

Modern-Day Linear Accelerator Acceptance Testing and Commissioning

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I. Introduction

The delivery of radiation treatments is reaching new pinnacles with continued advancement in accelerator and computer control technology. Computer-controlled linear accelerators (linacs) are increasingly being used clinically in small, as well as big, institutions. There is a complete shift in the paradigm of the treatment delivery process. Historically, linear accelerators have been used to deliver radiation of uniform intensity through field apertures shaped by blocks. Now the emphasis is to shape the field apertures with a multileaf collimator system and vary the radiation intensities with dynamic motion of the collimator system to deliver conformal radiation to the target volume. The fundamental premise is that the high-dose volume is restricted to the shape of the target tissue while excluding as much normal tissue from the high-dose volume as possible. Therefore, the acceptance testing and commissioning of a computer-controlled linac can be quite complex and may vary from institution to institution depending on its anticipated use.

The process of purchase, acceptance testing, and commissioning of a computer-controlled linac is a major undertaking that can take up a considerable amount of time, effort, and expense. Therefore, it is crucial that a great deal of thought and care go into the initial planning. The primary objective is that the accelerator specifications must meet the clearly defined needs of the facility over the projected lifetime of the accelerator, which can be up to 10 years. It is very important that the selection process for the equipment includes input from radiation oncologists, physicists, therapists, and facility engineers. The selection, acceptance testing, and commissioning of a linac involves;

- evaluation of clinical needs
- review of specifications and purchase agreement
- design and construction of the facility to house the new machine
- installation of the machine, safety checks, and initial radiation survey
- acceptance testing of the machine
- commissioning of the machine for clinical use
- final report and documentation
- training of the staff in the safe and efficacious use of the accelerator
- establishment of the baseline quality assurance parameters and schedule

The purpose of this presentation is to describe the general concepts and philosophies that are useful for a physicist who is charged with the task of bringing into clinical use a new computer-controlled linac.

II. Criteria for Linac Selection

The selection of a linac is critically dependent on its clinical utilization. Fortunately, the choice of commercially available, FDA-approved medical linacs is primarily limited to three major linac manufacturers: Elekta, Siemens, and Varian. Each of these manufacturers offers linacs that are capable of delivering both uniform and modulated intensities of radiation under computer control. Therefore, the task is limited to selecting the most appropriate machine from those commercially available and developing the purchase specifications to meet the clinical needs. This task is best accomplished by the formation of an ad hoc committee in the department that includes at least a physicist, radiation oncologist, therapist, and engineer. The charge of this committee should include

- A systematic review of current and projected clinical needs and types of patients who will be treated on the machine
- A careful review of deliverables, functionality, technical and physical specifications, and cost of all commercially available linacs
- Review of available space, available funds, available or needed support staff, and available in-house technical support and expertise
- Evaluation of future upgrades, warranties, and maintenance contracts
- Evaluation of the quality of the manufacturer's service and technical support
- Final recommendation for the linac

The criteria for selecting a linac can become quite controversial, complex, and time consuming. There is often a pressure from sales representatives of the manufacturers, who at times do not clearly distinguish between what is currently deliverable on the machine and what is planned for it in the future. It is the responsibility of the equipment selection team to discern that by contacting personnel at facilities that have similar machines and are using it clinically. It is good to contact only those facilities that have technical resources and patient distributions comparable to yours. Site visits to the factory or to a manufacturer's designated facility are rarely useful unless a special and new modality or option of treatment delivery is under consideration.

A generic decision tree, which was originally presented by Almond and Horton in an ASTRO refresher course (1993), is shown in the Figure. This flow chart may be used to establish criteria in the selection of a linac. It can take considerable time and effort to go through some of the steps described in this figure. It is important, however, not to skip any of the steps.

