Code of practice for brachytherapy physics: Report of the AAPM Radiation Therapy Committee Task Group No. 56

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Recommendations of the American Association of Physicists in Medicine (AAPM) for the practice of brachytherapy physics are presented. These guidelines were prepared by a task group of the AAPM Radiation Therapy Committee and have been reviewed and approved by the AAPM Science Council. © *1997 American Institute of Physics.*[S0094-2405(97)01410-7]

Key words: brachytherapy, interstitial brachytherapy, intracavitary brachytherapy, remote afterloaders, quality assurance

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PART 1. INFORMATION FOR RADIATION ONCOLOGY ADMINISTRATION

The present document has been developed in a style similar to the 1994 AAPM code of practice for radiotherapy accelerators,[1] which was devoted to x-ray and electron beam radiotherapy machines. It is intended to cover similar issues related to brachytherapy. Part I of this document is addressed to the radiation oncology administration, which may include a chief radiation oncologist, radiation oncology department administrator, or a hospital/free-standing center administrator. In these guidelines, the AAPM recognizes the importance of a team effort by administrators, radiation oncologists, medical physicists, dosimetrists, radiation therapists, health physicists, and engineers in establishing an optimal brachytherapy program.

Brachytherapy is the clinical use of small encapsulated radioactive sources at a short distance from the target volume for irradiation of malignant tumors or nonmalignant lesions. It plays an important role in the management of cancers of several sites, including the brain, head and neck, uterine cervix, endometrium, and prostate. Recently, there is growing interest in using brachytherapy for reducing restenosis after treatment for vascular diseases. Compared to conventional external beam therapy, the physical advantages of brachytherapy result from a superior localization of dose to the tumor volume. On the other hand, the dose gradients around an implant and dose heterogeneity within an implant are much higher than those in external beam radiotherapy. Unlike external beam fractionated radiotherapy, in low-dose rate brachytherapy, radiation is continuously delivered over an extended period of time. There are two forms of brachytherapy: intracavitary brachytherapy uses radioactive sources placed in body cavities in close proximity to the tumor; and interstitial brachytherapy uses radioactive seeds implanted directly into the tumor volume. Intracavitary brachytherapy is always temporary and usually takes from one to four days. On the other hand, interstitial brachytherapy can be temporary or permanent. Also, several manual and remote-controlled afterloading techniques have been introduced to reduce radiation exposure to medical personnel. Remote afterloaders, which have become very popular in the last ten years or so, provide the ability to irradiate tumors at a variety of dose rates from high-dose rate to conventional low-dose rate in a continuous or pulsed sequence. High-dose rate afterloaders provide brachytherapy as an outpatient procedure in many cases. Comprehensive radiation oncology services should have access to a remote afterloader.

Over the past two decades, great strides have been made in the technology of diagnostic imaging as a basis for tumor localization, in the physics of radiation dosimetry, in computer-assisted radiation treatment planning, and in the technology of external beam radiation machines and remote afterloading brachytherapy. These technological developments offer a wider spectrum of brachytherapy sources and technical capabilities, with new therapeutic possibilities. However, they pose new questions and problems to not only the radiation oncologist and the physicist, but also to the

institution's management team. Decision making in regard to new brachytherapy facilities involves many individuals with different expertise. It should start with the formulation of the radiation oncology needs of the institution based on the expected patient population and include the development of specifications for all proposed equipment, housing and support requirements, selection of the equipment itself, acceptance testing, commissioning, quality assurance, maintenance, and finally initial and continual staff training. Compliance with state and federal regulations, as well as recommendations from bodies such as the National Council on Radiation Protection and Measurements (NCRP), must be assured. In this document, where we differ on procedures or practices currently mandated by regulatory agencies, a footnote has been added to highlight the difference.

Brachytherapy treatment techniques are highly variable with respect to their complexity, the extent to which they are individualized to particular patients, and the degree to which they rely on prospective planning and dose calculations. On one end of the spectrum are manually afterloading intracavitary procedures, utilizing relatively simple devices (a fixed permanent radioactive source inventory and applicators), and straightforward manual calculations to define the loadings and treatment times for individual patients. In contrast, many recently developed brachytherapy techniques heavily utilize advanced technology for target localization, for planning and optimizing the proposed implant geometry, and for delivery and verification of the treatment itself. For example, three-dimensional localization of the target volume by magnetic resonance (MR), computed tomography (CT), ultrasound, or other imaging modalities is now standard of practice for implantation of tumors of the brain, prostate, and eye. The use of remote afterloading technology for both inpatient-and outpatient-based brachytherapy is rapidly growing, as is the use of image-guided applicator positioning technologies, e.g., stereotactically guided brain tumor implantation. This has been accompanied by rapid growth in the functionality and complexity of treatment planning software. Currently available systems commonly support improvement of implant quality by optimization of individual dwell times, correlation of dose distributions with imaging studies, and control of the remote afterloader during treatment delivery, in addition to the classical function of computing and displaying dose distributions.

Such technology-intensive treatment planning and delivery techniques offer the prospects of improved clinical outcome (in terms of improved local control and reduced complications), improved cost effectiveness, enhanced patient convenience, and, in some cases, a more conservative, organ-preserving treatment alternative to more morbid and disfiguring radical surgical approaches. However, such improvements come at the price of increased complexity, increased risk of serious treatment delivery errors and system malfunctions, and increased utilization of medical physicists, dosimetrists, therapists, health physicists, and radiation oncologists. Safe and effective use of any brachytherapy technique, however simple or complex, requires the involvement of a qualified medical physicist to (1) design and implement a brachytherapy facility that meets the clinical needs of the institution, (2) develop and implement treatment delivery procedures (for each clinical site and type of brachytherapy procedure) that accurately realize the clinical intent of the radiation oncologist, protect the patient from treatment delivery errors, maximize safety of the patient and staff, and, finally, minimize the legal and regulatory liability of the institution, and (3) ensure the accuracy and safety of each individual brachytherapy treatment through review of calculations, monitoring treatment team compliance to established procedures, and adapting procedures to meet the needs of unusual patients.

Each of the major roles listed above will be reviewed briefly in the following paragraphs. It is important for administrators to understand that brachytherapy treatment delivery is a team effort consisting of the medical physicist, along with appropriate support staff (dosimetrists, therapists, health physicists, and, in some cases, nurses) working in concert with the radiation oncologist to accurately and safely deliver the prescribed treatment. The physicist effectively serves as the leader of the team with respect to planning and treatment delivery, determining which tasks and quality assurance checks can be delegated to the team members, and which completed tasks require physicist review. For relatively simple manual afterloading implants, tasks such as source preparation, loading, room posting, and patient surveys can be assigned to support staff, and the direct role of the physicist limited to verification of treatment time and dose calculations, periodic quality assurance, and periodic record audits. On the other extreme, high-dose rate brachytherapy procedures and procedures requiring an implant to meet complex dosimetric specifications may require extensive involvement of the physicist in each case. The amount of physicist time and expertise required will depend on many variables, including (1) the sophistication of the technology used in planning and delivering treatment, (2) the extent to which implant dose distributions must be individualized to particular patients and the complexity of the optimization endpoints specified by the radiation oncologist, (3) the extent to which complex planning and delivery tasks have been ''proceduralized'' so that they can safely be assigned to support staff, (4) availability and sophistication of support staff, and (5) availability of labor-saving technology, such as computer-assisted optimization, which can eliminate the need for the time consuming and laborious manual optimization.

''Facility'' is used here in a general sense to include all permanent resources needed to implement the desired brachytherapy program including technical support personnel, treatment planning and delivery equipment, and dedicated space such as high-dose rate brachytherapy procedure rooms and inpatient rooms needed for delivery of low-dose rate brachytherapy. Facility design begins with the specification of sources, applicators, treatment delivery systems, software packages, and other needs. This involves close collaboration between the physicist and radiation oncologist to formulate the clinical needs of the program, the expected case load, and to identify specific pieces of equipment that

meet this need. Specification and identification of appropriate spaces for treatment delivery, source storage, and preparation is a task that requires close collaboration between the physicist and appropriate representatives of the hospital administration. An important endpoint is protection of personnel and visitors who occupy the spaces surrounding the treatment and source preparation facilities. A physicist is the only professional qualified to perform an analysis of the expected workload, and to design a system of structural or portable shielding to ensure that no staff or visitors receive exposures in excess of limits proscribed by Federal and state regulations.

Another important function of the physicist is licensing the proposed facility with the appropriate regulatory agency. In the U.S., medical use of reactor by-products, which includes virtually all radionuclides used in clinical brachytherapy, is very tightly and aggressively regulated at present by the U.S. Nuclear Regulatory Commission (NRC). Approximately two-thirds of the states, called agreement states, have negotiated an agreement with the NRC in which day-to-day NRC enforcement and licensing activities are assumed by an appropriate state agency governed by state regulations that parallel those of the NRC. In agreement states, the hospital must license its brachytherapy activities with the appropriate state agency.

All brachytherapy programs must be conducted under the authority of a license, i.e., a document that specifies the radioactive materials that may be possessed, their allowed uses, and the authorized users (usually board certified radiation oncologists) who may treat patients in the facility. The license is a contractual agreement between the hospital (not the physicians or the medical physicist) and the regulatory agency; thus the hospital administration is ultimately responsible for compliance with the terms of license. All licenses require that the institution have a radiation safety committee, consisting of representative users and a senior management representative, which monitors the use of radioactive materials in the hospital. The AAPM recommends that a brachytherapy physicist should be included as a member of the radiation safety committee. The hospital must have a radiation safety officer (RSO) who is responsible for operating the associated radiation safety program, which involves many activities, i.e., monitoring all occupationally exposed persons to ensure that their exposures are as low as reasonably achievable (ALARA); properly receiving, surveying, and logging in all radioactive sources; and implementing a quality management program (QMP) that complies with the regulations. The RSO is often a physician or a medical physicist in smaller programs. In large institutions, the RSO is usually a full-time professional health physicist.

In a small hospital that has not previously been a member of the regulated community, the physicist is the only on-site professional with the expertise to write a license application and to work with the administration to develop a radiation safety program and associated administrative structure. In large institutions the addition or enhancement of a brachytherapy program can often be handled by means of a license amendment or an additional specific license. In this case the medical physicist can work with the existing RSO and radiation safety committee to develop the application. The license will specify many procedural details that can have significant impact on day-to-day clinical operations, including the type and frequency of quality assurance procedures, nursing and operator training requirements, and even how often nursing personnel must check the implant for correct positioning. Whatever details the licensee agrees to in the licensing process become binding rules with the force of federal law behind them. By using an experienced physicist to draft the technical parts of the license application, the crippling effects of an overly restrictive license agreement can often be avoided.

Hospital administrators are warned to take very seriously the need to comply ''to the letter'' with all regulations and license requirements. The NRC and many agreement state counterparts have adopted a zero tolerance stance toward the regulated community. Inspectors will cite and fine the institution (and in some cases, individuals) for violating regulations and deviations from license commitments. Through its QMP regulations, the NRC has enlarged its domain to include quality and accuracy of patient treatments, as well as personnel protection. Certain types of treatment delivery errors, called ''misadministrations,'' must be reported to the NRC within 24 hours, regardless of whether there is potential for harm to the patient. A misadministration will almost certainly result in a special NRC inspection of your facility, notices of license and federal law violations, possible levying of fines and other punishments, such as publicizing the treatment error in the press, and requiring senior administrators to attend enforcement conferences at the NRC regional headquarters. Responding to misadministrations can consume hundreds of staff hours. Fortunately, the likelihood of such a scenario can be reduced to negligible levels by allocating sufficient time to a qualified medical physicist for developing and maintaining an appropriate quality assurance (QA) program. The main goal of the QA program is to protect the well-being of the patient and staff; however, an important secondary goal is to protect the legal interests of the institution.

The final components in implementing a brachytherapy treatment facility are installation, acceptance testing, and commissioning of all equipment. Again, the level of expertise and amount of time necessary for these activities depends on the complexity of the technology involved and the extent of the institution's established brachytherapy facilities. Installation can range from overseeing the construction of a dedicated HDR treatment suite, including structural shielding and dedicated imaging capability, to simply receiving a new set of manual afterloading sources. Acceptance testing and commissioning involve subjecting the newly installed equipment to exhaustive performance testing to determine whether the vendor's technical specifications and the institution's clinical specifications are met, and to collect whatever physical and dosimetric data are required for clinical implementation of the system. This includes verifying the calibration and internal dimensions of sources, and verifying

the positional and temporal accuracy of remote afterloading equipment.

In general, the medical physicist is the only professional at the hospital qualified to perform the activities described in this section, including resource specification, facility planning, license preparation, and commissioning/acceptance testing of brachytherapy equipment, as well as that of computerized treatment planning systems. Although the input of support personnel should be sought when appropriate, in general few, if any, of these activities can be delegated to support staff.

Following installation and acceptance testing of brachytherapy equipment, the physicist shifts to the task of developing detailed procedures for planning and executing the proposed patient treatments. This involves sketching out the flow of the proposed treatment, including preoperative planning, applicator insertion, implant imaging, and dose calculation, and finally, source preparation and treatment. At each point in the delivery process, the information required, and actions and decisions required, should be identified.

Vulnerable decision points in the delivery process, where human error or device failure could cause errors in source positioning, duration of treatment, or dose delivery, should be identified and appropriate redundant checks designed (QA checks). The physicist works closely with the radiation oncologist and support staff to make sure all important logistic problems are covered and all actions and decisions requiring physician intervention, feedback, or approval are identified. The proposed delivery process is carefully reviewed from the perspective of NRC/agreement state regulations and license requirements so that all information required to document compliance is captured.

The next step in procedure development is to assign roles and responsibilities to the support staff (dosimetrist, therapist, source curator), including those activities that require direct involvement or interaction of the physicist. Development of written procedures, including emergency procedures, procedures for treatment planning, optimization, and dose specification, and appropriate forms and checklists is the next step. Forms are usually developed to rationalize the following activities: source receipt, calibration, inventory, and disposal; prescription; patient survey and source removal; simulation and source localization; periodic QA of treatment delivery equipment; manual verification of computer dose calculations, and auditing of records as required by the QMP program. QA checklists are very useful for defining the procedure flow, training new staff, and documenting regulatory compliance. All members of the treatment delivery team must be trained in their function and have the opportunity to develop the necessary technical skills, e.g., remote afterloader programming, treatment planning system operation. For very complex procedures, dry run rehearsals may be needed, and the physicist will need to work closely with all treatment team members during the first few treatments until training and finetuning of the procedure are completed. Appropriate training of personnel in the correct execution of brachytherapy procedures and the correct operation/application of brachytherapy equipment/applicators is essential.

Finally, before a new facility is put into clinical service, a periodic QA protocol should be developed. The purpose of this program is to ensure that all devices required for treatment planning and delivery (sources, afterloaders, treatment planning systems, localization systems) continue to function as assumed by the treatment delivery protocol. This protocol usually consists of a subset of commissioning tests which are to be performed at fixed intervals (annually, quarterly, monthly, or daily). Oftentimes, daily QA tests are assigned to the support staff, while the more involved test sequences, performed at longer intervals, remain the physicist's responsibility. Checklists and forms can greatly improve efficiency and completeness of QA testing, as well as automatically documenting compliance.

Development of well-documented procedures is a complex and time-consuming activity. However, the payback in terms of error-free, consistent, and efficient treatment delivery is large. Although development of procedures is primarily the responsibility of the physicist, close collaboration with the radiation oncologist and other members of the treatment delivery team is critical. In general, little of this development activity can be delegated to support staff.

Good medical practices for brachytherapy have been described by medical and physics organizations including the AAPM through its task force reports,[2,3] the American College of Radiology through its practice standards for brachytherapy,[4–6] and the American Brachytherapy Society.[7] Such standards describe the level of service, staffing, clinical competence, and treatment recommendations needed to promote a safe, successful brachytherapy program. A significant commitment of personnel and equipment resources by the hospital administration is necessary to establish a brachytherapy program to support this clinical team.

The decision to provide brachytherapy services must be accompanied by the concomitant decision to have the required dosimetry and treatment planning equipment with the appropriate staff of qualified radiation oncology physicists. This code of practice recommends the radiation oncology physicist be certified in radiation oncology physics by either the American Board of Radiology, the American Board of Medical Physics, or the Canadian College of Medical Physics (Appendix A). We recommend that radiation oncology facilities be staffed at levels not less than the guidelines given in the ''Blue Book'' (the report of the Inter-Society Council for Radiation Oncology).[8] In order to have a good quality brachytherapy program, we recommend that facilities have a full-time qualified radiation oncology physicist. If only a part-time consulting physicist is used, he or she should provide radiation oncology physics services of a quality necessary for state-of-the-art brachytherapy treatment.

As noted above, the physicist's level of involvement in each patient procedure can vary significantly. Use of high-dose rate remote afterloading technology has increased the physicist's involvement. Current NRC regulations require a physicist to attend each treatment to ensure rapid and expert response to any emergency situation. For low-dose rate re-

mote afterloading, an on-call physicist should be available to respond to any technical or safety problem. The responsibilities of the medical physicist and other team members are listed in Appendix B.

It is necessary that the qualified radiation oncology physicist have the appropriate equipment and test instrumentation needed for source calibration, acquisition of dosimetry data for the treatment planning computer, and the required periodic QA tests. A list of the necessary equipment is given in Appendix C.

In summary, the decision to provide a community with brachytherapy facilities not only involves a decision to enlist the services of a radiation oncologist, but also means enlisting the services of a qualified radiation oncology physicist and providing appropriate brachytherapy instrumentation. In addition, adequate support staff such as medical dosimetrists is essential for a safe and cost-effective operation of the physics service. It is stressed that proper brachytherapy treatment is a team effort, and communication among team members encourages quality assurance. Due to the larger degree of interdepartmental coordination needed, i.e., nursing, diagnostic imaging, surgery, etc., a higher level of cooperation compared to external beam radiotherapy must be developed.

A few comments on terminology are in order. There are three levels of imperatives distinguished in this report:

(1) *SHALL OR MUST:* These terms are applied when the imperative is dictated by law.
(2) *RECOMMEND:* Phrases like ''we recommend'' and ''requires'' are intended to convey that the AAPM considers the procedure referred to as important. If modification is considered, we recommend that it would occur only after careful analysis demonstrates that quality would not be degraded. When a tolerance level or frequency of testing is given, it can be assumed to be a recommendation or law.
(3) *SHOULD:* There are many aspects of QA where tolerance levels and frequencies cannot be given, and in which quality can be maintained via many different approaches. In these instances, which apply to many aspects of QA, modals like ''should'' are used. The AAPM recognizes the complexity of the treatment planning and treatment process, and the inadvisability and impossibility of giving precise direction to QA in this respect. However, the AAPM considered it important to suggest avenues for such quality assurance.

In Part II of this document we present a code of practice for brachytherapy physics, which is based upon principles for good medical practice and management of risk.

PART II. A CODE OF PRACTICE FOR BRACHYTHERAPY PHYSICS

I. OVERVIEW

Brachytherapy had its beginnings in Europe in the late 1890's with the discovery of radioactive radium-226. The early application of radium to skin lesions demonstrated the effectiveness of this new treatment technique. Since that time, many radionuclides have been developed offering a wide range of half-lives and radiations. There is also a large variety of clinical instrumentation available today for implementing numerous types of brachytherapy procedures.

Brachytherapy with radium, cesium, cobalt, or iridium sources has traditionally been given at dose rates of 0.4–0.8 Gy/h, a level referred to as low-dose rate (LDR). Using these radionuclides, the early pioneers of radiation therapy developed highly successful treatment schedules for gynecologic malignancies. In the past few decades, high-dose rate (HDR) brachytherapy has been developed as an alternative to the LDR brachytherapy. HDR refers to a dose rate in excess of 0.5 Gy/min, a rate commonly administered with linear accelerators for external beam therapy.

Intracavitary brachytherapy is the placement of radioactive sources in an applicator that has been positioned in a body cavity, i.e., the uterus, vagina, etc. Acceptable cure rates using intracavitary brachytherapy are dependent on being able to deliver significant radiation doses to tissues at considerable distances from the cavity surface, e.g., to the pelvic walls in gynecological brachytherapy. To meet these goals, applicator modifications, insertion techniques, dose specification, and fractionation schemes have been highly developed for LDR and HDR intracavitary brachytherapy systems.

Intraluminal brachytherapy is the temporary placement of a radioactive source or sources in a linear arrangement inside the lumen. It is often used for tumors that obstruct the opening of a pulmonary bronchus, biliary duct, esophagus, etc. Catheters placed by endoscopy are afterloaded with radioactive sources to deliver a dose that can relieve the obstruction.

