of preparing a system for clinical use. Beam characteristics for all IORT applicator sizes must be measured and presented in an easily usable format because little time is available during the IORT procedure to make detailed dosimetric calculations. Typically, lateral extent and depth of target volume are determined either by direct manipulation in the surgical wound or by means of an ultrasonic scan with a transducer inserted into the surgical cavity. Electron energy and applicator size are selected such that a 90% isodose surface would cover the tumor bed with some margin. Available dosimetry data are used to make a quick calculation for the monitor unit setting.

Definitions

The dosimetry quantities permit the calculation of monitor unit settings for delivery of a prescribed target dose at a selected depth on the central axis of the electron-beam field. The central axis for beveled applicators has little significance clinically because vertical depth from the phantom surface has more relevance in IORT; therefore, a new "clinical axis" is defined as the line projecting perpendicularly from the phantom surface and intersecting the central axis of the applicator at the surface,

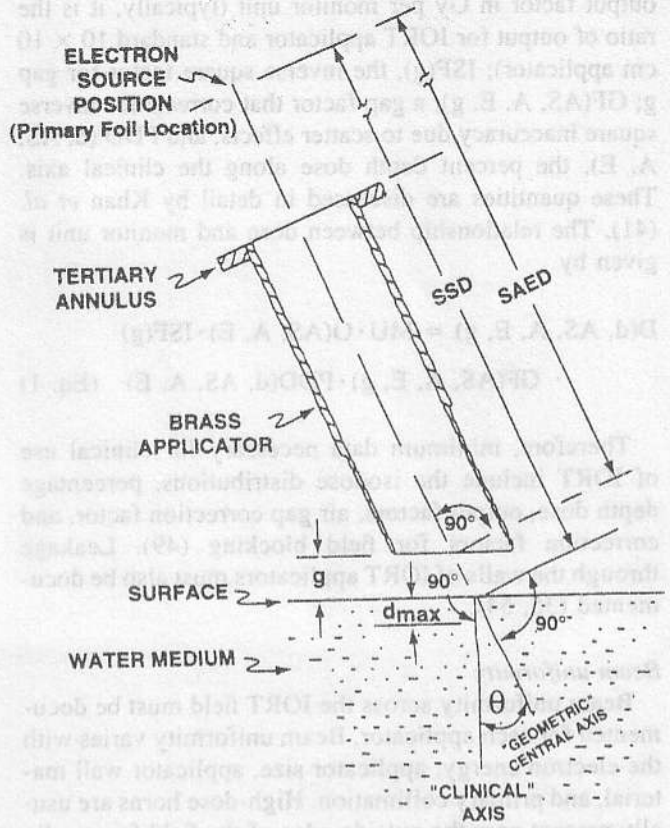

Fig. 4. Definition of "clinical" and "geometric" axes for dosimetry measurements where θ is the bevel angle for IORT applicators. SAED is the source-to-applicator-end distance. SSD is the source-to-surface distance. Redrawn from Nyerick, C. E.; Ochran, T. G.; Boyer, A. L.; Hogstrom, K. R. Dosimetry characteristics of metallic cones for intraoperative radiotherapy. Int. J. Radiat. Oncol. Biol. Phys. 21:501–510; 1991 (Fig. 2, p. 503).

as shown in Fig. 4. For straight applicators, the angle of incidence θ is equal to 0°; however, for beveled applicators, θ is equal to the angle of the bevel, and the clinical and central axis are not identical.

Typically, all available electron energy modes are calibrated to deliver 0.01 Gy per monitor unit at a reference depth that is near the depth of maximum dose on the central axis for a standard 10 × 10 cm applicator, at a standard treatment distance of 100 cm. The pertinent variables of the IORT dosimetry system are *applicator size* (AS), the internal diameter of the circular applicators or the length and width of a rectangular (or other shaped) applicator; *applicator angle* (A), because both straight- and bevel-ended applicators may have the same diameters; *depth* (d), the distance from the surface to the prescription depth (along the clinical axis); *electron-beam energy* (E), the nominal electron-beam energy; and *gap distance* (g), the distance from the end of the applicator to the treatment surface.

The following dosimetry factors determine the relationship between dose and monitor unit: O(AS, A, E), the

output factor in Gy per monitor unit (typically, it is the ratio of output for IORT applicator and standard 10 × 10 cm applicator); ISF(g), the inverse square factor for gap g; GF(AS, A, E, g), a gap factor that corrects for inverse square inaccuracy due to scatter effects; and PDD (d, AS, A, E), the percent depth dose along the clinical axis. These quantities are discussed in detail by Khan *et al.* (41). The relationship between dose and monitor unit is given by

$$D(d, AS, A, E, g) = MU \cdot O(AS, A, E) \cdot ISF(g) \cdot GF(AS, A, E, g) \cdot PDD(d, AS, A, E) \quad \text{(Eq. 1)}$$

Therefore, minimum data necessary for clinical use of IORT include the isodose distributions, percentage depth dose, output factors, air gap correction factor, and correction factors for field blocking (49). Leakage through the walls of IORT applicators must also be documented (35, 54).

Beam uniformity

Beam uniformity across the IORT field must be documented for each applicator. Beam uniformity varies with the electron energy, applicator size, applicator wall material, and primary collimation. High-dose horns are usually present near the outside edge of the field for acrylic applicators. Their magnitude increases with energy. Various methods have been used to reduce the horns, including placing inserts on the inside portion of the applicator (54) and varying the primary photon jaw size (14, 62). It is recommended that the nonuniformity of the dose over the area to which the prescribed dose is to be delivered should be no greater than 10%, measured at half the depth of d_{90}.

Depth dose

The central axis and the clinical axis for the treatment applicators were defined and are shown in Fig. 4. The geometric central axis is the central axis of the applicator for both beveled and straight applicators. The clinical central axis is defined as the line projecting perpendicularly from the phantom surface and intersecting the geometric central axis of the applicator surface. Although it would be more natural for the radiation physicist to discuss depth dose along the geometric central axis, the clinical central axis is perceived to be more relevant to IORT. Thus, all depth doses should be measured along this clinical central axis and normalized such that 100% represents the value of maximum dose. Depth doses can be measured in water, using either an ion chamber or a diode. Particular attention should be paid to detector characteristics for electron beam measurement. For example, conversion of ionization to dose requires correction for point of measurement, stopping-power ratios, chamber replacement corrections, and a host of other factors when side-scatter equilibrium is not established. All of these dosimetric parameters are described in an American Association of Physicists in Medicine (AAPM) Task Group report (41). Radiographic film can also be used to make this measurement (59). Typical percent depth–dose curves are shown in Fig. 5, and parameters are shown in Table 1. Depth of penetration along the clinical axis decreases significantly with the angle of the bevel because of oblique incidence (13, 22). Methods have been proposed (47, 48) to predict the depth doses for beveled applicators with depth–dose data for flat applicators. The proposed relationships must be verified experimentally for validity. A specially designed water phantom (19) can facilitate measurements of depth dose for beveled applicators. Also, depth of penetration decreases with the decrease in applicator size. This effect is more pronounced with increase in energy and the bevel angle. The change in depth dose with field size for a flat applicator and a beveled applicator is shown in Fig. 6.

Surface dose. Measurement of surface dose in the buildup region is very important to the IORT procedure and should be made with great care. Because of the nature of the procedure, the end of the IORT applicator is in contact with the area to receive the prescribed dose. Diodes can be used to measure the surface dose in the buildup region in a water phantom, or a parallel plate chamber can be used in either a water phantom or a solid phantom. The surface dose should be close to the prescribed dose. It is important to know at what depth along the central axis this dose has reached the maximum in the buildup region, information that can be given either in a figure or in table form for review at the time of electron energy selection for IORT. While the surface dose increases with energy, it does not vary significantly with primary collimator or applicator size.