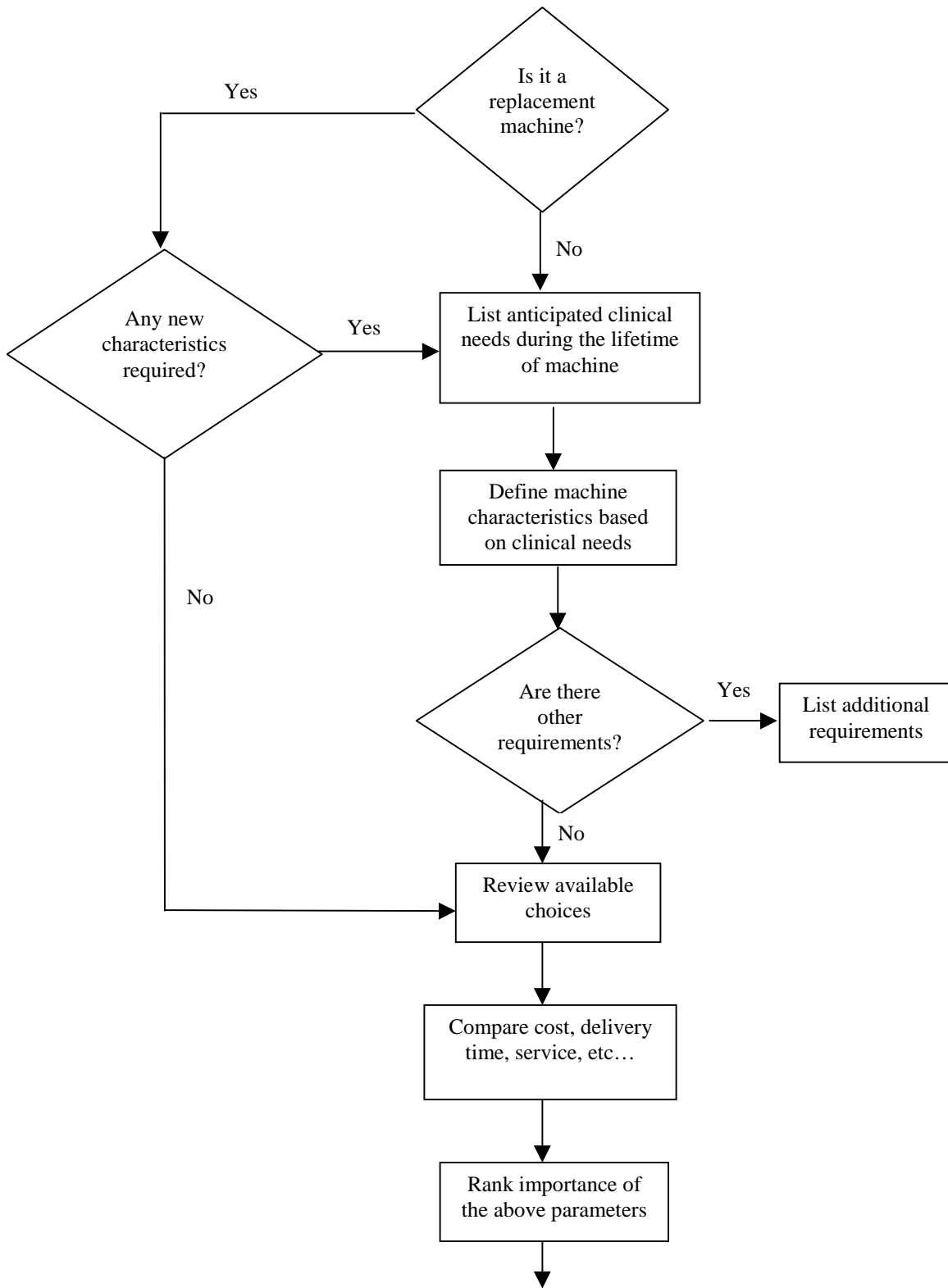


Figure: Decision tree (continued on next page)