Interstitial brachytherapy is temporary or permanent implantation of radioactive seeds or needles directly in a tumor volume. It is particularly suited for prostate, gynecologic, and locally recurrent cancers. Therapy is accomplished using LDR or HDR techniques of manual or remote afterloading. In an afterloading technique, first hollow catheters or guide tubes are inserted in the target volume and they are loaded with radioactive sources afterwards. Computerized dose calculation prior to interstitial brachytherapy is often necessary for delivering a homogeneous tumor dose and avoiding hot spots in the tumor and surrounding normal tissues.

This part of the code of practice presents the AAPM recommendations on the physical aspects of all types of brachytherapy, LDR, or HDR. After describing the goals of a quality assurance program in Sec. II, the physical quantities used in brachytherapy are described in Sec. III. The specification of the strength of brachytherapy sources in terms of air kerma strength is recommended. Single source reference data and a formalism for dose calculations for interstitial brachytherapy are presented. Also described are the techniques for source localization in the patient.

In Sec. IV, implant design and evaluation are described. Traditional dose specification systems such as the Paris, Manchester, and Stockholm systems of brachytherapy are described first. Both image-based and applicator-based computerized planning systems are described next. In the later

parts of Sec. IV, various methods of dose planning, evaluation, specification, and reporting are described.

Section V deals with the implementation of a brachytherapy implantation. Initial planning, treatment prescription, ordering sources, receiving sources, checking sources, source and applicator preparation, loading applicators, removal of sources, and return of sources to vendor are some of the issues discussed in this section. Finally, in Sec. VI, a quality assurance program for brachytherapy is recommended.

This task group does not address the issues dealing with the design and commissioning of brachytherapy facilities. This topic will be reviewed further by the radiation therapy committee in a future report.

Much of the text in this report is descriptive in nature. It reflects current of state-of-the-art in clinical brachytherapy with an extensive bibliography. Where appropriate, the AAPM makes specific recommendations regarding good medical practice of brachytherapy. Part of the objective of this report is educational and the other is to recommend a standard of practice for brachytherapy.

II. QUALITY ASSURANCE PROGRAM GOALS

The goal of the brachytherapy quality assurance (QA) program is to maximize the likelihood that each individual treatment is administered consistently, that it accurately realizes the radiation oncologist's clinical intent, and that it is executed with regard to safety of the patient and others who may be exposed to radiation during the course of treatment. The QA program consists of a set of mandated redundant performance checks, physical measurements, documentation standards, training and experience standards, and guidelines for the development of treatment procedures that are designed to minimize the frequency of human errors, miscommunication, misunderstandings, and equipment malfunctions. With respect to treatment delivery, accurate treatment means that the intended sources are delivered to their intended positions within the correct applicator, remain there for the correct length of time, and accurately deliver the absorbed dose required to realize the radiation oncologist's written prescription. This of course presupposes that the implant design and evaluation results in a spatial–temporal distribution of radioactivity consistent with the goals of treatment and with the applicator arrangement inserted into the patient. A comprehensive QA program addresses each of the three basic processes:

(1) *Applicator insertion process.* Applicator selection and placement in the patient is under control of the radiation oncologist and referring physician: Its success depends on the experience and surgical skill of these physicians. Physics QA duties include documentation of the applicator system inserted, its correct operation, and correct correlation with target volume.

(2) *Implant design and evaluation process.* This process begins with selection of applicator type and implant design. Following surgical realization of the implant, it continues with formulation of the prescription, radiographic examination of the implant, definition of the target volume, and computer-assisted dose calculation and optimization. The end result of this process is identification of the desired spatial–temporal distribution of radioactivity needed to fulfill the prescription. For manual brachytherapy, this includes applicator loadings and durations. For remotely afterloaded brachytherapy, the end result of treatment planning includes programming parameters for afterloading, i.e., the correct dwell positions and dwell times for each catheter. Correct parameters mean those required to accurately deliver the prescribed dose distribution, including any volume or dose constraints on normal tissue irradiated. A QA program must ensure, in general and for each treatment, that the treatment planning program functions accurately, that the system for inferring dwell locations from simulation radiographs performs accurately, that the target volume rendered on these films is consistent with all known tumor localization data, and that optimization endpoints used by the treatment planning program are appropriate.

(3) *Treatment delivery process.* For remote afterloading, the delivery process includes entry of the programming parameters into the remote afterloader, connection of the patient to the device, and delivery of treatment. The quality assurance program must contain procedures for validating the entered data, responding to unexpected machine malfunctions and emergencies, and documenting the delivered treatment. For manual brachytherapy, treatment delivery includes selection, preparation, and insertion of the sources as well as removal of the sources at the designated time. For all treatments, the delivery process includes procedures necessary for patient and staff safety throughout the process.

A. Quality assurance program endpoints

The variability in brachytherapy device features and clinical practice standards (see Part I) precludes development of a fixed QA protocol. Therefore, from basic principles, each physicist must develop a program specifically suited to his or her individual clinical environment. Indeed, one of the challenges of clinical brachytherapy physics is to identify the relevant quantitative endpoints and the accuracy with which they must be realized to carry out the radiation oncologist's clinical intent in a practical and reasonable fashion. Systematic development of a QA program that encompasses both device function and human factors requires that the clinical goals of the treatment program be identified, translated into physical endpoints, and assigned tolerances for acceptable performance under realistic practical situations. For any clinical brachytherapy application, these endpoints fall into four broad categories:

1. Safety of the patient, the public, and the institution

This QA endpoint addresses all populations whose well being is potentially threatened by the brachytherapy program. Safety of the public and involved health care personnel includes control of radiation exposure to staff and members of the public, adequacy of the facility shielding barriers, and procedures to maintain control of all radiation sources. Promotion of patient safety entails prevention of catastrophic

treatment delivery errors, or other conditions that threaten the well being of the patient, as a result of device malfunction or human errors in the design, evaluation, and execution of the brachytherapy procedure. For remote afterloaders, patient safety QA includes verifying correct function of relevant error recognition features, interlocks, treatment status indicators, and emergency response systems. A safety QA check has the general form, ''Does specified hazard X (e.g., the source been transported to the wrong location) exist? If X exists, then perform emergency response Y (e.g., halt the treatment, retract the sources, and summon expert help) or else continue the treatment.'' Specification of the expected emergency responses of automated treatment devices, or desired emergency procedures when prescribed human responses are required, is an important element of the program. Protection of institutional safety involves minimizing conditions that create potential legal or regulatory liability, even though they pose no threat to patient care or staff well being. For example, making inaccurate entries into a patient's treatment record, even when the information in question is clinically irrelevant to the particular patient, may increase the institution's legal liability by calling the credibility of the record keeping process into question in event of a future lawsuit. Certain Nuclear Regulatory Commission (NRC) regulations (e.g., quarterly facility surveys for ^{192}Ir HDR units) add little to the quality of patient care or staff safety, but must be completed and documented properly to avoid regulatory enforcement actions. By maintaining expertise in regulatory detail and documenting compliance to all regulations, the physicist makes an important contribution to institutional safety.

Safety QA procedures and endpoints have been heavily influenced by NRC (or agreement state counterpart) regulations. The governing guidelines are spelled out in great detail by the Nuclear Regulatory Commission in Title 10, Parts 20 and 35 of the Code of Federal Regulations (10 CFR Part 20 and 10 CFR Part 35). Part 20 outlines area and personnel exposure limits as well as requirements pertaining to labeling, storage, shipping, and handling of sealed sources. Part 35 outlines the responsibilities of the Institutional Radiation Safety Committee and Radiation Safety Officer as well as the minimum credentials physicians must possess in order to be authorized users, i.e., to be allowed to prescribe brachytherapy to human patients. Part 35 contains many highly detailed regulations addressing, e.g., source inventory and check-out procedures, frequency and type of exposure surveys required, frequency and type of treatment record audits required, and the entries required for brachytherapy prescriptions (or ''written directives'' in NRC jargon). Appendix D lists NRC documents outlining essential regulatory, licensing, and compliance standards for brachytherapy.

With the rapid growth of regulatory initiatives in brachytherapy and more aggressive intrusion into clinical practice, a temptation to confuse adequate QA with regulatory compliance is understandable. This is a serious error. Regulatory QA and safety mandates, in general, are neither sufficient nor necessary conditions of accurate and safe brachytherapy treatment. For example, while NRC strictly regulates the calibration procedures for survey meters, there are no requirements regarding accuracy or traceability for LDR brachytherapy source calibrations. A major task of the brachytherapy physicist is development and maintenance of a QA program that ensures good medical practice standards: Regulatory compliance is only one component of this larger and more general mandate.

2. Positional accuracy

Verification of positional accuracy requires that one confirms that the intended sequence of active sources or dwell positions is delivered to the correct position in the correct applicator. ''Correct position'' refers specifically to the positions defined directly or indirectly by the attending radiation oncologist. Often, the target source locations are identified relative to radiographic images of dummy seeds or radiographic markers which are inserted into the applicator of interest prior to simulation. For surface-dose or gynecological intracavitary applicators, the correct position may be defined as the expected position relative to the applicator surfaces. Positional accuracy assessment reduces to verifying the protocol (hereafter called simulation source localization procedure) for calculating the source loading instructions used to position the actual source at a desired location in the catheter defined by the radiographic marker seeds. When remote afterloading devices are used, these instructions are machine programming parameters (length, position, channel number). In most clinical applications of afterloaders, a positional accuracy of ± 2 mm relative to the applicator system (not anatomical landmarks in the patient) is reasonable. [Note that for remote afterloaders, the NRC insists on a positional accuracy criterion of ± 1 mm (policy and guidance directive FC 86-4). This more rigid standard is not realizable in a clinically meaningful sense for many applicator-source combinations.]

3. Temporal accuracy

A treatment system achieves temporal accuracy if each source sequence or single source dwell position remains at its intended position for the length of time specified by the treatment program. For manually afterloaded temporary implants, the goal is to develop a procedure to ensure that the radioactive sources are removed upon completion of dose delivery. Remotely afterloaded brachytherapy places treatment duration under control of an electronic timer. Tests of absolute timer accuracy are required whenever source calibration is based on an external time standard, whereas relative tests suffice when the machine timer is used both to control treatment delivery duration and to integrate charge measurements during source-strength calibration. An accuracy criterion of $\pm 2\%$ seems easily achievable, both by manual afterloading techniques and commercially available remote afterloading systems. In addition, the influence of transit dose on dose delivery accuracy must be evaluated and corrected for, if necessary. Transit dose is the additional dose delivered while the source is in motion.

4. Dose delivery accuracy

Even with completely error-free delivery of the spatial–temporal distribution of radioactivity, i.e., accurate realization of source positioning and treatment duration, many other variables must be controlled in order to assure accurate delivery of absorbed dose in tissue. It is useful to subdivide dose delivery accuracy into physical and clinical aspects. Physically accurate dose delivery is achieved if the predicted dose and actual dose absorbed by the medium are equal at reference points specified without positional error relative to the applicator. Physical dose delivery accuracy neglects the difficult problem of defining dose calculation points relative to patient anatomy. Accurate calibration of the source in terms of a well-defined physical quantity, preferably air kerma strength, is among the most important physical dose delivery parameters. Other factors include selection of accurate dosimetric data for calculating the single source dose distribution and the influence of applicator attenuation and shielding corrections on the dose distribution. It is difficult to assign a meaningful tolerance to this endpoint as no practical and validated dose measurement technology is available to the hospital physicist. However, a source calibration accuracy of $\pm 3\%$ relative to existing air kerma strength standards seems reasonable. Based on recent low-dose rate dosimetry experience, physical dose delivery accuracy on the order of 5–10% is achievable at distances of 1–5 cm from most common LDR sources. Finally, relative to the input data supplied and the algorithm assumed, the computer-assisted dose calculations should have a numerical accuracy of at least $\pm 2\%$.

Clinical dose delivery accuracy includes a large array of often difficult-to-solve problems. Relatively straightforward issues include the accuracy with which the dosimetrist and treatment planning computer reconstruct the relative three-dimensional geometry of the implant. In intracavitary brachytherapy, consistent, if not accurate, localization of bladder and rectal reference points is often important. Finally, if dwell weights are optimized to achieve dose uniformity or adequate coverage of a specified target volume, careful attention to optimization endpoints, prescription criteria, and quality of the resultant implant is required. The more difficult problems include identification of the target volume and critical organ margins relative to the implanted applicators and controlling or compensating for patient motion. Clearly, if uncertainties in the clinical procedure are large, then the accuracy of physical dose delivery is less important. The tolerance level, therefore, should be determined by each user based on practical considerations.

B. Developing a quality assurance program

Most errors in brachytherapy are the result of human errors, miscommunications, or misunderstanding of equipment operation rather than failure of the treatment delivery and planning devices to perform properly. Brachytherapy treatment planning and delivery are complex human activities involving cooperation of physician, physicist, technologist, nurse, and dosimetrist, all of whom must execute their functions correctly and must unambiguously receive and transfer critical information from one another. A team approach is recommended. All team members should be encouraged to double check each other and identify problems without fear of retribution. Error identification should be praised and rewarded as a sign of good QA. QA program development most focus on (1) correct function and physical characteristics of treatment planning and delivery devices (including sources, afterloaders, dose calculation tools, and test instruments) and (2) the correct execution of each brachytherapy procedure, i.e., procedure specific QA.

1. Quality assurance of treatment delivery devices

Device QA, covered in Sec. VI of this report, includes initial acceptance testing and commissioning of devices. Its purpose is not only to determine whether each system functions as specified, but to identify its operational characteristics, to give the physicist an opportunity to become an expert user, and to develop procedures for using the device to treat patients. A program of QA checks to be repeated at prescribed intervals must be put into place. The goal of periodic device QA is to confirm that the important operating characteristics of the device remain unchanged through time. Other aspects of system-wide QA include developing training materials and curricula for nurses, dosimetrists, and therapists involved in treatment delivery, as well as verifying through analysis of attendance records, that training remains current.

2. Procedure-specific quality assurance

A procedure-specific QA protocol is a set of specified actions selected to ensure that each important step leading to delivery of a brachytherapy procedure is correctly carried out. Often the specified actions are redundant tests and checks designed to confirm correct execution and activity. More commonly, QA guidelines are rules or procedures that define the procedure chronology or restrict the range of actions that are possible at any point, thereby limiting the types of errors that can be made. For example, insisting that only nurses with radiation safety/radioactive procedures training can care for brachytherapy patients or that a medical physicist must perform certain types of calculations reduces the likelihood of error by requiring that expert personnel be available at specified points in the treatment delivery process to ensure that key actions are executed with a high level of confidence. Similarly, requiring that the radiation oncologist complete the written prescription before initiating the treatment evaluation process minimizes the likelihood that isodose calculation will be based on incorrect source loadings or prescribed doses. QA program development involves not only development of redundant checks, but carefully designing the flow of the procedure itself to minimize the likelihood of serious errors. Because practice standards and complexity of treatment planning and design are so variable, procedure-specific QA is highly individualized not only to the institution but to each type of procedure. Commonly accepted procedure-specific QA elements are reviewed in Secs. IV, V, and VI.

To develop an effective procedure-specific QA program, the AAPM recommends the following step-by-step procedure:

(1) Define the anticipated or actual flow of the procedure, including all major steps (e.g., implant design, applicator insertion, implant imaging, implant evaluation, etc.). At each step, identify the involved team members (physician, therapist, etc.), the critical activities to be performed and the information that must be captured.
(2) The AAPM strongly recommends use of carefully designed forms for capturing and documenting all critical information, including the implant drawing, applicators utilized, catheter numbering system, target localization data, and written prescription. Easy-to-use documentation will ensure accurate communication among brachytherapy team members (e.g., from the physician to the physicist and treatment planner), among the various physical locations involved (e.g., operating room to imaging suite). In addition, such written documentation (2–5 forms, depending on procedure complexity), forms the basis of the patient's permanent treatment record.
(3) Identify vulnerable points in the treatment delivery process, where mistakes, misjudgments, or inaccurate transmission of data can jeopardize the outcome of the procedure. A redundant check should be designed, specifying who is to perform the check and what actions are to be taken if the test result deviates from the expected outcome. Both severity and likelihood of the target error should be taken into account in deciding how to distribute available QA resources. Low probability catastrophic scenarios (e.g., failure of HDR source to retract) should not be emphasized to the exclusion of more common but less severe human errors (e.g., misidentification of source strength, erroneous estimation of source positioning parameters from simulation films).
(4) Develop a written procedure, outlining the brachytherapy procedure chronology, team member functions, QA checks, and associated documentation. Each brachytherapy practice should develop written procedures and patient-specific documentation for each major type of procedure, as described above. In addition, each institution should develop a mechanism, formal or informal, for confirming compliance with the written QA program. One approach is to formalize the execution of the treatment delivery process by means of QA check-off forms. Developing such forms forces one to systematically conceptualize the treatment delivery process. In addition to documenting compliance with QA requirements, check-off forms are useful for training new team members, and for guiding the flow of infrequently performed procedures. However, the AAPM recognizes that formal documentation of all QA checks constitutes a significant burden and is not the only approach to confirming QA. For a highly experienced treatment delivery team, which frequently performs brachytherapy procedures, QA checklists may not be as useful and mandatory. In such cases, the alternative approach should be clearly outlined.
(5) The AAPM further recommends that the brachytherapy QA program should be integrated into the overall departmental QA program (QA system) as defined by AAPM Task Group No. 40.[3] This assignment gives the departmental QA committee (QAC) responsibility for monitoring the performance of the brachytherapy QA program so that any shortcomings can be identified and corrected. The QAC can monitor brachytherapy QA system performance by independently auditing a sample of patient records and QA checklists to confirm that written QA procedures are being followed. QAC review of any brachytherapy treatment delivery errors is another feedback mechanism by which deficiencies in the QA program or its implementation can be identified. Another highly desirable enhancement of the basic QA program is to institute a formal continuous quality improvement (CQI) process. Cost effective utilization of QA resources, as well as minimization of treatment delivery errors, is another QAC function. After finding that a particular QA test reveals an acceptably low incidence errors, the QAC might recommend dropping the test or increasing the action level. [The QA system recommended here is only superficially similar to the NRC quality management program (QMP) as described in 10 CFR 35.32. The QMP is a highly prescriptive rule defining precise endpoints, checks, auditing, and review procedures. The NRC's QMP goal is very limited: ''...to provide high confidence that byproduct material ... will be administered as directed by the authorized user.'' In contrast, the QA system as defined and endorsed by the AAPM in this document allows institutions wide latitude in defining QA endpoints, documentation standards, QA test methodologies, test outcome action levels, auditing, and other oversight mechanisms.]

III. PHYSICAL QUANTITIES IN BRACHYTHERAPY

A. Brachytherapy source strength

Source-strength designation has gone through several changes over the years.[9] The earliest quantity (mass of radium) was commonly referred to by the unit, milligram radium. It was later generalized to milligram radium equivalent for other radionuclides, and this quantity (equivalent mass of Ra) is still in use. Milligram radium equivalent (mgRaEq) means that the source so designated produces an exposure rate in free space at a large distance on its transverse axis, equal to that for the same mass of radium encased in a capsule of 0.5-mm Pt wall thickness. A ''large'' distance, in this context, means large enough that the inverse square law is obeyed. Although this designation could be used for any radionuclide, it is meaningful only for those emitting high-energy photons, such as ^{137}Cs, ^{192}Ir, etc. Equivalent strength sources of these radionuclides will yield nearly equal dose rates in tissue along their transverse axes. However, for low-energy photon emitters such as ^{125}I, the attenuating effect of tissue is much greater such that an in-air mgRa equivalency does not translate to an equivalency of dose in tissue.

Most treatment planning systems allow source strengths to be specified as mgRa equivalent or in terms of the more generic quantity, activity. The latter is the number of disintegrations per second and is applicable to radionuclides of any energy. However, this quantity is not widely used in brachytherapy. For sealed sources, especially those of low energy, the encapsulation reduces the air kerma and dose rates below those which would be produced by the bare source. Thus the strength is generally given as apparent activity, which is less than the encapsulated activity. Apparent activity is the activity of a hypothetical point source of the same radionuclide which would produce the same air kerma rate, at the same large distance, as that measured on the transverse axis of a sealed source. The design of the source capsule also influences the dose distribution around the source. It is quite possible for two sources of the same radionuclide and same apparent activity to have different dose distributions.