Therapeutic depth for flat- and bevel-ended applicators. Therapeutic depth is defined as the distance from the surface to a depth along the clinical axis where a prescribed dose is to be delivered. The geometric depth dose will remain almost the same for a given applicator size, but the clinical depth dose will become less as the bevel angle increases. This is very important during the applicator selection process.

Lateral therapeutic coverage

Isodose contours representing all available energies for each applicator should be measured; depending on the shape of the applicator, multiple planes may have to be measured. Placing a horizontal reference line at the percentage depth dose most commonly used (for example, 90%), as well as placing two reference lines projecting the inside of the applicator wall from the surface to the depth, can be helpful, as shown in Fig. 7. Scattering of the electrons in a medium causes dose contours to widen with depth, which is important information when one is trying to limit the dose to tissue outside the treatment

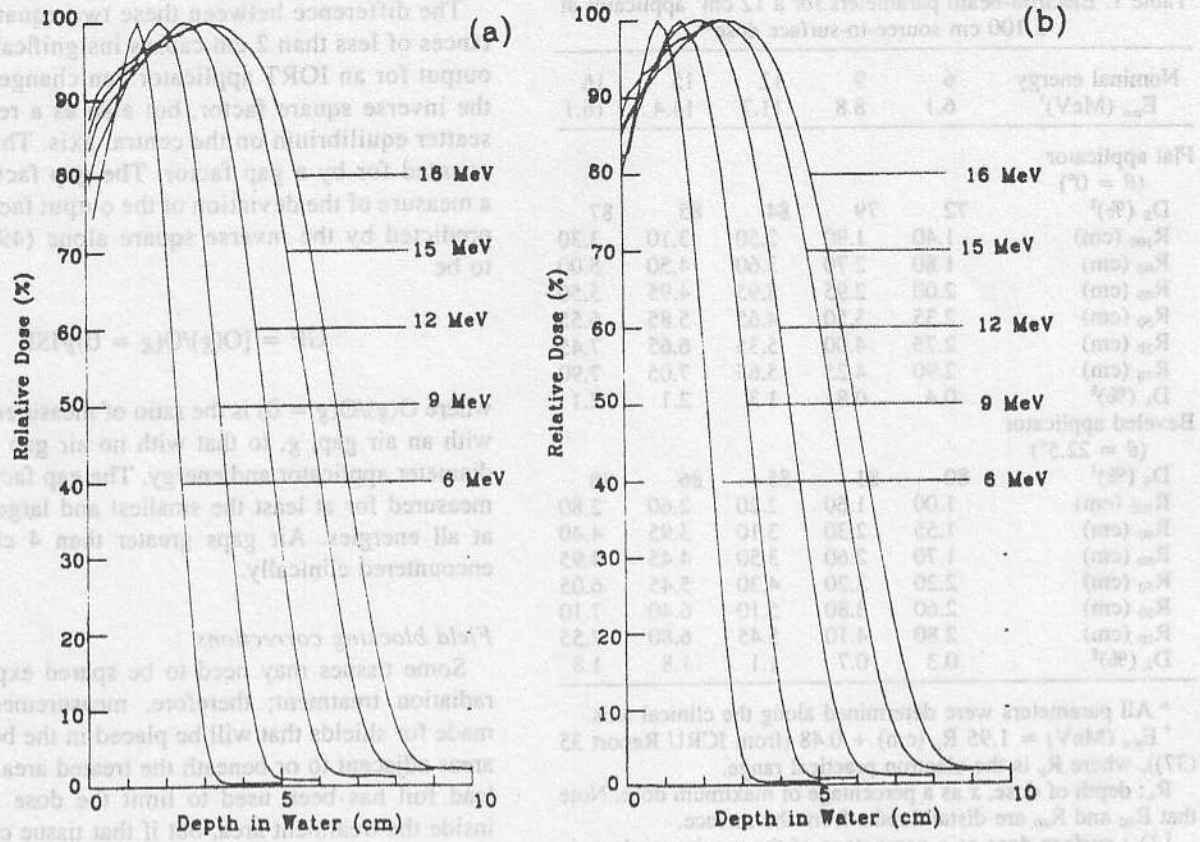

Fig. 5. Percent depth dose measured on the clinical axis for 6, 9, 12, 15, and 16 MeV used with (a) 12-cm diameter flat applicator at 110-cm SSD, and (b) 12-cm diameter 22.5° beveled applicator at 100-cm SSD. From Nyerick, C. E.; Ochran, T. G.; Boyer, A. L.; Hogstrom, K. R. Dosimetry characteristics of metallic cones for intraoperative radiotherapy. Int. J. Radiat. Oncol. Biol. Phys. 21:501–510; 1991 (Fig. 3, p. 504).

field. The width of isodose contours at all depths is important. An example of a table of the widths of different isodose contours at the depth of the prescribed percentage depth dose (for example, 90%) and the width at one-half the depth of the prescribed percentage depth (i.e., one-half of 90%) is shown in Table 2. Having actual isodose distributions available for review at the time of IORT is, however, much simpler and more illustrative.

Flat applicators. The use of flat-ended applicators (geometric and clinical central axes being the same) makes for an easy definition of the therapeutic treatment area. The ideal treatment volume would be a flattened cylinder because of the typical electron isodose pattern, with constriction of the higher and expansion of the lower isodose surfaces.

Beveled applicators. Beveled applicators allow for delivery of IORT on the pelvic side wall, for example, as well as to other areas that are not easily accessible to a straight-line approach. The elongated edge may act as a retractor, which can be quite advantageous in certain clinical situations. Care must be taken in this case to know how much leakage occurs through the applicator wall. The leakage radiation can be as high as 25% of the prescribed dose (54). Ideally, one would like to have a treatment area that is a tilted cylinder. Isodose contours must be measured in the elongated direction and the short axis of the applicator. A beam's-eye view of the treatment area at the depth of half of 90% and at 90% depth is quite useful to understanding the narrowing of the therapeutic beam.

Applicator factors

Each IORT applicator has an output factor (applicator ratio) designated by a number of terms: given dose per monitor unit, d_{max}, and Gy per monitor unit. Applicator ratio is defined as the ratio of the dose reading at the depth of maximum dose (d_{max}) for the IORT applicator to the dose reading for the standard calibration electron applicator. These readings are taken along the central axis at the normal calibration SSD. Because the d_{max} depth moves toward the surface when IORT applicators are used, it is important to locate the actual d_{max} point for each applicator. This is especially critical when measuring applicator factors for beveled applicators at lower electron energies.

SSD correction on air gap

For some IORT cases, anatomical structures interfere with applicator placement, making flush contact between

Table 1. Electron-beam parameters for a 12 cm applicator at a 100 cm source-to-surface dose*

Nominal energy	6	9	12	15	16
$E_{p,o}$ (MeV)†	6.1	8.8	11.7	14.4	16.1
Flat applicator (θ = 0°)					
D_S (%)‡	72	79	84	85	87
R_{100} (cm)	1.40	1.90	2.50	3.10	3.30
R_{90} (cm)	1.80	2.70	3.60	4.50	5.00
R_{80} (cm)	2.00	2.95	3.95	4.95	5.50
R_{50} (cm)	2.35	3.50	4.65	5.85	6.55
R_{20} (cm)	2.75	4.00	5.35	6.65	7.45
R_{10} (cm)	2.90	4.25	5.65	7.05	7.90
D_λ (%)§	0.4	0.8	1.3	2.1	2.1
Beveled applicator (θ = 22.5°)					
D_S (%)‡	80	81	85	86	88
R_{100} (cm)	1.00	1.60	2.20	2.60	2.80
R_{90} (cm)	1.55	2.30	3.10	3.95	4.40
R_{80} (cm)	1.70	2.60	3.50	4.45	4.95
R_{50} (cm)	2.20	3.20	4.30	5.45	6.05
R_{20} (cm)	2.60	3.80	5.10	6.40	7.10
R_{10} (cm)	2.80	4.10	5.45	6.80	7.55
D_λ (%)§	0.3	0.7	1.1	1.8	1.8

* All parameters were determined along the clinical axis.