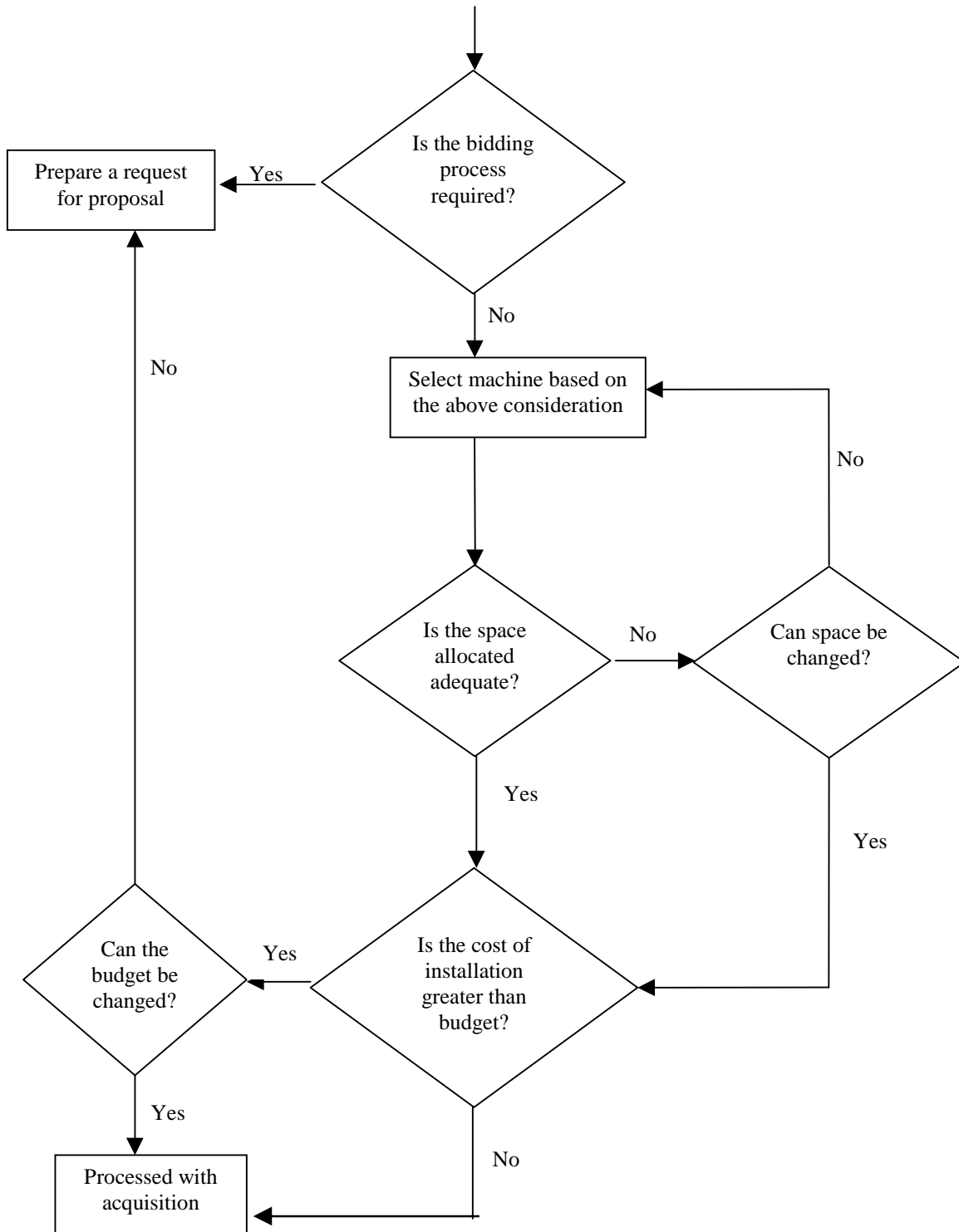


Figure: Decision tree (cont.)

III. Machine Specifications and Purchase Agreement

The recommendations of the equipment selection committee are followed by the development of comprehensive machine specifications and a binding purchase agreement. If the equipment is purchased through a bid process, then the machine specifications are developed before the decision is made to select a manufacturer. Otherwise, the final specifications may be developed in close collaboration with the manufacturer's representative. All manufacturers have developed product specifications for the functional performance of their equipment in response to requirements from potential users and in commercial competition with other manufacturers. These are available in the form of product data and specification sheets, which can serve as a good starting point for the purchase agreement. Any special requirement can then be added as an addendum. This saves lot of time and effort from being expended in repetitive work. An example of an addendum to the purchase agreement is presented in the Appendix, which illustrates how special requests are included in the agreement.