The emphasis today is to specify source strength by a NIST-traceable quantity, which is related to air kerma rate at some distance in air. Therefore, the recommended source specification is air kerma strength S_K given by

$$S_K = \dot{K} l^2, \tag{1}$$

where l is the reference distance at which the air kerma rate in free space, $\dot{K}$, is specified. The unit of air kerma strength is $\mu\text{Gy h}^{-1}\text{ m}^2$, which is numerically equivalent to $\text{cGy h}^{-1}\text{ cm}^2$. This unit has been denoted by the symbol U.

A National Institute of Standards and Technology (NIST) calibration of a brachytherapy source is simply an in-air air kerma rate ($\dot{K}$) measurement at a large distance (r_0) in free space on the transverse axis. It does not specify activity, apparent or otherwise. However, it has been customary for source vendors to convert the NIST-measured air kerma rate to apparent activity (A) using $A = \dot{K}(r_0) r_0^2 / \Gamma_K$, where Γ_K is the air kerma rate constant. As a first step in a dose calculation, the user might multiply the stated activity by a Γ_K value to obtain an air kerma rate. This Γ_K must be the same as that used by the vendor in order to restore the original NIST calibration, even if that value has no basis in reality. In effect, Γ_K is a dummy parameter.

The American Association of Physicists in Medicine[10] and the American Brachytherapy Society[11] recommend that air kerma strength be used at all levels in the brachytherapy treatment delivery process including ordering of sources, dose computation, treatment planning, treatment prescription, and implant documentation. Specifically, air kerma strength should be used to quantify source strength as follows:

(1) All NIST, accredited dosimetry and calibration laboratory (ADCL), and vendor certificates should use air kerma strength to describe strength of brachytherapy sources. Calibration factors for institutional calibration transfer instruments such as re-entrant chambers should be described in terms of air kerma strength.
(2) Input of data into computer-assisted treatment planning systems, as well as printed output documentation, should utilize air kerma strength. All treatment planning software vendors are urged to modify their dose calculation algorithms and user interfaces so that all displayed and printed references to source strength clearly and unambiguously describe this quantity and its units. All manual dosimetry aids, such as nomograms, surface dose tables, and planning algorithms, should be normalized in terms of air kerma strength.
(3) All published dose distribution data for brachytherapy sources should be normalized in terms of air kerma strength.
(4) Source loadings for individual patient implants should be prescribed and documented in terms of air kerma strength. All written brachytherapy treatment prescriptions requiring explicit reference to source strength should be stated in terms of air kerma strength. Published clinical studies in brachytherapy should utilize this quantity to report source strength and applicator loadings.

All members of the association are urged to work within their institutions to introduce and encourage use of air kerma strength in all clinical discussions, case presentations, and teaching conferences that involve discussion of brachytherapy source strength.

It should be noted that two different source designs of the same isotope and same air kerma strength can, particularly for low energies, produce different dose rates in tissue at equal distances along their transverse axes. For example, with ^{125}I sources, the dose rate at 1 cm along the transverse axis of model 6702 is approximately 8.5% greater than for model 6711, even though both are identically encased. The difference is attributed to fluorescent x-rays from the silver wire in the model 6711. Thus the Interstitial Collaborative Working Group (ICWG) recommended that does calculations be based on the product of dose rate constant and the source strength, defined to be the dose rate in medium per unit air kerma strength at a distance of 1 cm along the transverse axis.[12] This quantity should be obtained from in-phantom measurements or calculations for each source design. So far, this has been accomplished for the interstitial sources ^{192}Ir, ^{103}Pd, and the two models of ^{125}I, resulting in recommended dose rate constants for each.[13] This dosimetry protocol is further described in Sec. III C 1.

B. Source-strength calibration

1. Conventional strength sources for LDR applications

As a result of the decreasing use of radium sources, NIST no longer maintains a standard for radium. At present, NIST provides calibrations for most ^{137}Cs sources, several styles of ^{192}Ir, and ^{125}I sources. Air kerma strength standards for ^{137}Cs and ^{192}Ir were established from exposure measurements at a large distance using spherical graphite ionization chambers of known volume.[14,15] In 1985, NIST established an air kerma strength standard for ^{125}I using a free-air ionization chamber.[16] However, it was subsequently realized that the measured exposure included contributions from very low-

energy fluorescent x rays originating in the titanium capsule.[17,18] Since these nonpenetrating x rays do not contribute to the dose in tissue they should be excluded from the air kerma measurement. NIST is currently in the process of revising the calibration of ^{125}I to take this effect into account.

Standards for ^{125}I and ^{192}Ir brachytherapy sources are transferred by NIST to other sources through the use of a large volume spherical well-type ionization chamber. A calibrated source of a particular radionuclide is placed in the well chamber in a fixed geometry. This serves to calibrate the chamber. The standard is transferred to other sources by measuring them in the well chamber for the same geometry. The well chamber has a 4π geometry, while the source specification is for a point on the transverse axis. The chamber is therefore sensitive to the anisotropy of the air kerma distribution around the source. Thus calibration can be transferred only to sources having essentially the same design as those used in the initial free-air measurements. For ^{137}Cs sources the transfer of calibration is performed using a large volume chamber at a distance.

The NIST S_K standard is transferred to the ADCLs in a similar manner. A source of the proper design is sent to NIST for calibration and used to establish the standard for the ADCL well-type ionization chamber. The NIST standard or the ADCLs standards are considered as national standards. A customer's source is calibrated at an ADCL or NIST by placing it in the well chamber. Alternately, a customer's well chamber is calibrated at an ADCL or NIST against a national standard at an ADCL or NIST.

The AAPM Task Group No. 40 had recommended traceability of brachytherapy sources[3] in 1994. The AAPM updates these recommendations here. All sources for which NIST provides a calibration should have calibrations traceable to NIST in one of the following ways:

(1) *Direct traceability* is established when either a source or a transfer instrument (e.g., well chamber) is calibrated against a national standard at an ADCL or at NIST itself.
(2) *Secondary traceability* is established when the source is calibrated by comparison with the same radionuclide and design that has a directly traceable calibration or by a transfer instrument that bears a directly traceable calibration.
(3) *Secondary traceability by statistical inference* is established when a source is one of a group of sources of which a suitable random sample has direct or secondary traceability.

For brachytherapy sources that do not have a national standard yet users should develop a constancy check calibrated against the vendor's standard and use this constancy check to verify the source strength. Another option is to develop one's own secondary standard along the lines suggested by Goetsch *et al.*,[19] Das *et al.*,[20] and Verhaegen *et al.*[21]

Well-type ionization chambers make it easy to establish source calibrations with one of these traceabilities. Thus, for sources for which NIST provides calibration it is no longer necessary and should no longer be a practice to rely on source strengths quoted by the manufacturer. At least one long-lived source, ^{226}Ra or ^{137}Cs, should be kept in inventory for a quality control check on the well chamber's response prior to each use. A record maintained of the chamber's response to evaluate its precision and long term stability. Variations of less than 1% around a mean should be achievable. For air-communicating chambers, it is important to make temperature-pressure corrections, and for ^{137}Cs, to correct the chamber reading for source decay.

Ideally, every radioactive source that is to be implanted in a patient should be calibrated. In practice however, limitations of time, personnel exposure, or other physical constraints preclude this level of thoroughness. We recommend that all long half-life sources be calibrated. Traceability by statistical inference may be appropriate for short half-life sources, depending upon the number of ribbons or seeds in the designated strength groupings under consideration. If the grouping contains only a few seeds we recommend the calibration of all seeds. For groupings with a large number of loose seeds, we recommend that a random sample containing at least 10% of the seeds be calibrated; for a large number of seeds in ribbons, a minimum of 10% or 2 ribbons (whichever is larger) should be calibrated. For sources purchased in a sterile configuration, we recommend purchasing and calibrating a single (nonsterile) seed for each designated-strength grouping.

Brachytherapy sources are assigned a calibration by the manufacturer. Every institution practicing brachytherapy shall have a system for measuring source strength with secondary traceability for all source types used in its practice. Prior to using newly received sources for treatment, the vendor-supplied (with the exceptions noted in the preceding paragraph) calibrations must be verified as per Task Group No. 40 recommendations.[3] The institution should compare the manufacturer's stated value with the institution's standard. If the two are within acceptable limits (see Table I), either the manufacturer's or institution's value may be used. We recommend that if the institution's verification of source strength disagrees with the manufacturer's data by more than 3%, the source of the disagreement should be investigated. We further recommend that an unresolved disparity exceeding 5% should be reported to the manufacturer. It is always advisable to ask the manufacturer to review its calibration of the sources to help resolve these discrepancies. With a proper redundancy program to verify that the institution's dosimetry system has not changed with time, there remains a small risk of error when the institution's calibration value is used but differs from the manufacturer's data.

We support the earlier AAPM recommendations on source QA tests, their frequency, and tolerances as reproduced here in Table I. It should be noted that the recommended 3% tolerance between manufacturer and institution calibrations discussed above applies to the mean of a batch of sources. Since individual sources may differ from the mean by a greater amount, we recommend a maximum deviation from the mean of 5% for individual sources.

For long half-life sources, the uniformity of each source should be verified during the initial calibration procedure.

TABLE I. QA tests for brachytherapy sources. I, initial purchase; D, documented; and E, at every use.*

Type of source	Test	Frequency	Tolerance
Long half-life:	Physical/chemical form	I	D
Description	Source encapsulation	I	D
	Radionuclide distribution and source uniformity	I	1 mm
	Location of radionuclide	I	3%
Long half-life:	Mean of batch	I	5%, D
Calibration	Deviation from mean	E	[a]
	Calibration verification	I	D
Short half-life:	Physical/chemical form	I	D
Description	Source encapsulation	E	3%
Short half-life:	Mean of batch	E	5%
Calibration	Deviation from mean[b]	E	V[c]
	Radionuclide distribution and source uniformity		

*Reprinted with permission from ''Comprehensive QA for radiation oncology: Report of AAPM Radiation Therapy Committee Task Group 40,'' G. J. Kutcher, L. Coia, M. Gillin, W. F. Hanson, St. Leibel, R. J. Morton, J. R. Palta, J. A. Purdy, L. E. Reinstein, G. K. Svensson, M. Weller, and L. Wingfield, Med. Phys. **21**, 581–618 (1994). Copyright 1994 American Association of Physicists in Medicine.

[a]Visual check of source color code or measurement in a calibrator.

[b]For short half-life sources this may not always be practical.

[c]*V*, visual check, autoradiograph or ionometric check.

All seed ribbons should be verified during the initial calibration procedure and visually inspected to assure correct spacing of the seeds and the correct number of seeds. Differentially loaded ribbons require special consideration.

2. High strength sources for HDR applications

Currently, NIST maintains no primary air kerma strength standard directly applicable to HDR or PDR ^{192}Ir sources. Vendor-supplied calibration certificates are based on a variety of standards the precision of which and traceability to NIST standards are often obscure. In the absence of a suitable primary standard, the interpolative free-air secondary standard method has become the *de facto* interim standard for measurement of high intensity ^{192}Ir source strength. Briefly, this approach consists of measuring air kerma rate on the transverse axis of an HDR source at distances of 10 cm–100 cm in a free-air geometry using an ion chamber with a buildup cap thick enough to establish secondary electron equilibrium at the highest photon energy encountered (about 1200 keV). The ^{192}Ir air kerma calibration factor is derived by interpolating between ^{137}Cs and hard orthovoltage air kerma calibration factors obtained from the NIST or an ADCL calibration service. The buildup cap must be used for both ^{192}Ir calibration measurements and intercomparison against NIST air kerma standards. Methods for interpolating between the directly traceable external beam air kerma calibration factors to obtain an air kerma calibration factor for the HDR ^{192}Ir source have been reviewed by several authors.[19–23] Room scatter corrections are generally derived from the deviation of measured air kerma rate from inverse square law[19] or from shadow-block measurements.[23] Additional corrections for ion recombination and photon fluence gradients across the chamber volume are applied.

The interpolative free-air secondary standard has been implemented by two ADCLs (K & S Associates and the University of Wisconsin) and accredited by the AAPM as a calibration service. These ADCLs are authorized to calibrate users' re-entrant ionization chambers using this standard. Institutions opting to use a calibrated re-entrant ion chamber should obtain an instrument designed to high precision ($<2\%$) in the presence of the large ion currents characteristic of this measurement with minimal ion recombination effects ($P_{\text{ion}}>0.98$).

Specifically, the AAPM recommends the following:

(1) that a qualified medical physicist shall calibrate each HDR/PDR source prior to clinical use in terms of air kerma strength and use this value as the basis for treatment planning and treatment prescription;

(2) until an appropriate primary standard is available, the interpolative secondary free-air standard, described above, should be the basis of source strength determination in HDR and PDR ^{192}Ir brachytherapy. Each HDR facility should acquire a suitable re-entrant chamber, obtain an HDR air kerma strength calibration factor from an ADCL accredited to provide this service, and use this instrument for initial calibration of HDR sources. (The applicable recommendations of Table IV should be followed.) An acceptable but not recommended alternative is implementation of the interpolative secondary free-standard within the institution using an appropriate external beam ion chamber with directly traceable ^{137}Cs and orthovoltage air kerma calibrations;

(3) following the initial calibration of an HDR or PDR source, a confirmatory check of source strength should be made by a suitable tertiary standard that is capable of detecting 5% errors or changes in response of the secondary standard. To maximize redundancy, the tertiary standard should utilize a different electrometer and radiation detector. The radiation detector can be a different ion chamber or a suitable re-entrant chamber different from that used for the secondary standard. This system should use a fixed, reproducible geometry (free-air jig or machined phantom) that is initially calibrated against the secondary standard.

C. Single source dosimetry data

The accuracy of dose calculations for brachytherapy implants is, of course, dependent on the accuracy of the dosimetric data for the sources used. Most sources have cylindrical symmetry and exhibit an anisotropic dose distribution, with the dose along or near the longitudinal axis being less than that at the same distance along the transverse axis due to increased filtration. Various theoretical methods ranging from numerical integration of point source contributions to Monte Carlo simulations appear in the literature for calculating ''line source'' dose distributions. Likewise, measurements have been made in several ways with various types of detectors. Measured and calculated dose distributions are generally tabulated as two-dimensional arrays in either Cartesian or polar coordinates. In this section, calculated and measured distributions for single sources are briefly reviewed for ^{137}Cs sources, the high activity ^{192}Ir sources used in high and pulsed dose rate remote afterloaders, ^{241}Am sources developed for intracavitary use, ^{169}Yb sources currently being investigated for interstitial implants, and ^{192}Ir, ^{125}I, and ^{103}Pd interstitial sources. Methods of dose calculations for brachytherapy implants are briefly introduced in the next sections.

1. ICWG formalism

The dose calculation model proposed by the ICWG has gained wide acceptance and has been adopted by Task Group No. 43 of the AAPM Radiation Therapy Committee.[13] This is a modular approach in which the effects of radionuclide distribution within the capsule are taken into account through a geometry factor $G(r,\theta)$; the effects of absorption and scatter by the encapsulation and medium along the transverse axis are taken into account by a radial dose function $g(r)$ and in all other directions by an angular anisotropy factor $F(r,\theta)$. Specifically, the dose rate at a point r,θ in medium for a source of strength S_K is given by

$$\dot{D}(r,\theta)=\Lambda S_K \frac{G(r,\theta)}{G(1,\pi/2)} F(r,\theta)g(r), \tag{2}$$

where $\Lambda=\dot{D}(1,\pi/2)/S_K$ is the dose rate per unit air kerma strength at 1 cm on the transverse axis. For a point source $G(r,\theta)=r^{-2}$. The ICWG recommends that Λ be measured for each source design of each radionuclide. It is expressly recognized that sources of equal strengths of the same radionuclide but of different designs can produce different dose rates in medium. The other factors, $g(r)$ and $F(r,\theta)$, are also measured or calculated in a medium. For details, the reader is referred to the AAPM Task Group No. 43 report.[13]

2. Sievert integral model

The Sievert integral model[24,25] is the most widely used method for modeling single source dose distributions around ^{137}Cs tubes and needles. This model consists of integrating the point source dose distribution over the active length of the source, including corrections for photon absorption and scattering in the surrounding medium and oblique filtration of primary photons through the source capsule. The model requires the user to specify the physical and active source lengths, the radial capsule thickness, an effective attenuation coefficient (sometimes called filtration coefficient), along with the data required to implement the underlying isotropic point source model. Some algorithms model the effects of the finite-size active core, requiring the user to specify its diameter and filtration coefficient. For ^{137}Cs, the Sievert model has been shown to model accurately (within 5%) single source dose distributions when tested against dose measurements and Monte Carlo calculations.[26,27] This report recommends that readers proceed cautiously in applying the Sievert model to lower-energy sources, including ^{192}Ir wires and seeds. Although the Sievert model accurately models the dose rate distribution near the transverse axis of ^{192}Ir, errors in reconstructing the dose distribution near the longitudinal axis (where oblique filtration effects are important) as large as 20–40% have been reported.[28,29]

3. Interstitial source data

Interstitial sources (seeds) for permanent and temporary implants are usually cylindrically shaped, a few millimeters in length, and a fraction of a millimeter in diameter. The most common radionuclides under this category are ^{125}I, ^{192}Ir, ^{198}Au, and ^{103}Pd. TG-43 provides a set of data for some designs of these sources (except gold). These data should be adopted by all users. $F(r,\theta)$ exhibits the anisotropy typical of line sources and is given as a two-dimensional table for each source. Ideally, treatment planning computers should allow entry of such data tables. However, some systems treat these seeds as point sources producing spherically rather than cylindrically symmetric dose distributions. In some situations this approximation is satisfactory, especially if the implant contains a large number of seeds and/or randomly oriented seeds. For these cases, the angular anisotropy function $F(r,\theta)$ is replaced by its 4π average, which is referred to as the anisotropy factor. However, when sources are used in linear arrays of readily determined orientation, the $F(r,\theta)$ data tables should be used.

It should be noted that the Task Group No. 43 data cannot be extended directly to include tube sources or needles. Also, several new sources such as ytterbium and americium are emerging in the field. Standard dose calculation methods break down in the case of these intermediate energy photon emitters or for beta emitters that are under development for

intravascular brachytherapy. A full three-dimensional matrix of dose values need to be determined for such developmental sources. This is a nontrivial task and should be approached as a research project.

4. Cesium intracavitary source data

Over the years, various designs of ^{137}Cs sources have been manufactured. Probably the most common one in use is the 3M source. The only ^{137}Cs intracavitary source currently in production and clinical use is the very similarly designed CDCS-J-type source of Medi+physics, Inc. (Arlington Heights, IL 60005). Although dose distributions around these sources can be cast into the ICWG modular formalism, they appear in the literature in tabular form as a function of position around the source. The CDCS-J source has a slightly smaller active length (13.5 vs 14 mm) and thinner capsule (0.5 vs 1 mm) compared to the 3M source.

For treatment planning of implants using ^{137}Cs tubes and needles, this report recommends using single source distributions calculated by the Sievert integral model until more accurate and complete tables, derived from direct dose measurements or Monte Carlo calculations, are available. Specific recommendations regarding choice of input data and practical aspects of implementing these models are available from a variety of sources.[30–32] This report further recommends that such calculated dose distributions be carefully checked against an appropriate benchmark prior to clinical use. Published dose rate tables should be used as the standard of comparison whenever available for the source type in question. Two-dimensional dose rate tables based on the Sievert integral formalism are available for a variety of stainless steel sheathed ^{137}Cs tubes and needles or for the many ^{137}Cs source designs used for LDR remote afterloading. These data include dosimetry applicable to the widely used 3M Model 6D6C intracavitary tube[33] as well as for several obsolete source designs.[27,33] Unfortunately, complete two-dimensional tables are not available for the Amersham CDCS-J source; for a partial table see Ref. 34. In these cases, the accuracy of the algorithm and the user's understanding of its input data should be verified by simulating a closely related source design that is available in the literature. After validating the algorithm's accuracy and implementing it for the desired source type, the dose distribution should be checked against manual calculations at several points. Such checks can be performed using the general Sievert integral table[35] or by means of the unfiltered line source formula[26] in the case of lightly filtered sources.