† $E_{p,o}$ (MeV) = 1.95 R_p (cm) + 0.48 (from ICRU Report 35 (37)), where R_p is the electron practical range.

R_x: depth of dose, x as a percentage of maximum dose. Note that R_{90} and R_{80} are distal depths from the surface.

‡ D_S: surface dose as a percentage of the maximum dose.

§ D_λ: percentage of x-ray contamination, measured at a depth of R_{10} + 2 cm.

From Nyerick, C. E.; Ochran, T. G.; Boyer, A. L.; Hogstrom, K. R. Dosimetry characteristics of metallic cones for intraoperative radiotherapy. Int. J. Radiat. Oncol. Biol. Phys. 21:501–510; 1991 (Table 1, p. 504).

the end of the treatment applicator and the tumor-bearing site impossible. In such cases, the air gap (measured) and inverse square correction (calculated) factors can be used additionally to calculate the dose. Figure 4 defines the general clinical arrangements for IORT applicators with an air gap, g, measured perpendicularly from the water surface to the distal applicator end. To calculate gap factors, a few terms must be defined. Source-to-applicator-end distance (SAED) is defined as 100 cm in this instance and is related to the variable SSD by SSD = SAED + g.

Although the inverse square factor (ISF) is calculated using the relationship

$$ISF = [(SAED + d_{max})/(SSD + d_{max})]^2 \quad \text{(Eq. 2)}$$

it is precisely given by

$$ISF = [(SAED + \cos\theta \cdot d_{max})/(SAED + \cos\theta \cdot d_{max} + g/\cos\theta)]^2 \quad \text{(Eq. 3)}$$

The difference between these two equations for distances of less than 2 cm causes insignificant error. The output for an IORT applicator can change not only by the inverse square factor, but also as a result of side-scatter equilibrium on the central axis. This can be accounted for by a gap factor. The gap factor, which is a measure of the deviation of the output factor from that predicted by the inverse square alone (49), is defined to be

$$GF = [O(g)/O(g = 0)]/ISF \quad \text{(Eq. 4)}$$

where $O(g)/O(g = 0)$ is the ratio of measured dose output with an air gap, g, to that with no air gap for the same diameter applicator and energy. The gap factor should be measured for at least the smallest and largest applicator at all energies. Air gaps greater than 4 cm are rarely encountered clinically.

Field blocking corrections

Some tissues may need to be spared exposure to the radiation treatment; therefore, measurements must be made for shields that will be placed in the body to shield areas adjacent to or beneath the treated area. Sometimes, lead foil has been used to limit the dose to the tissue inside the treatment area, but if that tissue can be placed outside the treatment volume by selection of a smaller or differently shaped applicator, then that should be preferred. In general, the dose per monitor unit does not change significantly, provided the fraction of area blocked is small.

SPECIAL DOSIMETRY CONSIDERATIONS

Leakage

One of the advantages of IORT is that the area to be irradiated can be localized and critical normal tissue can be placed outside the targeted area with normal tissue, thus receiving a much lower dose. The dose to the surrounding tissues can still be greater than desired, however, because of leakage through the applicator wall and through the collimation system. The tissues of concern may be located lateral to the treated area beyond the applicator end or next to the side of the applicator.

McCullough and Anderson (46) reported that profiles in water below an IORT applicator showed leakage in excess of 10% outside the penumbra for 18 MeV electrons with large field sizes. This was due to leakage through the primary collimation system and was reduced by providing additional shielding using brass rings on top of the applicator. Fraass *et al.* (24) demonstrated an increased peripheral dose caused by leakage through an acrylic applicator wall with 20 MeV electrons. Sleeves of stainless steel were placed around the applicator to reduce the leakage radiation. Before placing a treatment applicator into clini-

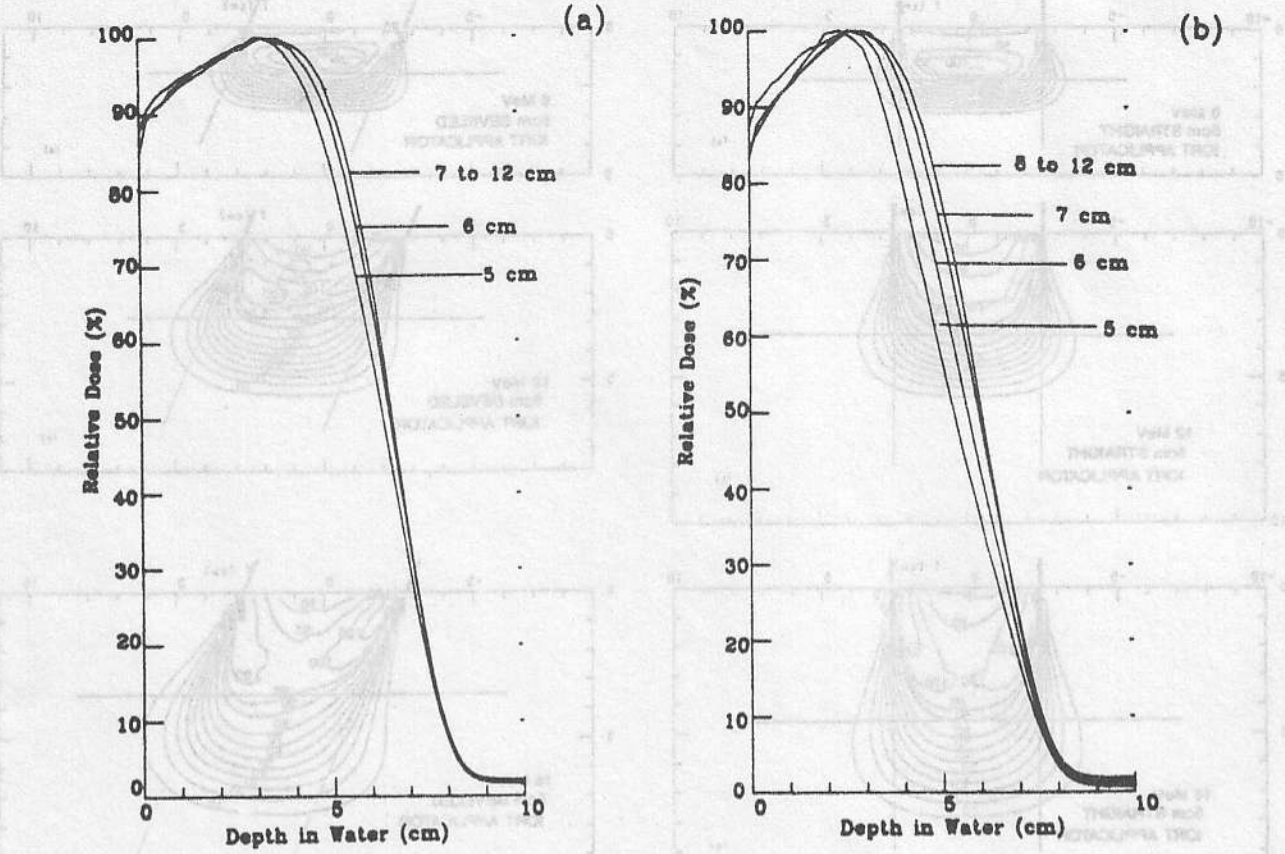

Fig. 6. Percent depth dose along the clinical axis for 16 MeV with IORT applicators ranging in diameter from 5 to 12 cm. (a) Flat applicators at 100 cm SSD, (b) beveled applicators at 100 cm SSD (bevel angle = 22.5°). From Nyerick, C. E.; Ochran, T. G.; Boyer, A. L.; Hogstrom, K. R. Dosimetry characteristics of metallic cones for intraoperative radiotherapy. Int. J. Radiat. Oncol. Biol. Phys. 21:501–510; 1991 (Fig. 4, p. 505).

cal service, extent of leakage around the end of the applicator and through the side wall should be determined.