It is imperative that the facility physicist develop a comprehensive acceptance testing document with a detailed test procedure to verify each term of the agreement and machine specifications. This document should be shared with the manufacturer's representative before the installation begins so that all ambiguities are clarified in advance. It is not prudent to depend on the manufacturer-supplied acceptance test procedure exclusively. However, it should be reviewed thoroughly before acceptance testing. IEC publication 976, entitled *Medical Electron Accelerators: Functional Performance Characteristics*, is an excellent resource to set up test procedures.

It is essential that the physicist review the facility layout with the planning and installation department of the accelerator manufacturer. They can provide very useful information on workflow, equipment layout and special requirements. A joint meeting of the equipment planning coordinator, architect, contractor, and physicist in the earlier stages of construction is very helpful and productive. This meeting can resolve all potential problems regarding electrical power supply, conduit layout, air conditioning, and chilled water requirements for the machine. The shielding design and its final approval are solely the responsibility of the physicist, even if generic vault design and shielding barrier thicknesses are available from other sources.

IV. Accelerator Installation

The physicist and facility engineer (if available) should work closely with the installation engineer. A close collaboration during the installation can reduce the acceptance testing time considerably. It is important that the facility personnel do not interfere in the work of the installation engineer but observe the progress in the background. As soon as the accelerator is capable of producing a radiation beam, a series of tests should be conducted to assure the safety of all concerned. These include

- Testing of door interlocks
- Testing of proper operation of the emergency off switches
- A preliminary calibration of the machine output in all modes

- A radiation survey in both controlled and uncontrolled areas around the treatment vault at the highest available dose rate and under worst irradiation conditions (without phantom)

A full radiation survey including the photon and neutron leakage measurements will still have to be completed to comply with regulatory requirements after a full calibration. The preliminary survey is done to assure the safety of individuals during the acceptance testing and commissioning.

V. Acceptance Testing

The installation is followed by acceptance testing by the physicist to ensure that the machine meets the product specifications and the purchase agreement. These tests are conducted according to the acceptance testing procedure agreed on between the manufacturer's representative and the facility physicist. Each facility should have the necessary equipment for acceptance testing. This includes a 3-D water phantom scanner with computer interface, ion chambers, and electrometer X ray films; film laser scanner; and precision level. It is important to know that each machine comes with the functional performance test values performed in test cells in the factory. These are helpful for comparison during acceptance testing. IEC Report 977 provides suggested values of functional performance that all manufacturers voluntarily comply with. A summary of the suggested values of functional performance is given in the Table. Some of these values are required to be more stringent for special application of the linac. For example, it is not unusual to require a radiation isocenter tolerance within 1 mm diameter of the linac scheduled to be used for high precision radiation therapy and radiosurgery.

Table
Suggested Values of Functional Performance
(Extracted from IEC Report 977)

DOSE MONITORING SYSTEM

Reproducibility	0.5%
Proportionality (> 1 Gy/ < 1 Gy)	± 2% / ± 2 cGy
Dependence on gantry angle	± 1.5%
Dependence on rotation of the gantry (moving)	± 2%

Stability of Calibration

10,000 cGy delivery	2%
One day	± 1%
One week	± 1%
Stability in moving beam therapy, preset versus delivered	
Terminate irradiation by gantry angle; dose:	5%
Terminate irradiation by dose monitor system; angle:	3°

Table, continued

DEPTH ABSORBED DOSE CHARACTERISTICS

X Radiation

Penetrative quality	(mfr)
Deviation from stated value	$\pm 3\%$, ± 3 mm*
Relative surface dose for 10×10 cm field	(mfr)
Relative surface dose for maximum field	(mfr)