5. HDR and PDR iridium-192 sources

Like most cylindrical sources, the high activity ^{192}Ir source used in HDR and pulsed dose rate (PDR) remote afterloaders exhibits an anisotropic dose distribution in water. For the HDR source, measurements in water were made by Baltas with a 0.1-cc ionization chamber[36] and in polystyrene by Muller-Runkel with LiF thermoluminescent rods.[37] Dose distributions for this and the PDR source of Nucletron Corporation (Columbia, MD) have been calculated by Monte Carlo simulation.[38] Measurements and calculations all had at least 10 cm of scattering material surrounding each data point. For the HDR source, all three sets of data are in good agreement except along or near the source axis, with calculations showing a greater anisotropy than the measured data. Along the source axis the calculated dose rates are about 15% less than measured by Baltas. The measurements of Muller-Runkel are in better agreement with the calculations than with the measurements of Baltas, being within 5% of the former and 10% of the latter. Williamson and Li[38] published two-dimensional away and along tables, as well as tables of radial dose function, anisotropy functions, and dose rate contours from their Monte Carlo data. Subsequent TLD and diode measurements around these sources by this group[39,40] have confirmed their Monte Carlo calculations. It should be pointed out that the data referenced above applies to Nucletron HDR/PDR sources only. The sources used by other vendors are not the same, and data on such sources are currently scarce.

6. Intersource, heterogeneity, and applicator effects on dose

Measurements of the dose distribution around gynecological colpostat applicators containing tungsten shields have been made by several investigators.[41–43] The goal of these measurements is to obtain enough three-dimensional data either to construct look-up tables[42] to be entered into treatment planning systems, or to derive input for simple one-dimensional dose computation algorithms.[43,44] Although it is not particularly difficult to incorporate these algorithms into planning computers, most commercially available systems have no such provision. Thus the effects of the tungsten shields are generally ignored. To date, measured and calculated distributions have been done for single colpostats only. Dose for an implant using two colpostats is taken as the sum of the contributions of each. This, of course, ignores colpostat-to-colpostat shielding. Similarly, in computer dose calculations for interstitial implants, interseed effects are ignored. Measurements[45] and Monte Carlo calculations[46] for ^{125}I implants show that for the specific geometries investigated the actual peripheral dose is about 6% lower than that obtained from summing single source doses. Unlike the situation with colpostats, there are as yet insufficient data to recommend incorporating interseed effects into treatment planning systems.

Gradually, data are becoming available to support shielded applicator design for lower energy radionuclides. Recently, dose perturbation factors (termed ''heterogeneity correction factors'') down stream of small disk-shaped shields of aluminum, titanium, steel, silver, and lead placed on the transverse axes of ^{125}I, ^{169}Yb, ^{192}Ir, and ^{137}Cs sources have been measured using diode dosimetry.[47] In many cases, these investigators found that these perturbation factors varied rapidly with the cross sectional area of the shield and its distance from the point of interest as well as the thickness of the material traversed by primary photons. This suggests that simple path length dose calculation algorithms[44,29] cannot

adequately model low-energy source dose distributions in the presence of high density, high atomic number shields. Williamson *et al.*[47] did find that if accurate three-dimensional models of the source and experimental geometries were used, Monte Carlo photon transport calculations were able to reproduce their measurements within a few per cent. Other than Monte Carlo simulation, no practical dose calculation algorithms exist for accurately modeling bounded heterogeneity effects. Convolution and scatter integration algorithms, which have the potential of greatly improved dose calculation accuracy, are currently under development.[48]

At ^{125}I and ^{103}Pd photon energies, photoelectric absorption contributes a larger proportion of the dose to tissue than for higher energies. Therefore, small variations in tissue atomic number result in significant effects on dose. The dose from ^{125}I to selected tissues has been calculated[49] and measured.[50–52] However, these studies involve measuring the effects of replacing the entire water medium by muscle-, breast-, and bone-equivalent media. Recently, some data have become available, illustrating the effects of more anatomically realistic bounded tissue heterogeneities surrounded by water equivalent media. Meigooni *et al.*[53] measured the perturbation caused by a large cylinder of polystyrene in a homogenous tissue-equivalent medium. They found that the measured dose rates just beyond a 2-cm-thick polystyrene heterogeneity changes by as much as 130%, 55%, and 10% for ^{103}Pd, ^{125}I, and ^{241}Am, respectively. In another recent study, Das *et al.*[54] used TLD dosimetry to measure dose perturbation factors for an ^{125}I source downstream of disk-shaped cavities filled with cortical bone, trabecular bone, fat substitute phantom, air, and lucite, and compared their measurements to Monte Carlo photon transport calculations. They found that the calculations and measurements agreed within 5%. They used the Monte Carlo technique to study the dependence of the heterogeneity correction factor on heterogeneity diameter, thickness, and distance from the source as a function of the source-to-measurement point distance. For cortical and trabecular bone, they found that the shielding effect varied by as much as factors of 5 and 1.33, respectively, with respect to distance and heterogeneity diameter, casting doubt on the utility of one-dimensional heterogeneity corrections for this application. For the lower density heterogeneities (air and fat), they suggested that one-dimensional algorithms have an accuracy on the order of 10%. As yet, there is no model that can be used to calculate the dose to a heterogeneous medium, other than Monte Carlo simulation. However, clinical implications for ^{125}I, breast implants have been discussed.[52]

D. Source localization

Realization of the potential of brachytherapy to deliver a high target dose and relatively small dose to surrounding normal tissue requires several stages of planning. One of these is source localization, which is the determination of the three-dimensional coordinates and the orientation of each source relative to the patient anatomy. It can be accomplished by a variety of methods, all of which require at least two images from different perspectives. An extensive bibliography can be found in a recent review of the subject.[55]

Localization usually begins by entering source film coordinates into the computer by means of digitization. Each view provides two coordinates with the rotation axis of the imager being a common coordinate. In some methods the sources must be manually matched on two films prior to digitization to be properly located within the patient. In other methods the sources can be randomly digitized from two or more films and the computer, using various criteria, automatically performs the matching. The latter are particularly helpful for large permanent implants with many sources, but few treatment planning systems offer such algorithms.

It is fairly common to assign an average magnification to each localization film, which is applied to convert film coordinates to patient coordinates for all the sources. If the implant is small and the magnification factor is that of the center of the implant, this is a reasonable approximation. A more accurate way to convert from film to patient coordinates is to use a ''geometric reconstruction'' algorithm, which combines the coordinates from each view, in effect, to determine the magnification of each source. Geometric reconstruction may be used with any localization technique. For references, please see the recent review by Meli.[55]

A common manual matching technique uses two isocentric orthogonal films taken with a treatment simulator. Because the anatomy is so different on orthogonal films, it is sometimes difficult to match the images on the two films corresponding to the same source. Dummy cables with coded markers are sometimes helpful in correlating sources between the orthogonal films. If available, the fluoroscopy of the simulator can be used to select films that maximize source image matching. Sometimes orthogonal films are taken with a portable x-ray unit. For these situations it is important to ensure that the films are truly orthogonal. Some treatment planning systems combine jigs and appropriate algorithms to correct for any lack of orthogonality. Localization may also be accomplished from two isocentric but nonorthogonal films or from two ''stereo'' films for which the x-ray target or patient is displaced linearly between the films. Two-film techniques using an interfilm angle of less that 90° and the stereo shift method make it easier to match sources because the source image configurations are more closely the same than on two orthogonal films. The smaller the separation between the films the truer this is. However, it is also true that the smaller the film separation, the poorer the localization accuracy. Of all techniques, orthogonal films provide the greatest accuracy because digitization errors translate to the smallest source coordinate errors, while stereo-shift films typically provide the least accuracy due to poor reconstruction of the depth dimension. With all techniques, digitizing accuracy improves with increasing magnification.

Regardless of the method used, it is good practice to document the localization accuracy. The best way to accomplish this is, after digitization, to reconstruct source positions for the orientation of another film taken at the same time as the localization films. Good agreement, best seen by overlaying the reconstructed source distribution on the third film, is

excellent verification that the sources were properly matched on the localization films.

The implant target is usually not identifiable on conventional radiographs. Thus there is no way of correlating sources and dose distributions with the intended target volume. For this reason it is becoming increasingly common to include imaging modalities, such as CT and MR, in the source localization process. CT-based source localization and dosimetry is the method of choice, except where the applicator contains sufficient metal to cause image artifacts. The advantages are twofold: (1) the problem of matching sources from film to film is avoided; (2) cross sectional isodoses can be directly superimposed on the target volume and surrounding anatomy. CT-based localization and dosimetry are particularly useful when poor quality lateral films, e.g., in the pelvic region, hamper one's ability to associate sources on the anterior–posterior film with those on the lateral film as in the case of perineal templates. Procedurally, one turns the gantry of the CT scanner perpendicular to the average direction of the needles. Slices are taken 1 cm apart corresponding to the 1-cm seed separations commonly used in iridium ribbons. One then assigns a seed at each needle (white spot) on each slice over the whole active length of the implant. For head and neck cases using nylon catheters, one can clearly see the black ''holes'' on each slice corresponding to the air in the catheters. For permanent seed implants, 3-mm-thick slices 3 mm apart are needed to minimize the possibility of having the same seed appear on more than one slice. Having done this, there will still be some seeds that appear on two adjacent slices. These seeds have to be assigned to one slice or the other. The error in doing this arbitrary assignment is not more than one-half the thickness of the slice (1.5 mm). Coordinates of these positions can be read off the CT console and input into the treatment planning system. On some treatment planning systems, one may digitize seed or needle locations from axial scans, one slice at a time, thus eliminating the process of entering the x,y,z coordinates from the keyboard. When dose distributions overlay CT slices, doses to the target volume and critical structures are easily determined and dose volume calculations can be performed for better assessment of the implant.

For CT localization, a number of new techniques are emerging. Some of them use scout films or digitally reconstructed radiographs and offer new solutions to streaking and aliasing artifacts. Other new techniques use ultrasound or MR images. For a review, the reader is referred to the 1994 AAPM summer school proceedings.[56] This is a fluid area under active development.

Any new algorithm or a revision of an old one for localization of sources should be tested for accuracy using a phantom.

IV. IMPLANT DESIGN AND EVALUATION

A. Manual methods

The classical and traditional methods of brachytherapy planning are available as sources of historical perspective and as methods of checking computer plans. In many situations these methods are valid starting points for computer-aided optimization by adaptive modification of the source configuration. When prior computer planning is not feasible, these may guide the radiation oncologist in implementation, and the physicist's role can be to instruct and explain.

1. Manchester and Quimby systems

In the Manchester system of interstitial implantation, peripheral sources define the target region and the goal is to optimize dose uniformity.[57,58] For planar and volume implants, planning relies on pre-calculated tables of the cumulated source strength per unit dose (in mg h per 1000 cGy) to be used for adequate coverage of a given area or volume. To obtain the total source strength, the table value is multiplied by the desired dose rate. The dose derived from the table values is called the stated dose and is 10% larger than the minimum dose in the treatment region, which is the plane directly opposite the source plane at 0.5-cm distance in the case of planar implants and the volume enclosed by peripheral sources in the case of volume implants. These tables are valid only if certain source-distribution rules are followed in performing the implant. These rules specify the fraction of the total source strength to be placed at the periphery, with the remaining fraction to be distributed uniformly over the interior. For rectangular planar implants, for example, the peripheral fraction is two-thirds if the area to be treated is less than 25 cm^2, one-half if the area is between 25 cm^2 and 100 cm^2, and one-third if the area is greater than 100 cm^2. For volume implants (of any shape), the peripheral fraction is three-fourths.

The Manchester tables were calculated for radium sources assuming only an inverse square attenuation of dose. The influences of tissue attenuation and scatter buildup were ignored. For high-energy photons this is a good approximation up to about 5 cm from the source, as absorption by intervening tissue is canceled by in-scattering from surrounding tissue. Thus the tables are appropriate for other high-energy photon emitting sources such as ^{192}Ir. However, the tables must not be used for low-energy emitting sources such as ^{125}I and ^{103}Pd, which have a dose falloff considerably more rapid than inverse square law predicts.

The Quimby implant system for interstitial implants uses equally spaced, uniform-strength sources distributed over a source plane or a treatment volume. For planar mold treatments, the stated dose was the maximum dose in the treatment plane. For Quimby volume-implant tables, the stated dose is the minimum dose within the volume. Although Quimby planar mold data did not become the basis for planar interstitial implant recommendations in the manner of the Manchester system, its uniform source placement rule continues to be widely applied in planar implants. It has been shown, for volume implants,[59] that uniform distribution of source strength leads to values of cumulated strength per unit dose that approach Manchester data ever more closely as the implanted volume increases. Moreover, if source spacing is the same in both directions for rectangular planar implants of seeds in ribbons, end seeds as well as lateral-ribbon seeds

may be considered peripheral, and it is found that Manchester placement rules are reasonably well followed, even when source strength is distributed according to the Quimby system. These considerations make it quite feasible to use Manchester data to perform approximate quality assurance checks of computer calculated plans for Quimby-type implant geometries. In the case of high-dose rate remote afterloading plans that have been optimized to produce uniform dose distribution, closer agreement (within 10% for idealized plans) may be expected.[58]

2. Memorial nomographs

With the advent of three-dimensional imaging techniques that allow more accurate assessment of resectability, fewer permanent volume implants of unresectable tumors are being performed. However, for those tumors that are implanted with ^{125}I seeds because unresectability is determined only at the time of surgery, a nomograph is still useful to indicate the total seed strength required to deliver a given dose to a tumor of measured dimensions and to provide some spacing guidance as well. For the nomographs developed at Memorial Sloan-Kettering Cancer Center,[60] total seed strength is a power function of target average dimension to deliver a matched peripheral dose (MPD) of 160 Gy for average dimensions of 3 cm or greater. The MPD method of dose evaluation by volume matching is discussed in Sec. V C below. The exponent (2.2) was obtained by fitting actual patient MPD data. For average dimensions less than 3.0 cm, a power of 1.0 was assumed, and the coefficient was taken to be 5 mCi (apparent) per cm, corresponding to the original average dimension rule,[61] which permits the dose to increase as the target gets smaller (proportional to the -1.2 power of average dimension). The nomograph includes additional scales to guide needle spacing for given spacings of seeds along the needle track. A similar nomograph has been developed for ^{103}Pd seed implants.[62] These nomographs are intended as intraoperative planning guides and should not be substituted for more definitive planning (e.g., for prostate implants) that uses three-dimensional images.

3. Paris system

The Paris system[63,64] was developed for temporary implants of ^{192}Ir wire. As a planning tool, it is idealized to the extent that it assumes parallel, uniformly spaced source lines of equal length and source strength, disposed in one or more parallel and uniformly spaced planes. In addition, since dose specification is primarily in the central perpendicular plane, there is the requirement that the line centers fall in that plane, i.e., that the implants be rectangular in shape. For multiplanar implants, the wire locations in transverse cross section should be at the vertices either of squares or of equilateral triangles. Linear strength density must be constant throughout the implant.

The thickness and width of the treated volume in the Paris system are specified in the central plane, and target length is specified in the source plane. Each dimension is considered to be the average of individual minimum distances between opposing undulations in the treatment isodose contour. In order to obtain adequate coverage with either single- or multiple-plane implants, implantation guidelines require source lines to be about 50% longer than the treated length when the latter is only 4 cm and about 25% longer when the length is 12 cm. In many cases this requirement is difficult to meet. The ratio of the treated thickness to the source spacing falls in the range 0.55–0.65 for planar implants, 1.55–1.60 for two-plane square implants, and 1.25–1.35 for two-plane triangular implants, the ratio generally increasing with source length and number of source lines. Extension of the treatment width beyond the lateral source lines is about 33% of the spacing between lines for planar implants, 27% for two-plane square implants and 20% for two-plane triangular implants.

Individual basal dose rates are defined in the central plane, for planar implants, at points midway between adjacent source lines and, for multiplanar implants, at the centroid of the squares or triangles formed by adjacent-source penetrations. The basal dose rate for the implant is taken to be the average of the individual basal dose rates. If the implantation rules have been followed carefully, the system assures that the isodose contour of a treatment (or reference) dose rate equal to 85% of the basal dose rate will closely encompass the treated-volume dimensions defined above. As a first-approximation example, planning for a single-plane implant to treat a target volume of dimensions L (length), W (width), and T (thickness) might proceed by choosing to use n wires, each of length $x=(1.13+1.5/L)L$, spaced at $d=1.67T$, with the number of wires given by $n=0.4+0.6(W/T)$.

The Paris system affords good coverage of the target volume, provided implantation is accurately performed, and yields good dose uniformity within the target volume. However, it includes a significant volume of normal tissue within the treatment isodose contour, and dose rate is adjustable only by varying the source strength per unit distance along source lines.

B. Computer methods of implant design

Compared to manual methods, computer planning allows a much better fit between achieved and desired dose levels at specified points of clinical interest. In general, the fit is attained by optimizing the source configuration (positions and/or strengths). Adjustments of the configuration may be performed intuitively by the planner, in which case versatile and user-friendly software is very important, or automatically by the computer, via algorithms that incorporate much the same decision criteria. In some instances the goal will be to optimize dose at points specified relative to an applicator and, in other instances, the targeted points will be obtained from three-dimensional images (CT, MR, or ultrasound) of anatomy. Optimization may be weighted, either to avoid underdosing tumor or to avoid overdosing normal tissue. The optimization software used should indicate the goodness of fit achieved, e.g., the standard deviation of the ratio of achieved/desired doses. Thorough testing of planning soft-

ware, whether obtained from commercial suppliers or developed locally, is absolutely essential prior to clinical use.[3] Repeat testing is required after any modification of the software.

1. Applicator-based planning

In some intracavitary and intraluminal treatments both dose prescription points and possible source positions are defined with respect to an applicator. For example, in high-dose rate (HDR) remote afterloading with a vaginal cylinder for vaginal cuff treatments of post-operative endometrial cancer, the target contour is usually 0.5 cm from the cylinder surface in the upper half of the vagina and source positions are distributed along the axis of the cylinder. Efficacious treatment delivery depends on proper insertion and fixation of the applicator, and radiographic verification of applicator position is strongly recommended, but film-based planning is generally not required. It is at least as accurate, and certainly more cost effective, to extract the required plan from a pre-calculated atlas of isodose rates obtained from optimized dwell-time patterns, one for every combination of cylinder diameter and treatment length for prescribed dose likely to be encountered.[65] One can scale dwell times for different doses but in practice, it is better to optimize for each dose level because round off to the nearest second can produce slightly different times.

HDR endobronchial treatments can also be planned by pre-calculated atlases, if a constant dose is prescribed at a given distance (usually 1 cm) from the line of source positions over the entire treatment length. To limit isodose surface undulations to less than 2%, the prescribed distance should be greater than the source spacing.[58] The length and location to be treated are decided by bronchoscopy and, again, radiographic verification is required. It is essential that any offset between the end of the catheter or dummy source cable and the distal end of the treatment region be properly taken into account.

In order to assure that the correct atlas plan has been retrieved from the computer, it must be checked by a member of the physics staff. We recommend that hard-copy isodose contours be generated for review by the physician. Plan parameters that need to be checked include correct applicator, source spacing, treatment length, stepping interval, source strength, and treatment dose. An overlay of the target outline on the isodose contours is frequently helpful as an aid to evaluation.

Optimization software should be used for special cases not covered by an atlas, possibly the same software that was used in generating the atlas. Such cases would include target volumes extending to the lower half of the vagina or multiple catheter endobronchial treatments in the area of the bifurcation. Also, low-dose rate treatments of the abovementioned sites would not, in general, be appropriate for an atlas, because of the difficulty of obtaining source strengths of precisely the right relative values.

Institutional practices for intracavitary treatment of cervix cancer vary widely. When treatment points are defined with respect to the applicator, atlases may be used to provide doses at tissue tolerance points (at markers in rectum, bladder, etc.). Otherwise, custom planning may be needed. Optimization entails trying to adjust source strengths, at radiographically determined positions, to bring the prescribed dose rate as close as possible to desired levels, while keeping dose rate to critical normal tissues below tolerance values. If optimization by computer is performed in LDR brachytherapy applications for the cervix, iterative optimization is required because only discrete source strengths are available[66,67] whereas, when HDR is used, the essentially continuous variability of source dwell time makes possible analytic computer optimization[68–70] (by least squares, for example). It is recommended that optimization, with the above objectives in mind, be performed for cervix applications, whether by an optimization algorithm or by trial and error.

2. Image-based planning

Increasingly, brachytherapy planning is based on three-dimensional images of patient anatomy. Notable examples, as already mentioned, are stereotactic temporary implants of brain tumors and percutaneous perineal prostate implants.