The effect of leakage through the side wall of the applicator can be measured by placing film in a solid phantom. The phantom should be placed perpendicular to the outer surface of the applicator and parallel to the central axis. Comparison of this exposed film to one exposed at the end of the applicator will demonstrate amount of leakage and where it is greatest. Leakage can also be measured by ionization chambers or thermoluminescent dosimeters (TLDs). An example of leakage through a methyl methacrylate plastic applicator measured by an ionization chamber is shown in Fig. 8. The amount of leakage through the applicator wall is dependent on size of the primary photon collimators, applicator wall material and thickness of the material, type and/or amount of shielding on top of the applicator or in the applicator adapter, and size of the applicator.

Surface dose

Surface dose in IORT should be close to the prescribed dose. Typically, lower energy electron beams have lower surface dose. It may sometimes be necessary to increase the surface dose. This can be achieved easily by covering the target surface with wet sterile gauze. If wet gauze is used to achieve the bolus effect, additional thickness should be accounted for in the selection of appropriate electron energy for IORT.

Field matching

Sometimes, the area to be treated is larger than the available applicator size, and it is necessary to match two or more fields. The IORT procedure involves giving a large single-fraction dose. Consequently, the effects of underdosing or overdosing the matching region may be more pronounced than seen with fractionated external electron treatments.

Fraass *et al.* (24) used either a gap or overlap, depending on the electron energy used, to achieve better dose uniformity in the matched region. In both cases, either rectangular or "squircle" (flat on one side, circular on the other) applicators were used.

Because abutting adjacent fields is difficult, the best method for treating large fields is to use large applicators that encompass the entire treatment area. Large elliptical and rectangular applicators can be made that will cover

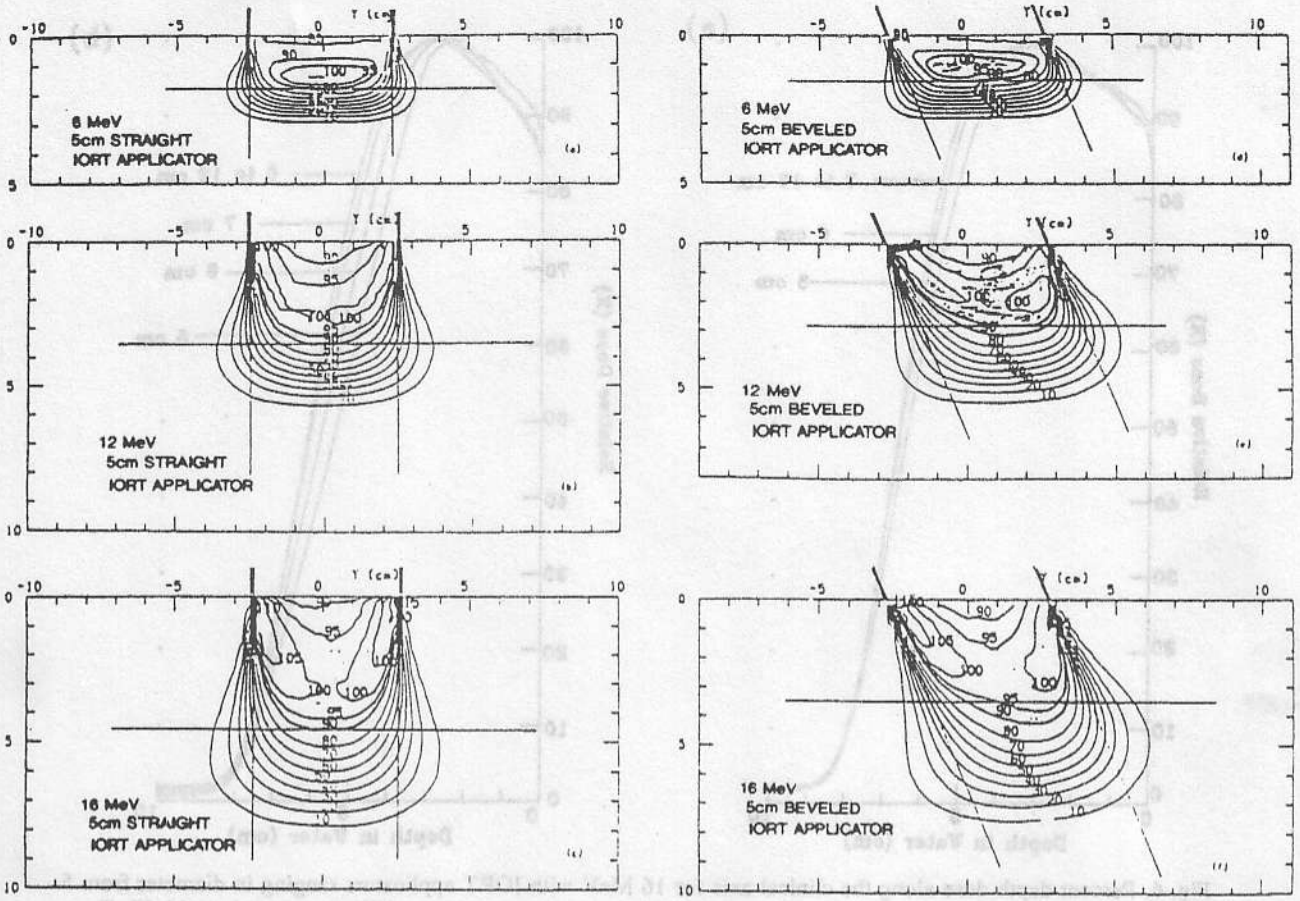

Fig. 7. Isodose contours measured with 5-cm diameter flat and beveled applicators at 6 MeV, 12 MeV, and 16 MeV. Note the horizontal reference line is at the depth of the 90% isodose; the two reference lines projected from the surface are parallel extensions of the inside applicator wall. From Nyerick, C. E.; Ochran, T. G.; Boyer, A. L.; Hogstrom, K. R. Dosimetry characteristics of metallic cones for intraoperative radiotherapy. Int. J. Radiat. Oncol. Biol. Phys. 21:501–510; 1991 (Fig. 6, p. 506).

the majority of treatment situations, reducing the need for matching fields to a rare occurrence.

Blood and fluid accumulation

Depending on the surgical site, blood accumulation can be of concern during the IORT procedure. Fluid buildup inside the applicator will decrease the tissue penetration of the electron beam, possibly resulting in underdosage of deeper tissues. Suction tubes can be placed around the outside of the applicator to remove any fluid during treatment. Most IORT applicators have an access port in the side to permit the insertion of a suction tube into the applicator.

TREATMENT DELIVERY AND DOCUMENTATION

The treatment procedure should be a process with checks and balances. As discussed at the start, the IORT team involves many different people with different responsibilities. It is recommended that a procedure list be developed. An example of a treatment checklist is shown in Appendix A.1.

Selection of applicator and bevel

The size and the bevel of the IORT applicator selected are determined by the lateral extent of the area to be treated, as well as the physical size of the body cavity. Adequate margins must be provided, taking into consideration the lateral constriction of the isodose curves as a function of depth. The beveled IORT applicators can help keep normal tissues out of the irradiated field, as well as accommodate different anatomical sites. Sometimes critical structures at the margin of the treatment area are also a consideration in the selection of the applicators.