Electron Radiation

Relative surface absorbed dose	(mfr)
Depth of maximum absorbed dose	≥ 0.1 cm
Practical range / depth of 80% absorbed dose	≤ 1.6
Penetrative quality	(mfr)
Deviation from stated value	$\pm 3\% \pm 2$ mm*
Stability of penetrative quality, electrons, variation with gantry angle and dose rate	$+ 1\%$, $+ 2$ mm*

UNIFORMITY OF RADIATION FIELDS

X Radiation

Flatness (max/min ratio)	
5×5 to 30×30 cm	106%
to maximum square	110%
Stability of flatness with angular position of gantry and beam limiting system	
< 30 MeV	3%
> 30 MeV	4%
Symmetry (ratio of symmetrical points)	103%
Maximum ratio of absorbed dose (at d_{max})	
5×5 to 30×30 cm	107%
to maximum square	109%
Wedge filtered X ray fields	
Wedge factor	$\pm 2\%$
Wedge angle	$\pm 2^\circ$

Electron Radiation

Flatness (shape of isodose contours)	
80% contour to geometric edge, at base depth	15 mm
90% contour to geometric edge/corner at S	10 / 20 mm
Symmetry (ratio of symmetrical points)	105%
Maximum ratio of absorbed dose at 0.5 mm depth to absorbed dose on axis at S	109%

PENUMBRA

(mfr)

INDICATION OF RADIATION FIELDS

X Radiation

Numerical field indication (% is of field size)	3 mm, 1.5%*
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Table, continued

Greater than 20 × 20 cm to maximum square	5 mm, 1.5%
Light field indication, edges (% is of field size)	
At normal treatment distance, 5 × 5 cm to 20 cm × 20 cm	2 mm, 1%
At 1.5 × normal treatment distance, 5 × 5 cm to 20 × 20 cm	2 mm, 2%
Center: NTD / 1.5 × NTD	2 / 4 mm
Reproducibility: Numerical field, light field edge	2 mm
Electron Radiation	
Numerical field indication	2 mm
Light field indication, edges	2 mm
Geometry of X ray beam limiting systems	± 0.5°
Illuminance and penumbra of light field	
Average illuminance	40 lux
Edge contrast ratio	4
INDICATION OF RADIATION BEAM AXIS	
Entry, X radiation (NTD + 25 cm)	± 2mm
Entry, electron radiation (NTD + 25 cm)	± 4 mm
Exit, X radiation (NTD -to+ 50 cm)	± 3 mm
ISOCENTER	
Displacement of X ray beam axis	± 2 mm
Displacement of indication of isocenter	± 2 mm
Indication of distance along radiation beam axis from isocenter	± 2 mm
ZERO POSITION OF ROTATIONAL SCALES	
Gantry, beam limiting device, table, table top	± 0.5°
CONGRUENCE OF OPPOSED RADIATION FIELDS AT ISOCENTER	1 mm
MOVEMENTS OF THE PATIENT TABLE	
Horizontal displacement for 20 cm vertical change	2 mm
Displacement of rotation axis from isocenter	2 mm
Angle between table and table top rotation axes	0.5°
Table height: 30 kg, retracted; 135 kg, extended	5 mm
Table top lateral tilt from horizontal	0.5°
Deviation of table top height with lateral displacement	5 mm

* = Whichever is greater. NTD = normal treatment distance. SMD = standard measurement depth.

Linacs equipped with special modes must be tested separately for each modality. For example, test TBI mode for maximum MU and dose rate; test high-dose-rate total skin electron therapy mode for maximum MU, dose rate, and field size interlocks; test electron arc mode for MU/degree and dose rate. Dynamic motion of the multileaf collimators should also be tested independently. AAPM is in the process of publishing a task group report on multileaf collimator dosimetry that describes the required testing procedures for multileaf collimator systems. There will be additional reports published on acceptance testing of intensity-modulated radiotherapy modules in the near future. In the meantime, physicists should follow the test procedures suggested by the manufacturers.