Most software used for planning stereotactic brain implants from CT images has been developed locally, and several approaches have been published. Some require interactive reconfiguration by the user, assisted by sophisticated manipulation and display capability,[71] and others involve automatic adjustments of source positions and/or strengths.[72–74] In one of the latter,[74] ^{125}I seed positions are iteratively least-squares optimized, first with only one seed per catheter and then after each of a sequence of maneuvers in which nearest-neighbor catheters are combined; the combinations, which continue as long as reasonable goodness-of-fit is maintained, serve both to reduce the number of skull penetrations necessary and to separate individual catheters enough that retainer buttons on the surface do not interfere with one another. For automatic position adjustments in this type of optimization, it is essential (for convergence) that seeds be constrained not to move outside a three-dimensional bit-map structure conforming either to target contours drawn on the scans or, if desired, to smaller contours (e.g., the enhancement margin presumed to indicate tumor). Planning includes transforming source coordinates planned on CT to equivalent coordinates in the stereotactic frame system and calculating the corresponding angular and depth settings of the frame. It is recommended that a member of the physics staff be present for the OR procedure, to help assure that the plan is accurately implemented.

Planning procedures for transperineal prostate implants using ^{125}I seeds or ^{103}Pd seeds range from CT-based optimization[75] for fluoroscopy-guided implants to ultrasound-based planning,[76] or sometimes no planning at all for ultrasound-guided implants. We recommend strongly against this last option, which we believe can more likely lead to morbidity and/or underdosage. CT-based planning facilitates localization of pubic bone and needle angulation for better anterior coverage of large prostates, whereas

ultrasound-based planning permits better definition of the prostate capsule and increases the likelihood of keeping seeds within it. One technique of needle angulation to miss pubic bone involves rotation, at the template end only, of an initially cylindrical array of needles, to produce an hourglass shape array that will be smaller in diameter in the vicinity of the bone than in the prostate.[77] This approach, of course, requires fabrication of a custom template. Ultrasound-based planning generally makes use of a standard template with parallel needles, and it may be necessary to exclude patients for which the anterior prostate is blocked by pubic bone. Whichever imaging method is adopted, it is recommended that the treatment plan is designed to place seeds peripherally to improve dose homogeneity and to avoid unnecessary radiation damage to the urethra.

C. Dose planning and evaluation

Whereas planning is carried out in advance of the implant procedure for the purpose of enhancing its quality, evaluation is performed after the implant in order to assess quality and to address the need for revising the source loading, treatment time, or written prescription. For implants performed following only nomographs or other general guidelines, evaluation usually involves assigning a treatment dose based on an analysis of isodose contours generated from radiographic images. Admittedly, for some types of brachytherapy, evaluation may merge temporally with planning, as in the case of HDR remote afterloading treatments and those LDR treatments where sources are fixed in applicators (e.g., eye plaques, cervix, and vaginal applicators, etc.); for such treatments it is important first to be sure that the treatment is delivered as planned and then to assess quality based on the plan.

1. Matched peripheral dose (MPD)

The MPD is defined, for permanent volume implants, as the dose for which the contour volume equals the volume of the target.[78] The target volume is most often approximated as the volume of an ellipsoid having the same (orthogonal) dimensions as the target, i.e., $V=(\pi/6)abc$. As a dose assessment, MPD is an approximate method that should be used only for implants performed in the absence of custom planning. It should no longer be used, for example, to assess prostate implant dose, for which planning is now based on three-dimensional images. It is always an overestimate of the minimum peripheral dose, since the shapes of the matched volumes are never identical and, assuming geographic accuracy, the two surfaces are interlaced, so that wherever the target protrudes from the treatment isodose, it protrudes to a lower dose level. The extent of the overestimate, not evaluable in the pre-CT era, has been estimated at a factor of 2, on the average, for prostate implants, on the basis of targets drawn on post-implant CTs.[79] However, this estimate itself may be an overestimate, probably due to lack of scan-to-scan continuity in target contours, since unpublished data from the same study also indicate a factor of 2 between the dose encompassing 94% of the target volume and the dose encompassing 100%.[77] In any case, it is evident that a small protruding spike as part of the target surface will greatly increase the degree of overestimate.

The MPD is linked to nomograph planning, since the total source strength specified by both ^{125}I and ^{103}Pd nomographs is based on MPD data for actual implants. If moving from nomograph planning and MPD evaluation to image-based planning (to achieve 100% coverage of the target volume), it may be advisable to lower the prescribed dose to better approximate actual doses delivered historically when the MPD method was used. For example, if satisfactory clinical results had been obtained with total source strengths specified by a nomograph, but post-implant MPD evaluations (from CT images) consistently overestimated the minimum target-volume dose by a factor of 1.4, it could be argued that image-based planning should aim for a minimum dose only 70% of the nomography-planned MPD. Realistically, however, 100% coverage will seldom be achieved, and a less drastic reduction in the planned minimum dose would be appropriate. Unfortunately, current data are insufficient to permit definitive recommendations in this instance.

2. Maximum continuous-contour dose for tumor bed implants

Planar implants (single or double plane) of ^{192}Ir or ^{125}I seeds in ribbons are frequently used to treat the tumor bed after excision of a soft tissue sarcoma. An important consideration is that no gaps appear between catheters in the treatment isodose contour.[60] The assessment procedure, based on films taken with dummy ribbons in place, involves generating isodose rate contours throughout the target region in closely spaced (1.5–2.5 cm) planes approximately perpendicular to the catheter direction. Contour dose levels should be no more than 20% apart, to facilitate selection within 10%. The innermost continuous contour in each plane is identified and from them the highest-dose rate that adequately covers the tumor is selected. Treatment time is determined as the quotient of the prescribed dose and the dose rate selected. If wide separation of catheters in one part of the target region has given rise to a dose rate selection more than 10%–15% lower than the desired dose rate (usually 10 Gy/day), it is recommended that the offending area be appropriately hot loaded and the evaluation procedure repeated. Since there is generally a (wound healing) period of several days between film taking and the start of irradiation, such adjustments and the ordering (or local assembly, for ^{125}I) of special ribbon loadings are likely to be quite feasible.

3. Maximum continuous-contour dose for volume implants

Ideally, dose evaluation in brachytherapy should be based on three-dimensional images of both sources and relevant anatomy, with the treatment dose specified as the dose for which the isodose contour just encloses the entire target volume. Although we should keep trying to expand the number of brachytherapy sites for which this ideal is approached,

currently there are only a few, and we return to temporary brain and permanent prostate implants to illustrate the concepts.

The quality of a stereotactic brain implant is directly related to the accuracy with which planned seed positions have been realized. Assessment of placement accuracy within 0.3 mm is readily possible, based on post-implant radiographs taken with a device, alternatively called a Lutz box or localizer, affixed to the stereotactic frame prior to the frame's removal from the patient's head.[80] Anterior–posterior and lateral films each image lead-shot markers fixed at the corners of a square in plastic holders on the near and far side of the head as well as implanted seeds (real or simulated). A projective geometry algorithm due to Siddon[80] enables localization of the seeds in the stereotactic frame system, and their coordinates are then transformed back to the planning CT scans via the same program that was used earlier to transform planned CT locations to the frame system. Individual and average ''miss distances'' can then be calculated and isodose contours plotted to check whether target coverage, at the dose rate planned, may have been compromised. It is highly recommended that this quality assessment procedure be performed for each seed implant of brain, in addition to an evaluation of target coverage based on post-implant CT scans. The latter evaluation requires redrawing of target contours.

For permanent transperineal prostate implants, dose contour evaluation is possible only if post-implant scans are obtained, and such evaluation is strongly recommended.[76,79] Seed locations should be determined directly from the CT images, using multiple images of the same seed to improve localization in the longitudinal direction. An auxiliary anterior–posterior radiograph is helpful to establish a firm seed count in case of ambiguity in the CT seed count. Isodose contours should be generated for overlay comparison with new target contours drawn by the radiation oncologist. It is important that these contours be based on the same anatomic criteria used in defining target contours on the planning CT images and that they not be influenced by the images of implanted sources. It may be anticipated that the dose reported ultimately will be that which covers a given fraction of the target volume (e.g., the 90% dose) and that, as technological advances improve both placement accuracy and post-implant target delineation, the coverage percentage of the reported dose will increase.

4. Dose volume histograms

Although minimum dose can be approximated fairly well from isodose overlays of target contours on CT scans, specification of the 99% dose (the dose that covers 99% of the target volume), for example, requires target-specific histogram data, i.e., information on what fraction of a given isodose contour volume falls within the target. Generation of this kind of data requires an algorithm that interpolates between target contours to establish a three-dimensional bit map of voxels that have, for example, values of zero inside the target and values of one outside.[74] Thus each voxel can be assigned to a given isodose contour volume if the dose calculated at its center is larger than the given dose and also assigned to the target if its bitmap element contains a zero. Since few commercially available treatment planning programs currently have this feature, the AAPM can only encourage developers to add it in the future. However, we strongly recommend that software include the capability to generate integral (or cumulative) dose volume data and preferably differential volume dose data, as well. A particular variation of the nontarget-specific differential histogram for brachytherapy is the natural histogram, also recommended, in which the distorting influence of the inverse square law is suppressed by plotting the volume per unit $-3/2$ power of dose rate vs dose rate on a $-3/2$ power scale.[81] This type of histogram is particularly useful in assessing source configuration with respect to dose uniformity, on the one hand, and volume peaking (at dose rates lower than the treatment dose rate) in normal tissue, on the other.

5. Quality quantifiers

Quantities such as percentage of target volume receiving greater than 1.5 times minimum tumor dose and percentage of normal tissue volume receiving more than 0.5 times minimum tumor dose are desirable. These can be achieved only through a dose volume analysis based on three-dimensional post-implant imaging.

Dose volume data, both target specific and otherwise, have been used by a number of authors to develop implant quality assessment parameters relating to target coverage, to dose uniformity, and to normal tissue irradiated. These have been summarized by Anderson.[82] Those that are recommended for incorporation into brachytherapy evaluation software, in keeping with the histogram recommendations above, are those that do not require target-specific data; they include (1) a conformity parameter defined as the ratio of treatment volume to target volume, as a measure of normal tissue treatment, and a uniformity parameter defined as the ratio of the average dose to the prescribed dose;[83] (2) either (a) a uniformity parameter called the dose homogeneity index (DHI) and defined as the fraction of the treatment volume that receives a dose between 100% and 150% of the prescribed dose;[84] or (b) a closely related uniformity parameter called the dose nonuniformity ratio (DNR) and defined as the fraction of the treatment volume irradiated to more than 150% of the prescribed dose;[85] and (3) uniformity and normal-tissue-irradiation parameters based on the natural volume dose histogram.[81] A well-designed implant may be seen as one for which the treatment dose rate (usually specified, by necessity, on the basis of target coverage) corresponds closely to the maximum DHI, the minimum DNR, or the lower half-maximum value of the natural histogram peak. Such correspondence assures that the target volume comprises largely the regions of quasi-uniform dose between and among implanted sources.

Recently, Low and Williamson[86] performed an analysis of implant quality and found that using the dose per integrated

reference air kerma (IRAK) helped to reduce prescription ambiguities.

D. Dose specification and reporting

A major concern among radiation oncologists practicing brachytherapy has been the difficulty of interpreting clinical dose response data from the literature. Although some of this difficulty must be attributed to the high-dose gradients found in brachytherapy, much of it has been related to the lack of standardized practices of reporting dose.[87] Among the several efforts to address this problem, we commend to your attention those of the International Commission on Radiation Units and Measurements (ICRU)[88,89] and the American Brachytherapy Society (ABS: formerly the American Endocurietherapy Society).[7]

1. ICRU recommendations for intracavitary brachytherapy

Intracavitary irradiation is characterized by steep dose gradients in the vicinity of the sources and throughout the tumor and target volume. This physical characteristic, along with under utilization of computed tomograms (CT) and magnetic resonance (MR) imaging techniques, makes specification of target absorbed dose and maximum dose to critical structures very difficult. Many quantities have been used to quantify, prescribe, and to constrain intracavitary therapy at gynecologic malignancies including dose to point A, mgRaEq h, vaginal surface dose, and treatment time. Major systems for treatment of cervix cancer differ not only in choice of dose specification criteria, but in applicator design and geometry, insertion and packing techniques, and relative importance of the external beam and intracavitary components of irradiation. Both the lack of a universal system of dose specification and reporting and variation in treatment techniques have hampered the interpretation of data of tumor control and treatment sequelae from different centers.[89]

The International Commission on Radiation Units and Measurements (ICRU) has attempted to address this problem in its Report No. 38.[88] In addition to reporting source strengths, treatment time, and standard isodose contours (lateral and oblique frontal planes) the report committee recommends reporting (1) the dimensions of the 60-Gy isodose contour (including external beam as well as all intracavitary applications), (2) the dose at a bladder point at the posterior surface of the Foley balloon on the anterior–posterior line through the center of the balloon, (3) the dose at the rectal point 0.5-cm posterior to the (opacified) vaginal cavity along an anterior–posterior line midway between vaginal sources, (4) as defined by a lymphatic trapezoid, doses at points representing lower para-aortic as well as common and external iliac nodes, and (5) with reference to planes tangent to the acetabula, dose at points representing distal parametrium and obturator lymph nodes.

Several recent analyses of the ICRU 60-Gy reference volume have illustrated some of its weaknesses. Potish[90] has examined the correlation of the three orthogonal ICRU isodose dimensions (H, W, and T), as a function of implant dose rate, with the geometric characteristics of 90 Fletcher intracavitary implants. His study, as well as a similar study by Eisbruch,[91] demonstrated that while the individual isodose dimensions were correlated with such parameters as colpostat separation and tandem length, the most dominant parameter was mgRaEq h. Both authors showed that product of ICRU orthogonal dimensions, HWT, was uncorrelated with individual implant linear dimensions but highly correlated with mgRaEq h, for all dose levels in the therapeutic range of interest. Eisbruch further showed that HWT was a poor predictor of the geometric volume contained within the corresponding isodose surface and that its true volume, $V(D)$, could be inferred with an accuracy of 5% from the relation $V(D) \propto (\text{mgRaEq h}/D)^{1.64}$, where D is the dose from the implant. These two investigations demonstrate that the parameter $H \cdot W \cdot T$, derived from the ICRU Report 38 recommendations, is not a prognostic factor independent of the concept of mgRaEq h (or equivalently IRAK). Further, one function of mgRaEq h as a prescription or treatment constraining parameter is to limit volume of tissue taken to a specified dose by the implant.

2. Recommendations for intracavitary brachytherapy

Partly as a result of the dosimetric limitations described above, intracavitary brachytherapy treatment techniques, techniques, dose prescriptions, applicator designs, and knowledge of normal-tissue and tumor dose-response relationships, have evolved empirically, guided by observed control and complication rates in large groups of patients treated in a uniform fashion over many years.[92] Applicator insertion remains a surgical skill, guided by palpation and direct visualization rather than by a quantitative geometric model of the target volume and surrounding normal tissues derived from CT and MR imaging studies. It is important for the practicing physicist to accept that the major intracavitary brachytherapy treatment traditions are closed systems: average clinical outcomes for a group of patient treatments in terms of local control and complications will be predictable only if current applicator insertion and packing techniques, dosimetric practices, and treatment prescription and loading practices are consistent with evaluated base of clinical experience from which the radiation oncologist's training and knowledge of dose-response is derived. From this observation it follows that a major function of the physicist is to maintain consistency between past and current practice with respect to applicator dosimetric characteristics and calculation of prescription and treatment constraining parameters such as reference point doses (rectal dose, point A dose, vaginal surface dose, etc.). A frequently encountered problem is introduction of new sources, new applicators that differ in design from those previously used, and new treatment delivery technology such remote afterloading equipment. The goal is to develop modifications of the loading and dose prescription rules designed to reproduce the total dose distributions achieved with the old equipment using the new applicators and sources.

To aid the physicist and radiation oncologist in maintain-

ing the integrity of their treatment system, this report recommends the following:

(1) As recommended by the American Brachytherapy Society[11] (then American Endocurietherapy Society), that the concept of integrated reference air kerma (IRAK) be adopted in place of mgRaEq h or mg h as a dose specification and prescription parameter in intracavitary brachytherapy: Integrated reference air kerma or IRAK is denoted by the symbol K_{ref} and is defined as

$$K_{\text{ref}} = \sum_{i=1}^{N} S_{K,i} \cdot t_i , \tag{3}$$

where $S_K i$ is the air kerma strength of the ith source (units: cGy cm^2 h^{-1} for LDR or cGy cm^2 s^{-1} for HDR) and t_I is the treatment time (units: hours for LDR and seconds for HDR) of the ith source. The recommended units of K_{ref} are cGy cm^2. K_{ref} is related to mgRaEq h and mg h by

$K_{\text{ref}} = \text{mg h} \cdot 6.754$, for filtration $t = 1 - \text{mm Pt}$,

$K_{\text{ref}} = \text{mgRaEq h} \cdot 7.227$, for filtration $t = 0.5\text{-mm Pt}$.

(2) Radiation oncologists and physicists should work together to develop written policies of treatment that define the clinical indications for therapy, and as a function of tumor size, location, stage, and other relevant clinical parameters, define the external beam and brachytherapy dose prescriptions that constitute the desired course of therapy. Much mystery often surrounds the process of modifying the stated brachytherapy prescription to accommodate nonstandard tandem lengths, colpostat diameters, and other patient-specific parameters. For example, in mg h based treatment delivery systems, the final quantity of radiation delivered by a given implant, often involves a complex interplay between mg h, vaginal surface dose, rectal and bladder reference point doses, maximum time, and other parameters related to the applicator dimensions and anatomic characteristics of the patient.[93,91] Treatment delivery errors and even systematic misapplication of the system to large groups of patients can result when the rules guiding individual patient prescription are unspecified or known only by a few. The AAPM strongly recommends that physicians and physicists work together to formulate prescription practices in writing in as clear and straightforward a fashion as possible, and tolerances for accepted deviations from these rules developed. Physicist review of treatment plans and other implant calculations include an assessment of compliance with prescription rules and policies of treatment: deviations outside the zone of tolerance should be reported to the radiation oncologist before the completion of treatment.

(3) Conventions for radiographically localizing reference points, procedures for handling applicator shielding corrections, methods for performing associated manual treatment time/dose calculations, optimization endpoints and methods, and any other treatment planning practices identified as critical for maintaining the system should be codified in written form and every individual treatment plan reviewed for compliance.

(4) Both radiation oncologists and physicists should work together to identify those factors which must remain constant to maintain the consistency of the system. Physicists must come to understand that the system is absorbed as a whole by the radiation oncologist usually as part of his or her training. Mixing dose specification and treatment planning practices, applicator insertion techniques, and dose prescriptions from different published systems should be avoided since patient responses to treatment will not be predictable.

(5) The physicist should be involved in the process of introducing technical changes in the system designed to improve clinical outcome. In addition to contributing technical expertise to the complex process of empirical optimization, the physicist can ensure that desired modifications are consistently implemented.

3. ICRU recommendations for interstitial brachytherapy

A draft ICRU report on dose specification in interstitial brachytherapy has been prepared and a provisional summary of it has appeared in print.[94] On the basis of information available to date, the reporting parameters therein recommended are closely related to those of the Paris system. Thus reported doses are defined primarily in the central plane as in the Paris system, and the basal dose and the reference dose have been renamed the mean central dose and the peripheral dose, respectively. Two uniformity parameters are identified: (1) the spread in the individual central doses averaged to get the mean; and (2) the ratio of the peripheral dose to the mean central dose. We recommend that the final report be studied carefully when it is published.

4. ABS recommendations for interstitial brachytherapy

The ABS (AES at the time) physics committee, formed in 1986, adopted dose specification as its first assignment and published Society approved recommendations in 1991.[95] The principal categories of information recommended for reporting were (1) the method of specifying target volume, whether by (in order of preference) drawing target contours on CT or MR images, by placement of surgical clips, or by projections drawn on orthogonal radiographs, (2) a plan description, including source configuration, planning methodology (e.g., Manchester or Paris system, Memorial nomograph, custom template, optimization, etc.), and intended treatment and tolerance dose rates (at defined points), and (3) evaluation of the dose distribution achieved, including specification of the treatment dose and its definition (e.g., MPD, minimum dose, 99% dose, etc.), treatment time, volume of treatment isodose contour, with its ratio (in %) to the target volume, the ratio of average dose to treatment dose (as a measure of uniformity), and the dose at any special treatment or tolerance points. A suggested report form, completed for

four example cases, was included with the recommendations. We strongly recommend familiarity with this document and an effort to implement its recommendations.

5. AAPM recommendations for interstitial brachytherapy

The AAPM endorses the abovementioned recommendations of the ABS on dose specification and reporting of interstitial brachytherapy. It should also be noted the specification in terms of minimum tumor/target dose can easily lead to differences of up to a factor of 10 between prescribed and achieved dose near the boundaries of the target. Dose specification remains an area of current development. Currently, regulatory definitions of misadministration in terms of a dose deviation greater than 10% or 20% are quite meaningless in the clinical implementation of this modality.