Selection of energy

Two factors must be considered when selecting the energy and treatment depth. If critical structures lie deep to the treatment volume, then a balance must be struck in selecting an energy that will adequately cover the treat-

Table 2. Lateral therapeutic coverage of 90% isodose contour for different sized applicators at different energies

Nominal energy (MeV) Applicator diameter	Width (cm)	6	9	12	15	16
Flat applicator (θ = 0°)						
5 cm	*	tangent	tangent	tangent	tangent	tangent
	†	3.7	4.1	4.4	4.5	4.5
7 cm	*	5.1	4.3	3.6	tangent	tangent
	†	6.5	6.5	6.6	6.6	6.6
9 cm	*	7.3	7.1	6.3	6.0	5.0
	†	8.6	8.7	8.7	8.7	8.6
12 cm	*	10.9	10.5	10.3	9.6	9.3
	†	11.7	11.8	11.8	11.8	11.7
Beveled applicator (θ = 22.5°)						
5 cm	*	tangent	tangent	2.9	3.00	3.4
	†	4.3	4.7	4.9	5.0	5.0
7 cm	*	1.5	2.2	tangent	tangent	3.7
	†	6.9	7.1	7.2	7.2	7.2
9 cm	*	3.0	2.9	6.7	1.5	tangent
	†	9.3	9.3	9.4	9.3	9.3
12 cm	*	11.6	11.7	11.4	10.7	3.3
	†	12.8	12.8	12.8	12.7	12.7

* At depth of 90% isodose line (d_{90}).

† At half the depth of 90% isodose line ($d_{90}/2$).

Tangent indicates that width at depth of 90% isodose line is zero because of constriction of isodose line.

Tabulated from Nyerick, C. E.; Ochran, T. G.; Boyer, A. L.; Hogstrom, K. R. Dosimetry characteristics of metallic cones for intraoperative radiotherapy. Int. J. Radiat. Oncol. Biol. Phys. 21:501–510, 1991 (Figs. 6 and 7, pp. 506 and 507).

ment area, but also not overdose the critical normal tissue. The selection of the energy can be facilitated with the use of diagnostic ultrasound to accurately determine the depth of the target volume.

Field shaping

In some situations, normal tissues will be within the IORT field, and field shaping must be used. Sterile lead shields are commonly used and can be cut to the desired shape in the OR before being wrapped in sterile gauze. Other methods involve using applicator inserts or prefabricated templates.

Monitor unit calculation

The monitor units must be calculated that will deliver the prescribed dose for the energy and applicator selected. It is convenient to design a monitor unit calculation sheet on which all the important parameters are noted and monitor unit calculations are done manually (Appendix A.2). Monitor unit calculations must be independently double checked before the treatment.

Radiation treatment

Before treatment is initiated, a designated person should be responsible for assuring that all personnel have left the room and that all access to the treatment room is closed and locked. The individual operating the linear accelerator should be in communication with anesthesia and surgery personnel in case the treatment must be interrupted in an emergency situation.

Dose recording

Dose calculations must be documented, and a copy must be placed in the patient's chart. A hard copy of the ultrasound scan, if used in selecting the energy, should be placed in the patient's chart also. Sometimes, *in vivo* dosimeters like TLDs are used to monitor the dose delivered both to the treatment site and to surrounding tissues.

TREATMENT VERIFICATION

Because IORT treatments typically involve only a single fraction of dose, verification that the dose has been delivered to the proper anatomical location and depth is extremely important. Several methods of verification are outlined below. Careful documentation of all verification techniques should be included in the patient's record.

In addition, a description of the treatment in the chart is helpful in assessing the appropriateness of the treatment and in reconstructing the irradiated volume if retreatment is necessary.

Beam's-eye view photographs

Probably the simplest and most straightforward method for verifying the treatment area is the beam's-eye view photograph. As previously discussed, it is mandatory that

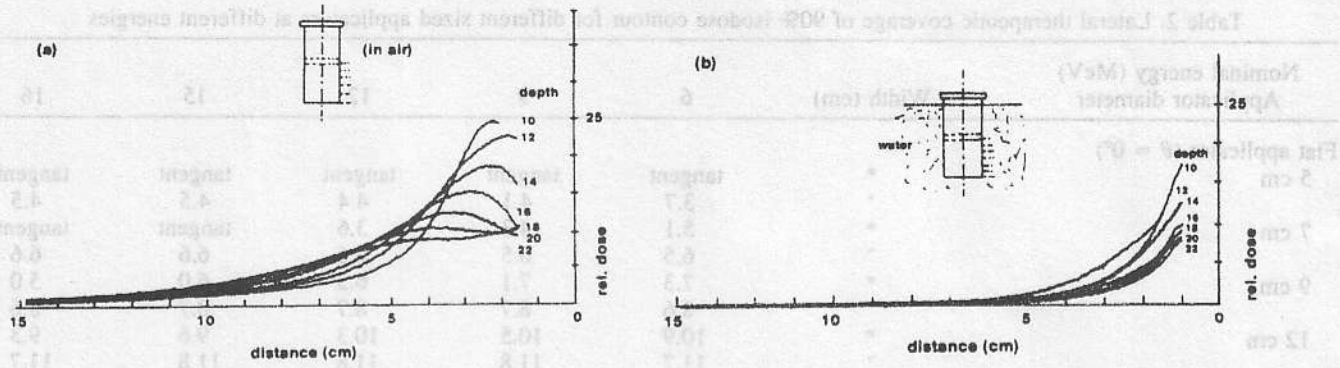

Fig. 8. Leakage radiation through the walls of the 10-cm diameter, 22-cm long applicator for 22 MeV electron beam. Data are normalized to the maximum dose in water on the clinical axis at 100 cm SSD. The depths are the distances from the top of the applicator. (a) Scans measured in air; (b) scans measured in water. The "distance" along the x-axis represents distance from the outer surface of the applicator. From Palta, J. R.; Suntharalingam, N. A nondocking intraoperative electron beam applicator system. Int. J. Radiat. Oncol. Biol. Phys. 17:411–417; 1989 (Fig. 9, p. 417).

the site to be treated, as well as critical structures adjacent to the treatment field, be visually identified, which can be done using either a periscope or a direct viewing device. A photograph of the view should be placed in the patient's treatment record as evidence that the applicator was correctly placed and aligned. Remote monitoring during the irradiation is suggested also.

On-line monitoring

With the availability of fiberoptic imaging devices and polyester film-mirrored camera systems, it is now possible to monitor the irradiation on-line during the actual treatment. Although this is recommended, it is not mandatory and is probably feasible only at the most active IORT facilities.

Ultrasound hard copy

Ultrasound should be performed just before applicator placement to determine the treatment depth and, therefore, the electron energy to be used. A hard copy of the ultrasound image should be included in the patient's record.

QUALITY ASSURANCE FOR IORT

The need for quality assurance (QA) in medicine, in radiation oncology in particular, and especially in IORT is evident. When a single large fraction of radiation is given to a particular area after a normal course of fractionated radiation, the total dose can often exceed the normal tissue tolerance if given to the wrong anatomic area. In the performance of IORT, because most personnel involved are from outside the radiation therapy department and are not trained in general radiation safety measures, the correct functioning of radiation safety interlocks is of special importance.

Quality assurance checks for IORT can be divided into those for dedicated machines and those for machines in the radiation therapy department that are normally used for external-beam treatment. For dedicated machines, perform the usual daily, monthly, and annual checks done for all radiation therapy treatment machines. The required checks are listed in a recent AAPM Task Group report on comprehensive quality assurance (45). On the other hand, output calibrations just before the IORT procedure are unnecessary if the electron beams are calibrated daily for external-beam therapy. Under those circumstances, the QA procedures for the nondedicated machine would be much simpler than for the dedicated machine.

Additionally, a dedicated machine for IORT located in the OR area probably has shielding that was designed for a maximum of 5–10 cases (or 100–200 Gy) per week. The check procedures used in this case should involve as little radiation exposure as possible. For example, film would be better than a water phantom scanning system for verifying isodose curves or percent depth–dose curves.