Other important aspects of acceptance testing are to assure the safety of the patients and machine operators and to provide critical baseline data for future quality assurance reviews. AAPM makes available three useful task group reports (TG-35, TG-40, and TG-45) that provide detailed discussions on accelerator safety, comprehensive quality assurance, and a code of practice for radiotherapy accelerators. It is essential that each physicist who is embarking on acceptance testing and commissioning a linac thoroughly read these reports.

VI. Commissioning

Satisfactory acceptance testing simply assures that the accelerator satisfies all agreed-upon specifications and pertinent safety requirements. The process of commissioning a linac for clinical use includes comprehensive measurements of dosimetric parameters that are necessary to validate the treatment planning systems used to select optimal radiation modality and treatment technique for individual patients. Commissioning also includes entry of beam data into a treatment planning system and testing of its accuracy, development of operational procedures, and training of all concerned with the operation of the accelerator.

Data collected during acceptance testing are often not adequate to commission a machine in the treatment planning system. Machine-specific beam data for commissioning is highly dependent on the dose calculation algorithms used in the treatment planning systems. The model-based dose calculation algorithms (convolution/superposition) require much less measured data than correction-based algorithms (equivalent TRP/TAR, etc.). Irrespective of the dose calculation algorithm, it is essential to have a minimum dataset that includes percentage depth dose, isodose distribution, and output characterization for a series of field sizes. It is very important that the measured dosimetric characteristics of the commissioned linac are compared with published data on the same make and model, if available. RPC in Houston is a great resource for such data. The company has data on practically all types of machines in its data base.

Physicists must avoid the pressure to initiate clinical treatments as soon as the acceptance testing is finished. Rushing into clinical implementation without completing proper commissioning can potentially cause harm to the patients. Therefore, an appropriate time that is based on the projected use of the machine must be set aside for this activity. It is imperative that the physicist must have proper instrumentation to collect all necessary data. The *AAPM Code of Practice for Accelerators* (TG-45) provides a detailed discussion on the commissioning philosophy and required machine-specific beam data. It also provides information on

commissioning of most special procedures except intensity-modulated radiotherapy, which is fairly new. The National Cancer Institute has funded a work group on intensity-modulated radiotherapy that is scheduled to publish its report in a scientific journal later this year. This working group is chaired by Dr. James Purdy of Washington University. The Radiation Therapy Committee of the AAPM has also formed a subcommittee, chaired by the author, to monitor the scientific activities on this subject and propose the formation of new task groups.

VII. Summary

This refresher course provides information on acceptance testing and commissioning of a computer-controlled linac. It is emphasized that great care and diligence should be exercised in selecting, installing, testing, and commissioning a linac. The time commitment and money can be substantial, and errors and oversights can be costly. Therefore, the responsible physicist must act responsibly and not compromise on any aspect of the process. The physicist's responsibilities can be summarized as follows:

- To develop requirements and specifications for the purchase of an appropriate linac
- To plan the facility (including shielding design)
- To monitor facility construction and machine installation
- To perform acceptance testing and safety checks
- To commission the machine for all designated clinical uses
- To establish treatment procedures and train personnel
- To prepare acceptance testing and commissioning documentation

VIII. Reading Material

AAPM Report Series booklets

- The Physical Aspects of Total and Half-Body Photon Irradiation (1986)
- Total Skin Electron Therapy: Technique and Dosimetry (1987)
- Stereotactic Radiosurgery (1995)

AAPM Task Group Reports

- Clinical Electron Beam Dosimetry; TG-25 (1991)
- Medical Accelerator Safety; TG-35 (1993)
- Comprehensive Quality Assurance; TG-40 (1994)
- Code of Practice for Accelerators; TG-45 (1994)

IEC Reports 976 and 977

Medical Electron Accelerators: Functional Performance Characteristics and Guidelines (1985)

Appendix

Addendum to Purchase Agreement with Elekta Oncology Systems, Inc.