V. PERFORMING A BRACHYTHERAPY PROCEDURE

The following is intended to serve as a step-by-step guide to performing a brachytherapy procedure in keeping with good medical and physics practices.

A. Initial planning

The physician–physicist interaction is a critical link in promoting safe and accurate brachytherapy practices. The quality of a brachytherapy procedure is dependent on the degree to which the physicist and the physician communicate before, during, and after the implant. Initial planning may be as simple as scheduling a patient for a routine brachytherapy procedure that is performed many times a month. When possible, implants of a similar nature should be standardized as to sources, applicators, planning, and evaluation techniques. Even in commonly performed, uncomplicated procedures, a systematic procedure to all aspects of initial planning, applicator insertion, dose determination, and dose delivery should be part of written procedures. For more complicated procedures the physicist and physician should discuss the objectives of the procedure and how to proceed to achieve the goals. In either case, initial planning means that the physicist and physician have communicated about the proposed procedure to ensure that both are familiar with the apparatus, have identified the target volume on an image, and agreed to an approximate isodose distribution.

The physicist should inform the physician as to the practical, technical, and physics limitations inherent in a proposed brachytherapy case. The physicist should provide a realistic assessment of the accuracy with which the dose can be delivered to the proposed target volume. To facilitate communication the planning form should include the implant objective, the site and type of implant, apparatus needed, type and number of sources, anticipated geometry of the sources, dose to be delivered to the target volume and normal tissues, and other details of the implant.

For implants where source positions do not change from case to case, such as single line sources (esophagus, some bronchial, and tandem alone), vaginal or rectal cylinders, certain templates, and some tandem and colpostat applications, standardized (library) isodoses are a reasonable alternative to the generally preferred option of customized computer planning. These libraries can exist in hard-copy form or on the treatment planning computer. For more complex cases, such as some tandem and colpostat, perineal templates, prostate templates, ^{125}I seed cases, and multi-plane implants, the physician should have pre-implant images on which the target volume can be drawn (preferably CT scans). A diagram of the applicator with proposed loaded source positions should be prepared. In the absence of images, nomograms or other geometrically based systems can be used to define source loadings. In either case, initial planning includes the following steps: (1) the physician identifies the target volume, preferably on some image, otherwise relative to a fixed geometry applicator or by anatomical reference, or simply by three spatial dimensions; (2) often with physics staff, the physician chooses the implant apparatus and source geometry which suits the implant site and target volume; and (3) an approximate isodose distribution is calculated or obtained from a library of plans based on the physicist's understanding of the case.

As experience with these more complicated cases grows, rules of thumb and standardizing can be practiced to simplify the process and enhance quality assurance. Until that experience is developed, patient-specific isodose curves should be generated based on the planned source placement. These isodoses not only can help the physician determine the optimal source placement but can even rule out certain applicators in favor of others. Procedures for obtaining source localization films for each type of case should be well understood, as it is difficult to re-take CT's or radiographic films in the event that the first set is unusable.

B. Treatment prescription

The purpose of a treatment prescription in any area of medicine is to provide an unambiguous set of directions to another person carrying out procedures on behalf of the physician, such as a pharmacist filling out drug orders prescribed by a physician. For brachytherapy, the physician writing the treatment prescription and the person performing the implant are generally the same person. Therefore, the brachytherapy physician has the right and responsibility to modify prescriptions as required by further examination and new developments in the clinical case. Since brachytherapy procedures are surgical in nature, some aspects of the implant may change from the pre-implant treatment plan because of changing circumstances encountered during the implant procedure. Therefore, a distinction should be made between two phases of the prescription process: (1) the initial planning prior to the procedure as discussed above and (2) the post-implant treatment prescription. The pre-implant prescription shall be filled out before inserting radioactive sources, which often precedes availability of the final treatment evaluation/plan. For temporary implants, it should contain enough information to guide source preparation and loading by the physician's designee. Normally, this would include source type, source strength, batch number (where relevant), and

loading sequence/position in each catheter. The post-implant prescription shall be filled out after the evaluation process is completed but before the end of treatment. It should include additional data defining when sources are to be removed, usually including treatment time, prescribed dose (or equivalent parameters such as integrated reference air kerma, mg h), and dose specification criterion.

The brachytherapy treatment prescription is a legal document, which obligates anyone associated with the case to perform duties in a way to assure that the stated details of the prescription are carried out. As such, this document should be labeled ''BRACHYTHERAPY PRESCRIPTION FORM'' in order to distinguish it from any of the other notes, planning and summary data that may be generated during the treatment planning process.

Brachytherapy treatment prescriptions have similarities with external beam treatment prescriptions in that the dose per fraction, total dose, and treatment volume are subject to the clinical variability inherent in the practice of medicine. On the other hand, there is a wider range of acceptable doses in brachytherapy that provide for tumor control and yet respect normal tissue response tolerance. Therefore, it is clinically acceptable to prescribe a range of doses for a patient instead of a single dose value. Clinical uncertainty, medical exigency, and real life limitations mean the practice of brachytherapy is as much an art as other aspects of clinical medicine. The brachytherapy team must practice safe, high quality medicine with the patients best interest as their therapeutic goal.

It should be noted that the AAPM recommendation on treatment prescription is fundamentally different from the NRC definition of a ''written directive.''

C. Ordering sources

In the case where the sources needed for the implant are not held locally in safe storage, they need to be ordered from one of the several vendors across the country. ^{192}Ir seeds in nylon ribbons, ^{125}I and ^{103}Pd seeds are sources typically ordered from such vendors. Regulatory agencies place many constraints on the ordering, possession and control, and disposal of radioactive sealed sources. The institution's radioactive materials license (RML) specifies what type of sources and what total strength of each may be kept at any one time. If rented sources are not returned to the vendor in a timely manner, it is possible to exceed the total strength on hand permitted by the RML. This event would then preclude one from ordering any more sources. With this in mind, it is recommended that one specifies an ample strength limit for each type of sealed source specified on the RML. Sources can be ordered before the implant based on the anticipated loading arrangement, or one can wait until after the implant and computer dosimetry to order exactly what is needed. If dose optimization is to be achieved by using varying source strengths, one can expect added complexity, source handling concerns, and potential confusion and error regarding the ultimate location of each source strength. In the latter case, the patient may spend an additional day in the hospital while sources are in transit. Generally, it should be possible to order sources in advance of the implant because with experience one can closely predict what will be needed (a few extra seeds/ribbons can be ordered for good measure).

When ordering sources for a specific patient, one should request that the patient's name be placed on the source container, and that the sources should arrive before the day of the procedure (if possible). The number of ribbons and seeds should be specified along with the approximate strength of each source. For sources in nylon ribbons, the length of the plastic tip should be specified (not less than about 2 mm) as well as the inter-source spacing (usually 1-cm center-to-center). For any template cases, one should order colored filaments incorporated inside the ribbons extending from the outermost seed to the point in the ribbon that would correspond to the outer end of the hollow needle. The ribbon is to be inserted until the colored filament is just completely inside the needle. This detects situations where the needle is clogged at the end, causing the ribbon to only appear to be fully inserted. After the order for sources is placed, a log entry should be made of the patient's name and medical record number, what was ordered, and the date of the implant. A written procedure for ordering sources shall be prepared. Sources that are held in a source safe, such as cesium tubes kept permanently and ^{125}I seeds that are stored until used in a permanent implant, shall be inventoried every six months.

D. Receiving sources

When the sources are received, one shall check that the number of sources and strength of each as stated on the shippers bill of lading agrees with what the user had ordered. Sources should be received by trained personnel (radiation safety officer, designated staff from the radiation oncology department, or radiation safety office) in a controlled and secured area. Receiving sealed sources at the hospital receiving dock for later delivery to radiation oncology is not recommended.

All radioactive sources shall be stored in a lead source safe of sufficient thickness to reduce the exposure rate to acceptable levels. This source safe and a working area shall be in a secured room (hot lab). There shall be a ''CAUTION: RADIOACTIVE MATERIALS'' sign posted on the door to this area. Emergency instructions (including a call list of names and phone numbers) and a source inventory shall be posted inside the room. An individual trained in the use of radioactive materials (usually a physicist) shall be appointed to be responsible for keeping records of the issue and return of all sealed sources. A record shall be kept of every location where sealed sources are kept and the type and approximate strength of such sources. Remote afterloader units shall be kept in a secure location when the unit is not use. The treatment unit shall be posted with ''CAUTION: RADIOACTIVE MATERIALS,'' as well as the type and maximum strength of the source.

When opening the source packaging, it shall be determined that there is no contamination due to damage during

shipping. Current regulations require that the exposure rate at a meter (transport index, TI) and at the source container should first be determined along with wipe testing the outer container. The AAPM finds this regulation to be wasteful and unnecessary. Wipe tests are not necessary at this stage and the TI verification is needed only for high-energy photon emitter shipments with a total air kerma strength exceeding 50 μGy m^2 h^{-1}. The contents shall be examined for damage and the documentation shall be in agreement with what was ordered.

A log of the results of the exposure measurements, source-strength determination, source batch identification number, and package condition shall be kept along with the patient identification and room location. One of the primary concerns of the regulatory agencies is to ensure that the user is in control of radioactive material at all times. This means that the user should document the location of any source at any time. The logs for receipt, implantation, and shipping out can serve as this documentation.

E. Checking sources

Now is the point in the receipt of radioactive sources to verify the vendor calibrations, as per Sec. III B.

F. Source and applicator preparation

1. Iridium-192 seeds

Often it is necessary to edit the lengths of seed ribbons. This entails cutting off one or more seeds. Editing should be done in the hot lab behind a lead glass working area, never in the patient's room. Care must be taken to hold the seed to be cut off with forceps to avoid having the seed fly off. These edited seeds should be placed in a container labeled by batch number and marked ''RADIOACTIVE MATERIAL: ^{192}Ir'' and not stored inside the central bore of the lead carrier, which will subsequently be left in the patient's room (it is necessary to provide a safe area to store sources in the unlikely event that any become dislodged from the patient or applicator). No sources shall be left in the patient's room that are not part of the treatment. After preparing the ribbons, one shall survey the area to assure that there are no stray seeds. It is recommended that ribbons of varying lengths or activities be labeled as such before being taken to the patient's room. The ribbons should be transported to the patient's room in the lead shipping container inserted into a rolling cart. There shall be proper warning labels (''CAUTION: RADIOACTIVE MATERIAL'') affixed to the lead container that also describe the source type and strength. The patient or patient's bed should be tagged as containing radioactive sources. This would be useful in the event of an emergency where the patient had to be removed from the room.

2. Iodine-125 and palladium-103 seeds; other permanently implanted seeds

Iodine seeds are received as separate seeds in small glass vials carried in lead pigs. These seeds are then loaded into ''magazines'' for use in special applicators or are hand assembled into source-spacer trains in sutures or plastic carriers. Source carrying trays shall be labeled as to source type and strength. Mick or other seed inserters should be tested before being brought to the operating room. Needles and other equipment should be inspected for proper operation. This equipment can be flash sterilized near the operating room.

3. Cesium-137 tube sources

Tandem and colpostat source carriers shall be assembled in the hot lab. The tandem carrier commonly consists of a clear plastic tube with one end closed and a plastic insert (pusher) that has a cap at the handle end. These are bought as sets where the pusher length is the same as the carrier tube length. The total source plus spacer length is measured off on the ''pusher'' and cut away. Care should be taken that the final length of the ''pusher'' keeps the source at the tip of the plastic tube with no play. The sources and spacers are inserted into the clear tube followed by the pusher such that the cap just inserts into the carrier and makes a snug fit. For some of the gynecological applicators the colpostat carriers are metal ''buckets'' hinged at the end of long metal rods designed to fit inside the colpostat source handles. Care should be taken that the tube source does not fall out of the hinged bucket. The tandem and two colpostat source carriers shall be inserted into a metal carrier, which is inserted into a properly labeled lead pig.

Prior to sterilizing, the tandem and colpostat applicators should be checked for integrity, ease of operation, and fit of all colpostat caps. It is recommended that thin lead tape marker strips be placed around the belt of each large colpostat cap, a lead strip be run along the side of each medium cap, and that no strip be used for small caps. This or a similar system allows rapid identification on localization films. For remote afterloading cases, applicators and transfer tubes should be checked for damage and that they connect properly. A dummy source check run should be made prior to treatment for each channel to be used. This can be done automatically by many HDR units, otherwise a manual check for patency should be made.

G. Loading applicators and sources

Generally, the physicist alone should NOT load radioactive materials into the patient's applicator. This task should be performed by a two-member team consisting of a physician and a physics staff member. A member of the physics staff should also be present to make survey measurements. These survey measurements shall be made with a calibrated survey meter and a record kept permanently either in the patient's chart or in separate logs, either of which may be audited by regulatory agencies on a routine basis. A log of what type and strength of sources were loaded into the patient, the room number, and the date and time shall be kept. All personnel handling or assisting in the loading shall wear film or TLD collar badges and ring badges. A rolling lead shield or similar protective barrier shall be placed in the room as needed to assure that no area of the hallway, adja-

cent rooms, or other uncontrolled areas will exceed an exposure rate of 2 mR in any 1 h or more than 100 mR annually to any member of the general public taking into account workload, use factor, and occupancy factor. Protective barriers are not necessary for ^{125}I or ^{103}Pd seed implants. Generic surveys of uncontrolled area around specified rooms may be made and kept on file. In these cases, during an actual patient treatment, surveys of the bedside, 1 m away and in the hallway are sufficient. It is generally recommended that lead aprons or gloves NOT be used to reduce exposure, as these items are ineffectual for iridium and cesium and of marginal utility for ^{125}I and palladium (except for high strength sources used in temporary implants). Time and distance controls should be used for radiation protection. A ''CAUTION: RADIATION AREA'' sign shall be posted on the door to the patient's room as well as a description of the radioactive material (number of ribbons, seeds, tubes, etc.) and strength, and the means to contact the RSC and physician in an emergency. A statement as to the time the sources were inserted and the approximate time of removal should be made in the patient's hospital chart. A long handle forceps and a labeled lead transport container shall be left in the room. A Geiger Muller (GM) meter shall be readily available in case of emergency.

With sealed sources, there is no danger of radioactive contamination except by damage to or loss of a source. Surgical dressings and perineal pads should be changed only with the supervision of trained personnel. If a source should get free, it shall immediately be picked up with forceps and placed in the lead container. The radiation safety officer and radiotherapy personnel shall be notified at once.

The nursing staff should receive in-service training at least once per year on all aspects of radiation safety for brachytherapy patients. This training should include the identification of all applicators and sources, film badge procedures, patient handling procedures, emergency procedures for whom to call, radiation exposure limits, and perspectives on relative risks of radiation exposure versus other hazards encountered. Nurses should have a clear idea of how much time at any distance they can spend with each patient.

In some cases it may be necessary to instruct the patient to not get out of bed nor assume a position that would compromise the placement of the applicator. Nursing instructions should include statements similar to the following and shall be written and placed in the patient's chart: patient shall have a private room; nursing personnel shall wear film badges; visitors shall stay for only the time posted (provide a table based on total strength) at the indicated location in the room; no pregnant visitors; no visitors under 18 years of age; housekeeping may enter the room under nursing supervision but shall not remove anything (linen and trash is saved in the room for survey); a record of a dismissal survey stating that the there is no radiation present shall be made before patient is discharged.[96]

1. Iridium ribbons

Before removing any iridium ribbons from the lead container, a diagram or other system should be utilized to allow for quick and accurate loading of all catheters or needles. One should identify previously labeled ribbons and plan ahead as to the order of operations. Long handled forceps should be used to handle the sources; however, overlong, too heavy or otherwise cumbersome instruments that increase loading time should not be used. Funnel-end tools should be used for loading catheters and needles if the ends are not already funneled. There are many systems for loading ribbons into catheters. In one of the systems, when loading ribbons into nylon catheters, one should observe that the proximal end of the source ribbon advances to the end of the catheter or to the desired point. One should either melt or crimp the open end closed. Needles should have stylets left inside until loading to prevent clogging. About 1 cm of the nylon ribbon leader should protrude out from the needle for easy removal at the end of treatment. Rubber caps should be securely placed over the ends of the needles, providing slight pressure on the end of the ribbon. Alternatively, the exposed end of the ribbon can be folded over the end of the needle and then the rubber cap can be secured. The details in the second half of this paragraph are specific to a unique system. Alternate systems can be used to accomplish the same purpose of fixation of ribbons in the catheters.

2. Cesium tube sources

Tandem and colpostat source carriers should be secured inside the applicator by the screw-on endcaps. Care should be taken not to insert a tandem source carrier too short for the tandem, as this presents a problem both for assuring the carrier is inserted all the way and for later removal.

3. Iodine-125 seeds and palladium-103; other permanently implanted seeds

A record of seeds brought to the operating room and of those inserted into the patient through the applicator shall be maintained during the procedure. A survey meter with a scintillation probe designed for low-energy photon counting should be available and should be used to verify that there are no stray seeds in the procedure room or to find such seeds. At the conclusion of the procedure, an accounting of seeds used shall be performed. After the patient is removed from the operating room, a final survey shall be performed. A ''CAUTION: RADIOACTIVE MATERIAL'' sign shall be attached to the patient's bed during transport to the private room. Nursing instructions and instructions to the patient upon dismissal shall be both given to the patient and copies kept in the chart.

4. Remote afterloading

Before loading the applicator it is necessary to input programmed dwell times at the console of remote afterloaders. It is recommended that standard patterns of dwell times for similar applications be used whenever possible. This reduces the chances for error in keying in dwell times and positions. A second person shall check the dwell times and positions before treatment. If standard patterns are used, one person checking the times and positions is sufficient. The physicist

or trained radiation therapist should check the applicator position and the connections between applicator and afterloader head before treatment to be sure that they agree with the treatment plan. The radiation therapist or the physician operating the console shall be trained to interpret the treatment history printout during treatment in order to assure that all is proceeding correctly.

H. Removal of sources, their security, and return to the vendor

At removal, sources shall be placed in the shielded storage and transport container. Sources should be counted as they are removed. After removal, a dismissal survey shall be performed with an appropriate detector to monitor the patient and all areas of the room. The results of this survey shall be kept on record in the radiation oncology department and be available for inspection by regulatory agencies. The radiation oncology department should notify nursing (and nursing should notify housekeeping) that the room is clear. If a source of radiation is detected, it shall be located and steps shall be taken to eliminate it. A loose source shall be picked up with a long handled forceps or the equivalent, never with the fingers, placed inside the shielded container, and left in the patient's room until the physicist clears the room. An investigation of the circumstances surrounding the loose source shall commence with the goal being to determine what, if any, dose reduction occurred to the target volume, if any personnel exposure occurred, and what steps should be taken to prevent future recurrences. Reports to the NRC or other regulatory agencies are required in the event of lost or stolen sources. Sources shall be immediately returned to the shielded safe storage area after completion of treatment. Sources should be recounted in the storage area to ensure no sources have been lost in transit. An entry into the inventory log shall be made indicating which sources, by patient, were returned to the safe area. At this point any sources that are to be returned to the vendor should be transferred back into the shipping lead container. Each source shall be counted as this transfer is made to ensure that no sources are left behind, and as a final check that no sources are unaccounted for after the implant procedure. The lead container is placed back into the outer shipping container along with document that states what is being shipped back, and by whom. The exposure at 1 m from the source container (transport index) shall be determined. The Department of Transportation documents and shipping airbill should then be filled out and attached to the container. After the package is picked up, a receipt for the items taken shall be kept as proof of the disposition of each package. A final record shall be made in the source inventory that the lot of sources previously logged as having been received has now been returned to the vendor (specify the vendor and the date shipped).

1. Permanent seed implants

A permanent implant patient maybe released from the hospital if the total exposure to any other individual from the released patient is unlikely to exceed 500 mR over the life of the implant. It is permissible to include occupancy factors of less than unity, tissue attenuation effects, and the use of local shielding in assessing compliance with this limit. The NRC is currently modifying 10 CFR 35 to conform with this recommendation.

Unused seeds can be either used on a subsequent case or held for decay (greater than ten half-lives, two years for 0.5-Ci ^{125}I seeds) and then discarded. In either case, a record of the final deposition of each seed has to kept. When decayed seeds are discarded the user shall deface all radioactive material warning labels on the source container. [Current NRC regulation requires that a survey of the decayed sources with a suitable survey meter (GM) on its most sensitive setting shall result in a measurement indistinguishable from background radiation.]