The Radiation Therapy Oncology Group (RTOG) has sponsored the Radiological Physics Center (RPC) quality assurance program for interinstitutional electron IORT clinical trials. The ion chamber measurements from 16 institutions and readings from TLDs mailed to a total of 22 institutions suggest that outputs within

traditionally acceptable ± 5% ranges are achievable with electron IORT applicators (33). The evaluation of depth–dose data by the RPC suggests that care is needed in measuring the depth–dose characteristics for these applicators, especially for beveled devices, because approximately 10% of the beams measured in the QA survey did not meet the RPC 3 mm criterion for depth–dose agreement. Most of the measurements that disagreed by more than 3 mm were from either small applicators (≤ 6 cm diameter) or beveled ones. Services of the RPC are available to all IORT users, and it is recommended that they be used as a part of an outside, independent check on the institution's dosimetry.

QA checks before treatment

Quality assurance procedures for a dedicated IORT program are described comprehensively by Davis and Ochran (20).

1. Sterilize all applicators, other IORT devices, and lead sheets. (To allow sufficient time, this is usually done 1–2 days before the procedure.)
2. Check that all other apparatus and devices are functioning correctly. Check the mechanical security of docking apparatus and attachments, and the integrity of the sheet of strong polyester film that isolates the machine from the patient.
3. Implement a simplified procedure for checking the constancy of electron output. A quick, reliable procedure is especially important for a dedicated facility where access to the machine is very limited and checks must be made just before surgery.
4. Check door interlocks, warning lights, and video and audio systems for operational integrity.
5. Check the setting of the adjustable secondary photon jaws of the accelerator.
6. Check field size of tertiary collimators, if there are any.
7. Check document settings (energy, applicator size and shape, additional shielding, gantry and couch settings, and other pertinent factors) for each procedure on the appropriate check sheet.

Monthly QA checks

1. Calibrate electron beams using standard departmental procedures.

Yearly QA checks

1. Check applicator ratios for all applicators and energies. If, after a few years, the output factors appear to be constant to within 2–3%, then it is acceptable to perform annual spot checks on the applicator inventory. Different applicators and energies should be selected for testing each year.
2. Check percent depth–dose and isodose curves for sample applicators and energies. Again, different applicators and energies should be checked each year.
3. Check flatness for sample applicators and energies. For a dedicated machine, checking the flatness of an applicator-free open field may be useful.

DOSE SPECIFICATION AND REPORTING

Dose specification

Dose prescription point. For external electron-beam treatments, the depth at which the dose is specified has varied between the 80% dose and the 100% dose. The trade-off is between a lower energy that spares deeper tissues, resulting in a higher maximum dose, and a higher energy with a greater integral dose to underlying tissues, but a lower maximum dose. Traditionally, IORT procedures under the RTOG protocol have specified that the 90% isodose line covers the target volume, whereas the International Commission on Radiation Units and Measurements (ICRU) (37) recommends that the dose be prescribed at d_{max}. Therefore, both the 90% dose and the maximum dose should be reported.

Lateral coverage. The 90% isodose line is often used by the radiation oncologist to check whether the tumor is receiving sufficient dose coverage. This is best done by inspection of the appropriate isodose curves. Care must be used when judging this from beam profiles, because the 90% dose width changes rapidly with depth. Use of isodose curves in conjunction with the percent depth–dose curves to assess the adequacy of the coverage is recommended.

Dose reporting

Treatment volume: Depth and lateral dimensions. From the physical standpoint, the important treatment parameters to record are the beam energy, which determines the depth of the 90% dose, and the size and angle of the beveled applicator, which determine the size of the radiation field. This assumes that full dosimetric documentation of each applicator exists and can be referenced whenever necessary.

Maximum target dose. Location and size of the maximum target dose depend on the size of the horns, which, in turn, depends on the electron collimator system. The maximum dose generally is not easy to determine precisely, because, unlike a central axis maximum, its position depends on both depth and off-axis position; it can be determined, however, to within 2–3% with a scanning system.

Minimum target dose. The minimum target dose is usually taken to be the prescription dose. For electron beams with horns, where the 90% isodose line is pushed out, this is probably a safe assumption. If the beam has minimal or no horns, however, the possibility remains that an area of the target volume is below this dose. It

is important, therefore, to review the percent depth–dose data, isodose curves, and any other pertinent dosimetry with the radiation oncologist immediately before the treatment.