1. General Requirement:

Elekta Oncology Systems (EOS), Inc. shall sell two (2) medical linear accelerators as specified in purchase agreement numbers PT980436AB1 and PT980437AB1, dated March 9, 1999 to XXXXX Medical Center, XXXXXX, Florida. The system will be installed at XXXXXX Medical Center, XXXXXX, Florida. The delivery of the first machine (with 6 MV and 15 MV photons) shall be no later than Sept.1, 1999. The delivery of the second machine (with 4 MV and 6 MV photons) shall be no later than Dec. 1, 1999. Elekta Oncology Systems (EOS) shall be responsible for rigging both machines in the department and bear all associated costs. The installation and the acceptance testing of each linear accelerator shall not exceed six (6) weeks from the time of delivery. The acceptance testing shall be performed according to the guidelines provided by **IEC document 977**. The physics staff at University of Florida shall fully cooperate with EOS installation engineers in meeting this objective and provide all test equipment. Both accelerators shall seamlessly interface with the IMPAC Medical Systems facility management system through iCom Interface.

2. System Configuration and Specifications:

Each accelerator and its ancillary equipment shall meet or exceed the performance specifications described in the product data brochures: SLi Plus Digital Linear Accelerator, MLCi multi-leaf collimator system, Precise Patient Support System, iView electronic portal imaging system, and the Elekta Precise Treatment Desktop (including Premium Therapy modules). In addition each linear accelerator shall satisfy the following:

- The mechanical isocenter (as described by the locus of gantry, collimator, and couch rotational axes) shall be located within a sphere of 0.50 mm radius.
- Each accelerator shall be equipped with a high-dose-rate mode for both photon and electron beams.
- The RT Desktop for each linear accelerator shall provide an integrated platform for MLC, EPID, dynamic control of Precise Table, and advanced treatment techniques including IMRT (Step-and-Shoot) and Dynamic Therapy (IMAT). IMRT/IMAT prescriptions shall be imported directly into the RT Desktop through DICOM-RT protocol. Note: It is understood by both parties (EOS and XXXXX Medical Center) that some of the IMRT/IMAT functions of RT Desktop are not available at this time. EOS shall provide the hardware and software upgrades necessary for implementation of such functions as they become available for clinical patient treatment at no cost to XXXXXX Medical Center.
- Each accelerator shall be equipped with two (2) hand pendants.

- EOS shall provide a body frame (designed by Lax) for high precision extra-cranial localization at no additional cost to XXXXXX Medical Center.
- EOS shall be responsible for providing seamless transfer of DICOM-compatible images from iView to IMPAC facility management system.
- Each accelerator shall be equipped with a water chiller for controlled water temperature at no additional cost to XXXXXX Medical Center.
- EOS shall be responsible for acquisition and installation of setup laser systems for each accelerator treatment room at no additional cost to XXXXXX Medical Center (either Gammex or DIACOR is acceptable).

3. Special Requirements:

- EOS shall provide two (2) all-expense-paid visits to the Elekta factory (Crawley, England) for one XXXXX Hospital engineer to participate in the test cell evaluation of each linear accelerator purchased under this agreement.
- EOS shall provide periodic machine quality assurance testing software (Argus) for each accelerator at no additional cost to XXXXXX Medical Center under the condition that XXXXXX Medical Center negotiates a long-term service contract for the maintenance of the linear accelerator provided by EOS.

4. Warranty:

- EOS shall guarantee an uptime of 98% calculated yearly for each linear accelerator as long as a service contract is in effect between EOS and XXXXXX Medical Center for the linear accelerators.
- A penalty for uptime less than 98% per year shall result in the reduction of 5% in the cost of the maintenance contract for the subsequent year for each 1% additional downtime.
- Each week of delay in installation and acceptance testing of an accelerator shall result in an increase in the warranty coverage from EOS for the accelerator by one month.

5. Net System Price:

The net price for the systems as specified in purchase agreement numbers PT980436AB1 and PT980437AB1 and the addendum to the purchase agreement shall be \$ **x,xxx,xxx.xx**.

Addendum prepared by:

_____ Date: _____

Accepted by Seller's Duly Authorized Representative:

_____ Date: _____