2. High-dose rate remote afterloaders

For AAPM recommendations on HDR brachytherapy, the reader is referred to the AAPM Task Group No. 59 report, which is soon to be released.

I. Source localization

Except when the geometry is completely known, as in vaginal cylinders for example, source localization films or other images are necessary in order to reconstruct in three dimensions the source locations for dose calculation purposes (orthogonal films are useful in any case for documentation of applicator placement). At least two images taken from different perspectives are required. Whenever possible, CT or MRI images should be used both to locate sources and to provide an accurate anatomical background to the dose distribution. Various methods of source localization are reviewed in Sec. III D. It is recommended that the dosimetry/physics staff supervise the localization imaging so that fiducial marks, jigs, dummy sources, and imaging techniques are used correctly. Films taken in the operating room should be reviewed and approved before the patient is removed from the operating room.

J. Treatment evaluation

The planes of calculation are chosen to best represent the dose distribution relative to some anatomical structure or to the applicator. An inappropriate choice of calculation planes can result in misinterpretation of the dose and possibly lead to a misadministration. For example, in a tandem and colpostats case, the anterior–posterior dose distribution should be obtained by rotating the plane of calculation to be coplanar with the tandem and to bisect the vaginal sources. Otherwise foreshortened isodose curves about the tandem will result, giving the impression that stronger sources are required at the tandem tip. Also, when orthogonal films are used for source localization, but isodoses will be computed in an axial plane in order to be superimposed on CT slices,

the calculation plane must be properly oriented or the isodose curves that covers a particular anatomical structure may be incorrectly chosen.

Labeling of isodose curves is another practical issue. Any such plot should be labeled with respect to anterior, posterior, superior, inferior, right, or left. Many treatment planning systems are weak in their ability to label the isodose plots automatically. Dose delivery errors can result from incorrect or inadequate labeling.

For all of the following situations, the treatment time should be double checked by another physicist or dosimetrist. In addition, the localization films, source loading, isodoses, and treatment prescription should be checked for consistency and accuracy.

1. Computer plan output

Where atlases are not used, customized dose distributions are needed, which helps the physician determine the treatment time. In order for this information to be useful, a minimum set of data is needed. Dose distributions in the anterior–posterior and lateral planes or cross sections near the end of the implant and through the center should be obtained as a minimum. Additionally, the dose distribution should be obtained through a plane that shows the maximum clinically significant dose that is expected to occur based on the minimal set of plots and knowledge of the source distribution. Reference point doses should be obtained for critical structures and dose distributions should be calculated through these points to determine the volume enclosed by this dose. For geometrically irregular implants, additional dose calculation shall be done to assess the target volume dose and any hot or cold spots that may occur.

Dose specification should be based on the recommendations described in Sec. IV D. The minimum target dose, maximum clinically significant dose, and critical structure doses shall be determined by the physician. These doses shall be documented and any other relevant dosimetry shall be included in the therapy chart.

2. Special considerations for HDR brachytherapy

Due to the short time frame in which HDR treatments take place, special attention should be given to the procedures used to compute the dose and dwell times. Mistakes with HDR can occur if the physicist is pressured to perform calculations rapidly so that treatment can get started as soon as possible. One way to reduce this pressure is to use standard plans whenever possible. These are sequences of dwell times stored in the treatment console. The physicist should become familiar enough with the type of applicator and the possible errors involved with small deviations from the ideal placement. Upon reviewing the localization films, a decision can be made fairly quickly as to whether or not the application meets the geometrical requirements established for use of standards. This procedure also reduces potential errors in keying in new dwell times for each treatment. After the procedure, if there is the possibility of more than a 10% error in target dose, one should run a computer plan for that case and make up any differences in dose on the subsequent treatments.

K. Recording of physics data and other pertinent information in patient chart

The patient's chart shall contain the BRACHYTHERAPY PRESCRIPTION FORM signed and dated by the physician. The prescription may include total source strength, the dose per fraction, total dose, applicator, dose rate, and total time depending upon the clinical application (see Sec. V B). In addition, the chart shall contain enough physics data so that the patient's treatment can be reconstructed if the need arises. All such items inserted into the chart shall be labeled with the patient's name, record number, and anatomical orientation if applicable. The following is a list of items that the physicist should be responsible for including in the chart: description of source type (radionuclide, active and total length, strength); description of applicator; source loading pattern, spatial, and strength; individualized isodoses or generic as appropriate and point doses that substantiate the physician's treatment prescription; orientations should be labeled; localization films and target volume images; source insertion and removal times.

We recommend that written policies and procedures be developed for the following: (1) areas where sealed sources are stored; (2) special precautions when handling sources; (3) special instructions for nurses/housekeeping/visitors; (4) method of maintaining source accountability; (5) surveys to be performed during treatment and at conclusion after sources are returned to safe area (dismissal survey); (6) specific procedures for permanent seed implants—operating room procedures; (7) patient room assignments and posting requirements; (8) source loading and unloading; (9) emergency procedures posted and whom to contact; and (10) treatment planning and evaluation procedures for each major site or treatment procedure type.

VI. RECOMMENDED QUALITY ASSURANCE PROGRAM FOR BRACHYTHERAPY EQUIPMENT

A major focus of the QA program is to assure accurate operation of all mechanical, software, and radioactive devices used for the planning, delivery, or QA of brachytherapy treatments. This report divides device QA testing into two categories: (i) acceptance testing which is performed upon acquiring the equipment and (ii) periodic QA testing. Acceptance testing is a comprehensive set of tests which allow the physicist to evaluate the behavior and function of the devices. Such testing is straightforward for simple devices such as manual afterloading sources, but can be very complex and model specific in the case of remote afterloading units and treatment planning systems. While verification that the device performs as specified by the vendor is the formal endpoint of the acceptance testing, there are many other benefits of this process. For complex systems, acceptance testing is an opportunity for the physicist to learn in detail the operational characteristics of the system and cor-

TABLE II. Intracavitary source and applicator quality assurance.

Procedure	End point	Frequency
evaluate dimensions/ serial number	source identity physical length and diameter	initially
superposition of auto- and transmission radiographs	active source length and uniformity, capsule thickness accuracy of source construction	initially
source leak test	capsule integrity	see text[a]
source calibration	source strength	initially, annually
dosimetric evaluation of applicator	magnitude and geometric characteristics of shielding effect	initially
orthogonal radiographs of applicators	correct source position, mechanical integrity, internal shield positioning coincidence of dummy and radioactive source	initially, annually
measure applicator dimensions	correct diameter and length, correct diameter of all colpostat caps and cylinder segments	initially, annually
source inventory	correct source number	quarterly[b]
source preparation area survey	safety of brachytherapy personnel	as needed

[a]NRC requires leak testing, generally at 6 month intervals.
[b]The NRC requires (10 CFR 33.59) quarterly source inventories along with surveys of ambient exposure rates in brachytherapy source storage areas. NRC has very detailed requirements regarding the information that must be captured each time a sealed source is taken from or returned to its storage location (10 CFR 35.406).

TABLE III. Interstitial source and applicator quality assurance.

Procedure	End point	Frequency
evaluate spacing and no. seeds/ribbon	ribbon geometry and seed quantity	initially
source calibration	source strength	initially, each use
strength per seed or strength per unit length	source strength uniformity	initially
applicator integrity	varies: metal needles: sharpness and straightness templates: o-ring integrity and hole locations	initially, annually
evaluate dummy ribbon geometry	coincidence of dummy and radioactive sources	initially, annually
source leak test	capsule integrity	see text
source inventory source preparation area survey	correct source number safety or brachytherapy personnel	quarterly

rect any false beliefs about how it works. During acceptance testing all clinical procedures associated with device should be reviewed to ensure compatibility with its operational characteristics. This is also a good time to develop training programs for dosimetrists, technologists, and others who will be using the system on a daily basis. The appropriate subsets of the acceptance testing protocol should be repeated whenever major subsystems or components of the device are replaced, e.g., upgrading software in a treatment planning system. Asking a new physicist to work through acceptance testing of an unfamiliar device is an excellent method for rapidly assimilating him or her into an established brachytherapy program.

A suggested periodic QA program for brachytherapy equipment is described in Tables II–VIII and in the following paragraphs. The AAPM views the recommended lists of tests and test frequencies not as a rigid prescription of what must be done, but rather as a starting for point for developing a written QA program individualized to the needs of each institution. Some tests (e.g., source-strength verification) are so fundamental and universally important that the AAPM recommends that all institutions practicing brachytherapy shall adapt them. However, in general, both clinical brachytherapy practice standards and the demands placed on physics resources are highly variable from practice-to-practice and from anatomic site-to-site. The AAPM believes that such variability in clinical practice precludes recommending a single fixed protocol for periodic QA. Depending on the reliability of the device in question and the clinical importance of the target parameter, the optimal frequency of a given test may be either smaller or larger than recommended by this report. Each institution practicing brachytherapy shall develop a written periodic QA protocol defining the tests to be performed and their frequency for each major type of equipment.

A number of useful references are available for designing a program to confirm correct function of the devices and systems used in brachytherapy. The AAPM task groups 32 and 40 outline a number of basic tests and give recommendations as to frequency. Williamson[31,97] describes model programs and discusses, in detail, many QA tests for low-dose rate brachytherapy (manually and remotely afterloaded). The AAPM Task Group No. 40 report,[3] Williamson,[97] and the proceedings of the AAPM 1994 summer school[56] contain similar discussions for HDR and LDR remote afterloading technology.

A. Manual afterloading brachytherapy

Tables II and III outline core tests for manually afterloading sealed brachytherapy sources and applicators. Basically, the tests fall into four categories: (1) leak tests, inventories, and surveys designed to promote safety; (2) verification of source and applicator geometry/construction; (3) coincidence of simulation markers and radioactive sources; and (4) accuracy of source calibration.

The issue of leak tests illustrates a QA issue where the AAPM feels a that highly prescriptive and inflexible guideline is inappropriate. [With the exception of one type of ^{137}Cs intracavitary tube and ^{192}Ir ribbons, NRC requires (10

TABLE IV. Re-entrant ion chamber quality assurance.[a]

Procedure	End point	Frequency
repeated readings with low strength source	precision, stability	initially, annually
reading/S_K linear over range of use	linearity with respect to S_K or ion recombination	initially, annually for primary HDR source calibration, ion recombination should be measured each time
observe response as function of temperature or time	verify that chamber is sealed or vented, depending upon design	initially, annually
reading/S_K along well axis	spatial uniformity of response; definition of active-length correction factors	initially
reading/S_K for long-lived standard source	stability of response through time	initially, each use
reading/S_K for each source type using nist standard	define/verify calibration factors	initially, two year intervals for short-lived sources

[a]The NRC has no requirements for LDR brachytherapy source calibration and places no requirements on instruments used for same. For HDR remote afterloading systems, current NRC license review guidance (Policy and Guidance Directive FC86-4) requires source calibration to be performed by a board-certified physicist.

CFR 35.59) requires all brachytherapy sources to be leak tested at intervals of 6 months.] Many sources, ^{137}Cs intracavitary tubes, contain radioactivity bound in a nonsoluble, nonvolatile form which is heavily encapsulated in stainless steel. Unless physical inspection or history of use indicates the possibility of physical damage to the steel encapsulation, leak testing does not seem to be indicated at any fixed interval. Similarly, once released by the vendor leak testing of ^{192}Ir ribbons and HDR sources, which consist of a single metallic iridium–platinum alloy cylinder, is not indicated. On the other hand, ^{125}I in a volatile form is encapsulated in thin, easy-to-rupture titanium tubing for interstitial brachytherapy. Such sources must be handled very carefully to prevent leakage of ^{125}I. The AAPM believes that ^{125}I seeds need to be leak tested prior to use in a second patient or after form intensive handling or manipulation.

Dosimetric evaluation of intracavitary applicators is not straightforward as accurate measurement of brachytherapy dose rates remains a research activity. However, when adopting sources and applicators that differ significantly from those used previously, or when adopting new products for which published dose distributions are unavailable, careful consideration to its dosimetric properties should be given. Spot measurements with diode or TLD detectors, while time consuming, are straightforward if $\pm 10\%$ uncertainty is acceptable. Alternatively, Monte Carlo photon transport calculations can be used if the source/applicator geometry is known.

Tables II–IV suggest that a manual brachytherapy QA program should have three testing frequencies: initial acceptance, annual, and quarterly. Quarterly intervals are recommended for isotope laboratory surveys and inventories. Annual QA should be used as an opportunity to review applicator condition and geometric integrity. Annual calibration checks of all long-lived sources are recommended mainly to confirm that the sources are correctly sorted as to group, that source strengths have been correctly decayed, and that the origins of intracavitary source calibrations are not lost in the sands of time and personnel changes as the sources age.

B. Remote afterloading brachytherapy devices

As with any treatment delivery system, functional remote afterloading quality assurance tests should anticipate the probable modes of system failure. There are three principal quality assurance end points: accuracy of the source selection, spatial positioning, and control of treatment duration. In addition, all remote afterloaders have error and malfunction detection systems (''interlocks''), which are generally designed to retract all sources and sound an alarm when the target error condition occurs.

Specific QA procedures are dictated by individual system design of which there are three major varieties:

(1) Programmable source train devices such as Nucletron's Selectron LDR and HDR allow the user to specify the order in which equal strength radioactive spheres of ^{137}Cs or ^{60}Co and geometrically identical spherical spacers are loaded into each of the treatment catheters or channels. Different treatment times may be programmed for each channel. These systems support only intracavitary therapy.

TABLE V. Core daily quality assurance tests for a remote afterloading facility.

Test endpoint	Test methodology	System type
dose delivery accuracy	• Verify date, time and source strength in treatment unit and planning computer.	• all
	• Verify source strength and timer accuracy against a tertiary standard (see text).	• HDR/PDR
overall system function	• Run system through a complete cycle of simulated treatment:	• all
	- programming;	
	- source ejection;	
	- source retraction at end of timer countdown.	
	• Verify treatment status indicator lights and critical source control functions.	• all
	• Correct function of dedicated fluoroscopy/imaging system if present.	• HDR
patient/public/staff safety	• Correct function:	
	- door interlock;	• HDR/PDR
	- area radiation monitor;	• HDR/PDR
	- audio/visual system communication;	• HDR/PDR
	- portable survey meter;	• all
	- audible/visual error and alarm condition indicators;	• all
	• Safety equipment available:	• all
	- emergency instructions;	
	- emergency equipment (forceps, emergency safe, surgical supplies);	
	- operator's manual;	
	- survey meter.	
	• Measure hourly/weekly radiation levels after patient loaded and portable shields positioned	• PDR/LDR
verify positional accuracy within 1 mm	Many possible tests:	• all
	- primary positional accuracy test for a single catheter;	
	- deviation of ion chamber response placed near a programmed dwell position;	
	- multiple-channel autoradiograph of every active dwell position used in the patient treatment and compare programmed position to expected;	
	- visually check that relative position of source tip in a ruled catheter reproduces from day-to-day.	
	• Autoradiograph patient-specific configuration of sources loaded into intermediate safe of device.	• all fixed and programmable source-train units
temporal accuracy	• Many possible tests:	• HDR/PDR
	- time duration of ''source ejected'' light;	
	- perform a spot check of radiation output for a timed interval using tertiary calibration standard jig;	
	- compare source arrival and departure times on printed treatment documentation with a clock or stop watch;	
	- for LDR, subtract treatment interruptions from overall treatment time and compare to programmed time.	• LDR (optional)

(2) Fixed source-train devices have no capability of composing arbitrary source trains from elemental components (seeds, etc.). The user can only choose which of the available source trains to transport from the associated source storage container into the remote afterloader intermediate safe for use in subsequent treatment. These machines generally have no ability to distinguish one source from another so that loading the incorrect source into the intermediate safe is always a possibility. The source supply for interstitial therapy is designed for periodic replenishment and disposal by the user, creating the possibility that source order can be permuted.

(3) Single stepping source devices consist of a single cable driven high intensity source, which moves from each programmed treatment position in a catheter (dwell position) after the position specific treatment time (dwell time) has elapsed. After treating each position in a given catheter (channel), the source is retracted into the machine, and re-injected into the next treatment catheter by means of a selector. Within each catheter, the insertion depth of a dwell position sequence is continuously (or nearly so) adjustable in contrast to the programmable and fixed source-train devices, which have only a single treatment position. Technical flexibility is enhanced by the independently programmable dwell times, a feature that is exploited by dwell-weight optimization algorithms supported by HDR/PDR treatment planning systems.[98]

Single stepping source afterloaders are most commonly used for outpatient-based HDR brachytherapy, although HDR intracavitary therapy can be performed with programmable source-train devices equipped with ^{60}Co spherical sources. One vendor has developed a stepping source remote afterloader to support LDR brachytherapy: the MicroSelectron/PDR (PDR refers to pulsed dose rate brachytherapy).[99] This system simulates continuous LDR brachytherapy by a series of mini-HDR fractions (called pulses), requiring 10–45 min for delivery, followed by a quiescent period. The cycle is usually repeated at hourly in-

TABLE VI. Additional core quarterly quality assurance tests for a remote afterloading facility.

General endpoint	Specific tests/endpoints	System type
personnel safety	Head/machine survey with source retracted[a]	• all
patient safety	•Important interlocks and emergency response systems function: obstructed applicator, missing applicator, door, unlocked indexer ring, displacement, power/air pressure loss, backup battery system.	• all
	•Emergency source handling tools, shielded storage container, and supplies for emergency applicator removal available and functioning.	• all
calibration of optical and pneumatic source position/status detection systems; any other preventive maintenance or inspections	•As specified by vendor.	• all
correct operation of all applicators, transfer tubes and source localization dummies	•Examine all dummies for kinks or bends that may shorten their axial displacement through applicator assembly. Check integrity of all transfer tube-applicator interfaces.	• all
positional accuracy: single stepping source	•Verify that radioactive source position agrees with dummy marker within 0.5 mm previously tested against dwell position markers used in simulation.	all HDR/PDR single-stepping source devices
	• Confirm check cable operation. • Obtain multiple channel autoradiograph with unique dwell sequence in each channel: verify that dwell position spacing, assignment of dwell sequence to programmed channel, and relative indexer length to dwell 1 are correct within 1 mm. •Confirm accuracy of daily positional test protocol. •Transfer tube length (if stability through time is not confirmed and positional accuracy is influenced by tube length).	
positional accuracy: multiple-source machines	•Device positions source train in specified treatment location.	• all
	•Source trains delivered to programmed channels within 1 mm of intended location.	• all
	•Source trains correctly sorted and composed.	• programmable source train
	•Source inventory correct.	• all
	•Source trains stored in correct locations in user accessible storage location.	• fixed source-train devices
source calibration	Measure source air kerma strength using a 'secondary' standard as described in Sec. III.	HDR/PDR
redundant source calibration checks	•Difference between measured and vendor-specified air kerma strength is within expected margin. •Use tertiary source strength standard (e.g., daily/monthly output checking system) to confirm primary calibration within 5%. Different electrometerand detector to be used.	• HDR/PDR
• spot check of absolute timer accuracy • timer accuracy and linearity measurement	Various techniques available (Williamson, 1991 and 1994).	• all LDR • HDR/PDR
miscellaneous	•Update source strength in treatment planning computer initialization file, treatment unit and quarterly inventory.	• all
	•Have a second physicist independently review the quarterly report.	• HDR/PDR

[a]In addition, NRC requires a complete facility survey whenever an HDR or PDR source is replaced.

tervals under machine control. The dose per pulse is chosen so as to duplicate, on average, the hourly dose rate characteristic of the LDR treatment to be simulated.

The broad range of remote afterloader designs and their clinical applications precludes formulation of a single one size fits all set of QA tests: each brachytherapy physicist must develop procedures which address the failure modes characteristic of the specific equipment and clinical procedures current in his/her clinical practice. For all remote afterloading systems, the AAPM recommends applying QA tests at three frequencies: daily, quarterly, and annually/initially.

1. Daily remote afterloader QA protocol

For HDR brachytherapy, the daily QA routine should be executed before treating the first patient of the day, while for an LDR system it should be performed before initiating each patient treatment. Daily QA tests protocol need be performed only on days when patients are treated, and for a multiple-

TABLE VII. Additional commissioning and annual quality assurance tests for a remote afterloading facility.