REFERENCES

1. Abe, M. Intraoperative radiotherapy—Past, present, future. Int. J. Radiat. Oncol. Biol. Phys. 1987–1990; 1984.
2. Abe, M.; Fukuda, M.; Yamona, K.; Matsuda, S.; Handa, H. Intraoperative irradiation in abdominal and cerebral tumors. Acta Radiol. 10:408–416; 1971.
3. Abe, M.; Takahashi, M. Intraoperative radiotherapy: The Japanese experience. Int. J. Radiat. Oncol. Biol. Phys. 7:863–868; 1981.
4. Abe, M.; Takahashi, M.; Yabumoto, E.; Adachi, H.; Yoshii, M.; Mori, K. Clinical experiences with intraoperative radiotherapy of locally advanced cancers. Cancer 45:40–48; 1980.
5. Abe, M.; Takahashi, M.; Yabumoto, E.; Onoyama, Y.; Torizuka, K.; Tobe, T.; Mori, K. Techniques, indications and results of intraoperative radiotherapy of advanced cancers. Radiology 116:693–702; 1975.
6. Abe, M.; Yabumoto, E.; Takahashi, M.; Tobe, T.; Mori, K. Intraoperative radiotherapy of gastric cancer. Cancer 34:2034–2041; 1974.
7. Abuchaibe, O.; Calvo, F. A.; Azinovic, I.; Aristu, J.; Pardo, F.; Alvarez-Cienfuegos, J. Intraoperative radiotherapy in locally advanced recurrent colorectal cancer. Int. J. Radiat. Oncol. Biol. Phys. 26:859–867; 1993.
8. Archembeau, J. O.; Aitken, D.; Potts, T. M.; Slater, J. M. Cost-effective available-on-demand intraoperative radiation therapy. Int. J. Radiat. Oncol. Biol. Phys. 15:775–778; 1988.
9. Bagne, F. R.; Samsami, N.; Dobelbower, R. R. Radiation contamination and leakage assessment of intraoperative electron applicators. Med. Phys. 15:530–537; 1988.
10. Bane, C. L.; Shurkus, L. M. Caring for intraoperative radiation patients. AORN J. 37:840–846; 1983.
11. Bashein, G.; Russel, A. H.; Mommii, S. T. Anesthesia and remote monitoring for intraoperative radiation therapy. Anesthesiology 64:804–807; 1986.
12. Beck, C. An external roentgen treatment of internal structures (eventration treatment). N.Y. Med. J. 89:621–622; 1909.
13. Biggs, P. J. The effect of beam angulation on central axis percent depth dose for 4–29 MeV electrons. Phys. Med. Biol. 29:1089–1096; 1984.
14. Biggs, P. J.; Epp, E. R.; Ling, C. C.; Novack, D. H.; Michaels, H. B. Dosimetry, field shaping and other considerations for intra-operative electron therapy. Int. J. Radiat. Oncol. Biol. Phys. 7:875–884; 1981.
15. Biggs, P. J.; McCullough, E. C. Physical aspects of intraoperative electron beam radiation. In: Gunderson, L. L.; Tepper, J. E., eds. Intraoperative and external beam irradiation. Chicago: Yearbook Medical Publishers; 1983.
16. Calvo, F. A.; Micaily, B.; Brady, L. W. Intraoperative radiotherapy. A positive view. Am. J. Clin. Oncol. 16:418–423; 1993.
17. Calvo, F. A.; Ortiz De Urbina, D.; Abuchaibe, O.; Azinovic, I.; Aristu, J.; Santos, M.; Escude, L.; Herreros, J.; Llorens, R. Intraoperative radiotherapy during lung cancer surgery: Technical description and early clinical results. Int. J. Radiat. Oncol. Biol. Phys. 19:103–109; 1990.
18. Coia, L. R.; Hanks, G. E. The need for subspecialization: Intraoperative radiation therapy. Int. J. Radiat. Oncol. Biol. Phys. 24:891–893; 1992.
19. Dahl, R. A.; McCullough, E. C. Determination of accurate dosimetric parameters for beveled intraoperative electron beam applicators. Med. Phys. 16:130–131; 1989.
20. Davis, M. G.; Ochran, T. G. A quality assurance program for intraoperative radiotherapy linear accelerator. In: Starkschall, G.; Horton, J., eds. Quality assurance in radiotherapy physics; Proceedings of an American College of Medical Physics Symposium; 1991:113–119.
21. Dobelbower, R. R. Intraoperative radiation therapy. Rev. Bras. Cancerol. 33:207–226; 1987.
22. Ekstrand, K. E.; Dixon, R. L. The problem of obliquely incident beams in electron-beam treatment planning. Med. Phys. 9:276–278; 1982.
23. Finsterer, H. Zur therapie inoperabler magen- und darmkarzinome mit freilegung und nachfolgender röntgenbestrahlung. Strahlentherapie 6:205–213; 1915.
24. Fraass, B. A.; Harrington, F. S.; Kinsella, T. J.; Sindelar, W. F. Television system for verification and documentation of treatment fields during intraoperative radiation therapy. Int. J. Radiat. Oncol. Biol. Phys. 9:1409–1411; 1983.
25. Fraass, B. A.; Miller, R. W.; Kinsella, T. J.; Sindelar, W. F.; Harrington, F. S.; Yeakel, K.; Van de Geijn, J.; Glatstein, E. Intraoperative radiation therapy at the National Cancer Institute: technical innovations and dosimetry. Int. J. Radiat. Oncol. Biol. Phys. 11:1299–1311; 1985.
26. Goldson, A. L. Past, present, and future prospects of intraoperative radiotherapy (IOR). Semin. Oncol. 8:59–64; 1981.
27. Goldson, A. L. Preliminary clinical experience with intraoperative radiotherapy. J. Natl. Med. Assoc. 70:493–495; 1978.
28. Goldson, A. L.; Ashaveri, E.; Espinoza, M. C.; Roux, V.; Cornwell, E.; Rayford, L.; McLaren, M.; Nibhanupudy, R.; Mahan, A.; Taylor, H. F.; Hemphil, N.; Pearson, O. Single high dose intraoperative electrons for advanced stage pancreatic cancer: Phase I pilot study. Int. J. Radiat. Oncol. Biol. Phys. 7:869–874; 1981.
29. Goldson, A. L.; Delgado, G.; Hill, L. T. Intraoperative radiation of the paraaortic nodes in cancer of the uterine cervix. Obstet. Gynecol. 52:713–717; 1978.
30. Gunderson, L. L.; Cohen, A. C.; Dosoretz, D. D.; Shipley, W. U.; Hedberg, S. E.; Wood, W. C.; Rodkey, G. V.; Suit, H. D. Residual, unresectable, or recurrent colorectal cancer: External beam irradiation and intraoperative electron beam boost ± resection. Int. J. Radiat. Oncol. Biol. Phys. 9:1597–1606; 1983.
31. Gunderson, L. L.; Martin, J. K.; Beart, R. W., Nagorney, D. M.; Fieck, J. M.; Wieand, H. S.; Martinez, A.; O'Connell, M. J.; Martenson, J. A.; McIlrath, D. C. Intraoperative and external beam irradiation for locally advanced colorectal cancer. Abstract. Int. J. Radiat. Oncol. Biol. Phys. 12(Suppl. 1):147–148; 1986.
32. Gunderson, L. L.; Martin, J. K., Jr.; Earle, J. D; Byer, D. E.; Boss, M.; Fieck, J. M.; Kvols, L. K.; Rorie, D. K.; Martinez, A.; Nagorney, D. M.; O'Connell, M. J.; Weber, F. C. Intraoperative and external beam irradiation with or without resection: Mayo pilot experience. Mayo Clin. Proc. 59:691–699; 1984.
33. Hazle, J. D., Chu, J. C. H., Kennedy, P. Quality assurance for intraoperative electron radiotherapy clinical trials: Ionization chamber and mailable thermoluminescent dosimeter results. Int. J. Radiat. Oncol. Biol. Phys. 24:559–563; 1992.

34. Hilderley, L. J. The role of the nurse in radiation oncology. Semin. Oncol. 7:39–47; 1980.
35. Hogstrom, K. R.; Boyer, A. L.; Shiu, A. S.; Ochran, T. G.; Kirsner, S. M.; Krispel, F.; Rich, T. A. Design of metallic electron beam cones for an intraoperative therapy linear accelerator. Int. J. Radiat. Oncol. Biol. Phys. 18:1223–1232; 1990.
36. Hollon, D. A. Intraoperative radiotherapy: An overview. Radiol. Technol. 56:424–428; 1985.
37. ICRU Report 35. Radiation dosimetry: Electron beams with energies between 1 and 50 MeV. Bethesda, MD: International Commission on Radiation Units and Measurements; 1984.
38. Johnstone, P. A.; Sindelar, W. F.; Kinsella, T. J. Experimental and clinical studies of intraoperative radiation therapy. Curr. Probl. Cancer. 18(5):249–290; 1994.
39. Jones, D. Apparatus, technique and dosimetry of intraoperative electron beam therapy. In: Vaeth, J. M.; Meyer, J. L., eds. The role of high energy electrons in the treatment of cancer. Front. Radiat. Ther. Oncol. 25:233–245; 1991.
40. Jones, D.; Taylor, E.; Travaglini, J.; Vermeulen, S. A noncontacting intraoperative electron cone apparatus. Int. J. Radiat. Oncol. Biol. Phys. 16:1643–1647; 1989.
41. Khan, F. M.; Doppke, K. P.; Hogstrom, K. R.; Kutcher, G. J.; Nath, R.; Prasad, S. C.; Purdy, J. A.; Rozenfeld, M.; Werner, B. L. Clinical electron-beam dosimetry: Report of AAPM Radiation Therapy Committee Task Group No. 25. Med. Phys. 18:73–109; 1991.
42. Kinsella, T. J.; Glatstein, E.; Sindelar, W. F. Intraoperative radiotherapy. Hosp. Prac. 20:125–141; 1985.
43. Kinsella, T. J.; Sindelar, W. F. Intraoperative radiation therapy. In: DeVita, V. T.; Hellman, S., Rosenberg, S. A., eds. Principles and practice of oncology, 2nd ed. Philadelphia, PA: Lippincott Co.; 1985:2293–2304.
44. Konski, A.; Neisler, J.; Phibbs, G.; Bronn, D.; Dobelbower, R. R., Jr. The use of intraoperative electron beam radiation therapy in the treatment of para-aortic metastases from gynecologic tumors: A pilot study. Am. J. Clin. Oncol. 16:67–71; 1993.
45. Kutcher, G. J.; Coia, L.; Gillin, M.; Hanson, W. F.; Leibel, S.; Morton, R. J.; Palta, J. R.; Purdy, J. A.; Reinstein, L. E.; Svensson, G. K.; Weller, M.; Wingfield, L. Comprehensive QA for radiation oncology: Report of AAPM Radiation Therapy Committee Task Group 40. Med. Phys. 21:581–618; 1994.
46. McCullough, E. C.; Anderson, J. A. The dosimetric properties of an applicator system for intraoperative electron-beam therapy utilizing a Clinac-18 accelerator. Med. Phys. 9:261–268; 1982.
47. McCullough, E. C.; Biggs, P. Physical aspects of intraoperative electron beam radiation. Curr. Probl. Cancer 7:24–30; 1983.
48. McCullough, E. C.; Biggs, P. J. Intraoperative electron beam radiation therapy. In: Kereiakes, J. G.; Elson, H. R.; Born, C. G., eds. Radiation oncology physics—1986. American Association of Physicists in Medicine, Medical Physics Monograph No. 15. New York: American Institute of Physics; 1987:333–347.
49. Meyer, J. A.; Palta, J. R.; Hogstrom, K. R. Demonstration of relatively new electron dosimetry measurement techniques on the Mevatron 80. Med. Phys. 11:670–677; 1984.
50. Mills, M. D.; Almond, P. R.; Boyer, A. L.; Ochran, T. G.; Madigan, W. P.; Rich, T. A.; Dally, E. B. Shielding considerations for an operating room based intraoperative electron radiotherapy unit. Int. J. Radiat. Oncol. Biol. Phys. 18:1215–1221; 1990.
51. Nelson, C. E.; Cook, R.; Rakfal, S. The dosimetric properties of an intraoperative radiation therapy applicator system for a Mevatron-80. Med. Phys. 16:794–799; 1989.
52. Nishimura, A.; Nakano, M.; Otsu, H.; Nakano, K.; Iida, K.; Sakata, S.; Iwabuchi, K.; Maruyama, K.; Kihara, M.; Okamura, T.; Todoroki, T.; Iwasaki, Y. Intraoperative radiotherapy for advanced carcinoma of the pancreas. Cancer 54:2375–2384; 1984.
53. Nyerick, C. E.; Ochran, T. G.; Boyer, A. L.; Hogstrom, K. R. Dosimetry characteristics of metallic cones for intraoperative radiotherapy. Int. J. Radiat. Oncol. Biol. Phys. 21:501–510; 1991.
54. Palta, J. R.; Suntharalingam, N. A nondocking intraoperative electron beam applicator system. Int. J. Radiat. Oncol. Biol. Phys. 17:411–417; 1989.
55. Pass, H. I.; Sindelar, W. F.; Kinsella, T. J.; DeLuca, A. M.; Barnes, M.; Kurtzman, S.; Hoekstra, H.; Roth, J.; Glatstein, E. Delivery of intraoperative radiation therapy after pneumonectomy: Experimental observations and early clinical results. Ann. Thorac. Surg. 44:14–20; 1987.
56. Rich, T. A.; Cady, B.; McDermott, W. V.; Kase, K. R.; Chaffey, J. T.; Hellman, S. Orthovoltage intraoperative radiotherapy: A new look at an old idea. Int. J. Radiat. Oncol. Biol. Phys. 10:1957–1965; 1984.
57. Shibamoto, Y.; Yamashita, J.; Takahashi, M.; Abe, M. Intraoperative radiation therapy for brain tumors with emphasis on retreatment for recurrence following full-dose external beam irradiation. Am. J. Clin. Oncol. 17:396–399; 1994.
58. Shipley, W. U.; Wood, W. C.; Tepper, J. E.; Warshaw, A. L.; Orlow, E. L.; Kaufman, S. D.; Battit, G. E.; Nardi, G. L. Intraoperative electron beam irradiation for patients with unresectable pancreatic carcinoma. Ann. Surg. 200:289–296; 1984.
59. Shiu, A. S.; Otte, V. A.; Hogstrom, K. R. Measurement of dose distributions using film in therapeutic electron beams. Med. Phys. 16:911–915; 1989.
60. Sindelar, W. F.; Kinsella, T. J. Randomized trial of intraoperative radiotherapy in unresectable carcinoma of the pancreas. Abstract. Int. J. Radiat. Oncol. Biol. Phys. 12(Suppl. 1):148–149; 1986.
61. Sindelar, W. F.; Kinsella, T. J.; Tepper, J. E.; DeLaney, T. F.; Maher, M. M.; Smith, R.; Rosenberg, S. A.; Glatstein, E. Randomized trial of intraoperative radiotherapy in carcinoma of the stomach. Am. J. Surg. 165:178–186; 1993.
62. Svensson, H.; Hettinger, G. Influence of collimating systems in dose distributions from 10 to 35 MeV electron radiation. Acta Radiol. 6:404; 1967.
63. Tepper, J. E.; Cohen, A. M.; Wood, W. C.; Hedberg, S. E.; Orlow, E. Intraoperative electron beam radiotherapy in the treatment of unresectable rectal cancer. Arch. Surg. 121:421–423; 1986.
64. Tepper, J. E.; Gunderson, L. L.; Goldson, A. L.; Kinsella, T. J.; Shipley, W. U.; Sindelar, W. F.; Wood, W. C.; Martin, J. K. Quality control parameters of intraoperative radiation therapy. Int. J. Radiat. Oncol. Biol. Phys. 12:1687–1695; 1986.
65. Todoroki, T.; Iwasaki, Y.; Okamura, T.; Nagoshi, K.; Asakura, H.; Nakano, M.; Inada, T.; Tsunemoto, H.; Umegaki, Y.; Nishimura, A.; Nakano, M.; Sata, H. Intraoperative radiotherapy for advanced carcinoma of the biliary system. Cancer 46:2179–2184; 1980.
66. Toita, T.; Nakano, M.; Takizawa, Y.; Sueyama, H.; Kakihana, Y.; Kushi, A.; Ogawa, K.; Hara, R.; Sunakawa, H.; Arasaki, A.; Koja, S. Intraoperative radiation therapy (IORT) for head and neck cancer. Int. J. Radiat. Oncol. Biol. Phys. 30:1219–1224; 1994.

Appendix A1.

SAMPLE DOSIMETRY CHECKLIST

Date: _____
Patient Name: _____ I.D. # _____
Area Treated: _____
Radiation Oncologist: _____ Resident: _____
Surgeon: _____

1. [ ] Accelerator warmed-up and tested.
2. [ ] Beam output constancy checked.
3. [ ] Sterile dosimetry equipment available
   [ ] Applicators [ ] Applicator adaptor
   [ ] Lead [ ] Alignment tools
4. [ ] Remote monitoring equipment functioning.
5. [ ] Special dosimetry (e.g., TLDs) available.
6. [ ] Verify radiation safety exposure criteria.
7. [ ] Dose prescription.
8. [ ] Applicator selection.
9. [ ] Energy selection.
10. [ ] Primary collimation set for selected applicator.
11. [ ] SSD/Gap distance verified.
12. [ ] Machine and/or applicator interlocks set.
13. [ ] Blocking.
14. [ ] Monitor Units calculated.
15. [ ] Treatment room clear of personnel.
16. [ ] Treatment documentation.
17. [ ] List all dosimetry equipment used (applicators, lead, etc.)

_____

_____

Physicist: _____

Appendix A2.

SAMPLE MONITOR UNIT CALCULATION SHEET

Date: _____
Patient Name: _____ I.D. # _____
Area Treated: _____
Radiation Oncologist: _____ Resident: _____
Surgeon: _____
Accelerator: _____
Applicator size: _____ Electron energy: _____ MeV
d_{90} depth: _____ cm Surface dose: _____ %
Output factor: _____
Photon jaws: ___X___ cm Checked by: _____
Tumor depth: _____ cm
Prescribed dose: _____ Gy to _____ % isodose line.
Given dose = prescribed dose/ % isodose line · 100 = _____ Gy
Gap distance: _____ cm Applicator offset: _____ cm
Gap factor: _____ Offset factor: _____
Monitor unit (MU) = (Given Dose*Gap factor*Offset Factor)/Output factor
MU = (_____*_____*_____) / _____

Monitor Units Set
_____
_____
_____

Blocking: [ ] NO [ ] YES (description on other side)
Special Dosimetry: [ ] NO
[ ] YES (description on other side)
Time: _____AM PM _____
Physicist(s)
Sheet ____ of ____