Test endpoint	Test methodology	System type
personnel and public safety	• Review workload and annualized unrestricted area/personnel exposures.	• all
	• Perform facility survey if occupancy/building structure revised.	• all
dose delivery accuracy	• Intercompare secondary standard used for quarterly calibration against another departmental substandard. Obtain new calibration from ADCL if calibration more than two years old. Perform Table III tests for re-entrant chamber if used.	• HDR/PDR
	• Verify air kerma strength calibration and other annual Table I checks.	• LDR
positional accuracy	• Verify accuracy of any jigs or autoradiography cassettes used for daily/monthly positional accuracy verification.	• all
	• Verify construction/spacing of all simulation markers (dummy sources).	• all
	• Verify position of simulation markers agrees with radioactive source for all applicator types. Verify simulation source localization procedure.	• all
	• Apply Table I/II tests to all intracavitary/interstitial applicators.	• all
	• If positional accuracy assumes fixed transfer tube length, verify length/uniformity if not checked quarterly.	• all
temporal accuracy	• Verify timer linearity and absolute accuracy.	• all
	• Verify transit dose/source velocity.	• all
	• Verify pulse sequencing.	• PDR
additional interlock/emergency response tests	• Verify that unit detects simulated detached source capsule.	• HDR/PDR
	• Verify emergency retraction buttons in room and manual source retraction crank function.	• HDR/PDR
	• Verify that source retracts and emergency retraction motor activates when excessive friction/applicator obstruction encountered by source.	• all
miscellaneous	• Check that treatment unit correctly decays source strengths and corrects dwell times for decay.	• all
	• Review accuracy of all standard treatment configurations stored in treatment unit.	
	• Review quality assurance manual and update if necessary.	• all
	• Review compliance with personnel training requirements.	• all

day LDR treatment, need be executed only once before initiating the patient's treatment, not on each day of use. The daily QA protocol should be designed to comprehensively, if nonspecifically, to assess failure-prone QA endpoints of the treatment system. Such tests should be completed before beginning applicator insertion in the first patient, so that any machine malfunctions are identified before subjecting the patient to any risk bearing medical procedure such as anesthesia. Table V lists a set of core tests, on the assumption that the only other routine physics QA intervals are quarterly and annual. The most useful and important tests to perform are (1) tests of overall system function (running machine through simulated treatment cycle) and (2) availability of needed emergency and safety equipment. These tests greatly reduce the likelihood of subjecting the patient to an unnecessary procedure or being caught in an emergency situation without the resources needed to manage it.

The AAPM recommends performing some type of spot check of source radiation output and timer accuracy for single stepping high intensity source devices. A simple approach is to obtain a detector reading for a fixed dwell time with the source at a fixed location with respect to the detector. For example, Williamson[97] recommends a simple phantom that rigidly positions a Farmer chamber a short distance (1–1.5 cm) from an interstitial applicator. This tertiary calibration jig is calibrated against the quarterly secondary calibration standard. By comparing the measured charge per 60-s programmed dwell time to the expected value, an over-

TABLE VIII. Brachytherapy computer planning system quality assurance.

Function	Benchmark data	Frequency
verify geometric accuracy of I/O peripherals: digitizer, CT or ultrasound interface, and plotter.	digitize/plot pattern of known geometry; for CT/US, image and reconstruct phantom implant.	monthly
verify input parameters for all precalculated single-source arrays.	published recommendations, source vendor's mechanical drawings. initially, annually	
verify dose, dwell time, and treatment time calculations at representative points for all source files.	published dose rate tables, manual calculations.	initially, annually new software version or source identity
accuracy of single-source isodoses.	point source output.	initially, new software version
accuracy of multiple-source isodose contouring.	point source data for symmetric source arrays.	initially, new software version
accuracy of plan rotation matrix.	constancy of point doses, source positions, and isodoses under repeated orthogonal rotations for symmetric source arrays.	initially, new software version
consistency of printed plan documentation.	assumed input parameters.	every clinical use
accuracy of coordinate reconstruction.	radiograph phantom with known catheter geometry.	initially, new software version
accuracy of electronic downloading of treatment parameters of afterloader.	comparison of treatment unit and planning system printed output.	initially, new software version each treatment
dose-volume histogram/implant figures of merit.	• use isotropic point source or segment of line source allowing analytic calculation of DVH. • constancy of test case DVH.	• initially, new software version • annually
optimization software.	run series of test cases based upon idealized implant geometries of various sizes; develop a sense of what optimization does to an implant compared to uniform loading before trying it on patients.	initially, spot check when software changes by duplicating old cases
overall system test.	run series of standardized plans to globally test all clinically used features.	initially, new software version, annually

all check of machine timer accuracy, positional accuracy, and decayed source strength can be made in a few minutes. Obviously, any reproducible detector, e.g., re-entrant chamber, could be used for this purpose. In general, the AAPM feels that such daily output/timer checks are not necessary for conventional LDR remote afterloading systems.

The AAPM suggests including a positional accuracy test in the daily QA of all remote afterloading systems. For conventional fixed or programmable source-train devices, an autoradiographic record of the source configuration prescribed for the patient is suggested. If obtained using a properly calibrated jig, positional accuracy can be confirmed with a precision of about 1 mm. In addition, autoradiography confirms source selection accuracy, which is essential for fixed source-train devices for which the possibility of a permuted source-train arrangement always exists. For HDR brachytherapy, there are many methods of verifying positional accuracy (including full autoradiographic documentation of the dwell positions prescribed for each patient). At a minimum, the AAPM suggests measuring the location of a single dwell position and comparing it to its expected location. Recently, a simple method for detecting dwell position location using a re-entrant chamber has been proposed.[100]

2. Quarterly remote afterloader QA protocol

The AAPM suggests a quarterly review of remote afterloader function independent of any particular patient treatment. A quarterly interval is suggested because this is the

frequency with which HDR sources are replaced and the frequency of NRC-mandated source inventory procedures for LDR. For HDR/PDR brachytherapy, the tests listed in Table VI are intended to be completed after installation of the new source but before the device is released for patient treatment. For a conventional LDR remote afterloader, the quarterly frequency is suggested. Given an adequate daily QA regimen and in the absence of evidence suggesting unstable system operation, the AAPM does not believe that more frequent QA testing, i.e., monthly, is needed. [The AAPM recommendations deviate somewhat from NRC licensing requirements. NRC requires (PG&D FO86-4) monthly checks of positional accuracy, source calibration, timer accuracy/linearity, guide tube length constancy, and backup battery function. Surprisingly, NRC requires that correct placement of shields and other internal applicators be verified daily.]

Quarterly QA testing is more focused on measurement of specific operating characteristics, and is designed to be executed by the physicist, in contrast to the daily tests which may be performed by a therapist or dosimetrist. To obtain a comprehensive sense of machine operation, the AAPM recommends that the physicist perform all daily tests along with the additional quarterly tests specified in Table VI. For HDR/PDR units, a more rigorous test of absolute timer accuracy (see Williamson[97] for specific tests) should be performed along with linearity across the dwell-time range. For LDR units, a spot check of timer accuracy is suggested. For single stepping source machines, positional accuracy testing is dependent both on the machine model and simulation source localization protocol. At the very least, the inherent positional accuracy of the machine should be tested since the source has been changed. If source positioning accuracy depends on transfer tube length, and this parameter is monitored daily, it is recommended that the length be checked quarterly, until confidence in their geometric stability is achieved. Calibration of high intensity sources is addressed in Sec. III: Table V suggests two redundant checks be built into the calibration process (comparison of measured and vendor source strength and intercomparison of tertiary/daily calibration standard and secondary standard).

3. Acceptance testing and annual remote afterloader QA

The annual review of remote afterloader function should be comprehensive, approaching the thoroughness of initial acceptance testing in this regard. For LDR remote afterloaders, all source and applicator tests (see Tables II and III) should be performed, including verification of source strength and radiographic examination of intracavitary applicators. Timer accuracy and linearity should be measured more comprehensively (although measurement over range of use may be practical). Positional accuracy should be checked carefully, including the condition and dimensions of all dummy simulation sources. The radioactive source locations should be compared directly to their dummy source counterparts, possibly by superposing autoradiographic images with transmission radiographs of dummy sources on the same film for various types of applicators.

Additional HDR tests include comprehensive assessment of positional accuracy, including all Table II and III positional accuracy tests, measurement of transfer tube lengths, and direct verification of all simulation source localization protocols. Additional temporal accuracy tests include assessment of transit dose.[101,102,97,98] The AAPM Task Group No. 59 is currently developing guidelines for patient-specific QA of brachytherapy suing HDR remote afterloaders.

C. Quality assurance for treatment planning and evaluation systems

Relatively little has been written on QA of clinical treatment planning systems in general, and even less is available specifically for brachytherapy treatment planning systems. These systems generally have the following components, which need to be addressed in a QA program:

(1) A method of reconstructing the three-dimensional geometry of the implant, consisting of a digitizer and an algorithm for calculating the source positions from two-dimensional projections. In addition to reconstruction for orthogonal projections or stereo-shift images, modern HDR brachytherapy software is often equipped with more advanced features such as catheter-trajectory reconstruction algorithms and a menu of algorithms for digitizing sources from different types film geometries. Reconstruction algorithms based on CT image sets and topograms are likely to appear in the near future.
(2) A graphics-based system for visualizing the implanted sources. Virtually all systems allow the projection of the implant to be viewed in an arbitrarily oriented plane. Future systems are likely to permit visualization of the sources relative to soft tissue anatomy derived from CT images.
(3) A means of assigning the source type, strength, and treatment time (or dwell time) to each visualized source.
(4) An algorithm for calculating the absorbed dose distribution given the above assignments. Currently, very simple isotropic or filtered line source models are used to represent the dose distribution from each source type. Superposition is then used to calculate the multiple source dose distribution. More modern systems allow input of measured single source data and may model the effects of applicator and tissue heterogeneities.
(5) Methods of evaluating, representing, and optimizing the dose distribution. Conventional systems require the user to heuristically evaluate the dose distribution by examining isodose curve distributions in manually selected planes. More complex systems design for single stepping source remote afterloaders have more advanced features such as dwell-weight optimization algorithms, dose vol-

ume histogram-based figures of merit for quantifying implant quality, and three-dimensional display of isodose surfaces.

(6) A system producing hard-copy documentation of the plan, usually in the form of plotted isodose curves and associated plan documentation. HDR brachytherapy planning and evaluation systems often communicate electronically with the treatment delivery device, eliminating the need to manually program the remote afterloader.

In general, brachytherapy software packages, especially those used for HDR treatments, are sufficiently complex that it is impossible to test the response of the program to all possible sequences of user input. Table VIII outlines a series of tests designed to verify correct function of each major computational and graphic display function in relatively simple testing situations. Many subtle input history-dependent bugs will reveal themselves only in the course of intensive clinical use. Prevention of software related treatment errors, as well as data entry errors of human origin, requires careful scrutiny of each clinical treatment plan. An independent treatment time calculation should be performed to verify that the selected absolute absorbed dose distribution is at least approximately consistent with the specified arrangement, source positions, strengths, and dwell times. Williamson[97] reviews a number of simple table or manual calculation based approaches. Working through the tests described in Table VIII not only tests the software: It familiarizes the physicist with the details of system operation and pitfalls likely to be encountered during patient planning. Planning a complex or unfamiliar type of implant can be a stressful experience as one is under pressure to complete it as quickly as possible: The clinical setting is clearly not the time to gain familiarity with and to test unfamiliar program options.

Dose calculation algorithms should be tested both to verify that the algorithm executes as specified (for a given input, the observed output is consistent with the vendor's description of the algorithm) and for accuracy (algorithm output agrees with published reference data for the source type in question). The latter tests the user's selection or entry of basic data from which the single source dose distribution is derived.

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APPENDIX A: DEFINITION OF A QUALIFIED MEDICAL PHYSICIST

A qualified medical physicist is an individual who is competent to practice independently one or more of the subfields of medical physics. The following elements pertain to their fields:

Therapeutic radiological physics

- therapeutic applications of x rays, gamma rays, electron and charged particle beams, neutrons, and radiations from sealed radionuclide sources;
- equipment associated with their production, use, measurement, and evaluation;
- quality of images resulting from their production and use;
- medical health physics associated with this subfield.

Diagnostic radiological physics

- diagnostic applications of x rays, gamma rays from sealed sources, ultrasonic radiation, and magnetic fields;
- equipment associated with their production, use, measurement, and evaluation;
- quality of images resulting from their production and use;
- medical health physics associated with this subfield.

Medical nuclear physics

- therapeutic and diagnostic applications of radionuclides (except those used in sealed sources for therapeutic purposes);
- equipment associated with their production, use, measurement, and evaluation;
- quality of images resulting from their production and use;
- medical health physics associated with this subfield.

Medical health physics

- safe use of x rays, gamma rays, electron and other charged particle beams, neutrons, radionuclides, and radiation from sealed radionuclide sources for both diagnostic and therapeutic purposes, except with regard to the application of radiation to patients for diagnostic or therapeutic purposes;
- the instrumentation required to perform appropriate radiation surveys.

It is expected that an individual will not hold himself/herself out to be qualified in a subfield for which he/she has not established competency. An individual will be considered competent to practice one or more of the subfields of medical physics if that individual is certified in that subfield by any of the following organizations:

- The American Board of Radiology,
- The American Board of Medical Physics,
- The American Board of Health Physics,
- The American Board of Science in Nuclear Medicine,
- The Canadian College of Physicists in Medicine.

The American Association of Physicists in Medicine regards

board certification, in the appropriate medical physics subfield, and state licensure, in those states in which licensure exists, as the appropriate qualification for the designation of qualified medical physicist.

For brachytherapy, the AAPM considers the qualified medical physicist to be one who meets the above qualifications in the subfield of therapeutic radiological physics.

In addition to the above qualifications, a qualified medical physicist shall meet and uphold the ''Guidelines for Ethical Practice for Medical Physicists'' as published by the American Association of Physicists in Medicine, and satisfy state licensure where applicable.

APPENDIX B: BRACHYTHERAPY TEAM MEMBERS AND THE RESPONSIBILITIES OF THE MEDICAL PHYSICIST

- Brachytherapy team members include:
- radiation oncologists;
- medical physicists;
- maintenance engineers;
- radiation safety officers;
- radiation safety committee chair;
- hospital administration;
- nursing;
- radiation therapists (technologists);
- manufacturers;
- surgeons;
- primary physicians.

Brachytherapy team functions:

Brachytherapy requires significant involvement and communication among members of the physics, dosimetry, and medical staff. Meticulous attention to detail and considerable interaction among the team members is required during applicator insertion, determination of dose specification points or volumes, prescribing dose to the tumor and normal tissues, computerized treatment planning, and treatment delivery. The individual functions of brachytherapy team members are rooted in the training and education of the particular team member. However, the effective and safe use of brachytherapy depends on a thorough understanding of the science of all aspects of isotope treatment including the roles of all team members.

Brachytherapy is an interactive process. The physician needs to be aware of dose distribution around different source arrangements to adequately prepare for an implant. The physicist needs to be knowledgeable of anatomy such that the relationships between tumor volume and surrounding normal tissues are considered during the treatment planning process. This give-and-take is crucial to the planning, execution, and delivery of effective and safe brachytherapy. When physics is not on-site for pre-treatment planning, simulation of source and applicator localization, source loading and unloading, and the risk of miscommunication and treatment error may be increased.

Responsibilities of the medical physicist include:

developing requirements and specifications for the purchase of appropriate equipment;

planning facilities to house the brachytherapy machines (including shielding design);

participating in, overseeing and monitoring facility construction as needed;

monitoring machine installation by the manufacturer and providing assistance as needed;

performing acceptance testing of the machine after installation;

commissioning the machine for clinical use;

establishing methods for special clinical procedures and acquiring the necessary dosimetry data for them. These include special eye plaques, stereotactic implants, etc.;

establishing procedures for treatment time calculations for temporary brachytherapy implants;

establishing methods for the determination of dose distributions in the patient irradiated by the brachytherapy sources;

participating in patient data acquisition, treatment planning and implementation, and evaluation of brachy therapy treatments;

implementation and monitoring of a quality assurance program for personnel safety;

implementation and monitoring of a quality assurance program for patient safety and accuracy of dose delivery;

implementation and monitoring of a maintenance schedule for brachytherapy equipment;

development of new procedures that may lead to better and more cost-effective use of brachytherapy in radiation oncology.

APPENDIX C: INSTRUMENTATION NEEDED FOR A BRACHYTHERAPY PHYSICS PROGRAM

Brachytherapy can be practiced with any of several techniques. These include manual loading of sources for intracavitary therapy, manual loading for interstitial therapy, remote afterloading for low-dose rate intracavitary or interstitial therapy, stereotactically guided procedures for treating brain lesions, ultrasonically guided procedures for treating prostatic cancer, and eye plaques for treating ocular tumors. Since each requires specialized equipment, a complete brachytherapy program is very expensive, and generally confined to institutions with a large patient population. Most institutions limit their brachytherapy programs to one or a few of the above techniques. This section lists the equipment needed to perform each technique adequately. The list starts with a set of equipment for radiation safety applicable to all techniques, and necessary even if only one technique is used.

A. Equipment needed for any and all brachytherapy procedures:

survey meter (ionization chamber type);
geiger counter with low energy probes for ^{125}I and ^{103}Pd;
preparation/storage room;
lead blocks;
L-blocks;
forceps;
well-type NaI with single channel analyzer or other equipment for wipe tests;
calibration source for wipe test;
calibrated well chamber and electrometer or ionization chamber and jig with backup system;
portable lead container;
thermometer;
barometer;
treatment planning computer with brachytherapy software;
therapy simulator or portable x-ray unit for source localization;
mobile lead shield.

B. Equipment specifically for manually loaded intracavitary procedures:
cervix applicator set (tandem and colpostats);
set of cesium tube sources and dummy sources;
one cesium tube source with a NIST traceable calibration;
safe for storing cesium tube sources;
set of Heyman sources.

C. Equipment specifically for manually loaded interstitial procedures:
(1) permanent implants;
Mick applicator kit.
(2) temporary implants;
set of plastic and metal catheters and needles,
templates (Syed-Neblett, perineal, etc.),
wire cutters,
miscellaneous buttons, portable soldering iron, etc.

D. Equipment specifically for ultrasonically guided implants:
same as C 2;
ultrasound system with brachytherapy software;
ultrasound transducers.

E. Equipment specifically for stereotactically guided implants:
head frame set;
localization software;
CT and/or MRI;
catheter set.

F. Equipment specifically for eye plaque therapy:
standard ophthalmologic instruments;
gold plaque set;
personal computer with eye plaque software or a calculator.

G. Equipment specifically for remote afterloading:
(1) low-dose rate;
LDR remote afterloader,
sources,
applicator sets adapted to the specific LDR unit with dummy sources and connecting tubes,
portable radiographic unit,
area monitors,
calibration jigs,
film and processor,
(2) high-dose rate;
HDR source—replaced at three to four month intervals,
HDR remote afterloader,
applicator sets adapted to the specific HDR unit with dummy sources and connecting tubes,
portable radiographic unit,
computer, preferably with optimization software,
well chamber designed or adapted for HDR or ionization
chamber and electrometer,
area monitors,
film and processor.

APPENDIX D: MAJOR REFERENCE TO NRC DOCUMENTS REGARDING BRACHYTHERAPY

U.S. Nuclear Regulatory Commission, Title 10, Chapter 1, *Code of Federal Regulations-Energy, Part 20*, ''Standards for protection against radiation'' (Government Printing Office, Washington, DC, 1987).

U.S. Nuclear Regulatory Commission, Title 10, Chapter 1, *Code of Federal Regulations-Energy, Part 35*, ''Medical use of by-product material'' (Government Printing Office, Washington, DC, 1987).

U.S. Nuclear Regulatory Commission, *Guide for the Preparation of Applications for Medical Use Programs*, Regulatory Guide 10.8, Revision 2, Washington, DC, 1987.

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U.S. Nuclear Regulatory Commission, *Quality Management Program*, Regulatory Guide 8.33, Washington, DC, 1991.

U.S. Nuclear Regulatory Commission, *Release of Patients After Brachytherapy Treatment With Remote Afterloading Devices*, NRC Bulletin 93-01, U.S. Nuclear Regulatory Commission, Washington, DC, April 20, 1993.

U.S. Nuclear Regulatory Commission, *Loss of an Iridium-192 Source and Therapy Misadministration at Indiana Regional Cancer Center, Indiana, Pennsylvania on November 16, 1992*, Report NUREG-1480, U.S. Nuclear Regulatory Commission, Washington, DC, 1993.

U.S. Nuclear Regulatory Commission, *Information Required for Licensing Remote Afterloading Devices*, Policy and Guidance Directive FC 86-4, Washington, DC, 1994.

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