# Quality assurance for nonradiographic radiotherapy localization and positioning systems: Report of Task Group 147

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New technologies continue to be developed to improve the practice of radiation therapy. As several of these technologies have been implemented clinically, the Therapy Committee and the Quality Assurance and Outcomes Improvement Subcommittee of the American Association of Physicists in Medicine commissioned Task Group 147 to review the current nonradiographic technologies used for localization and tracking in radiotherapy. The specific charge of this task group was to make recommendations about the use of nonradiographic methods of localization, specifically; radiofrequency, infrared, laser, and video based patient localization and monitoring systems. The charge of this task group was to review the current use of these technologies and to write quality assurance guidelines for the use of these technologies in the clinical setting. Recommendations include testing of equipment for initial installation as well as ongoing quality assurance. As the equipment included in this task group continues to evolve, both in the type and sophistication of technology and in level of integration with treatment devices, some of the details of how one would conduct such testing will also continue to evolve. This task group, therefore, is focused on providing recommendations on the use of this equipment rather than on the equipment itself, and should be adaptable to each user's situation in helping develop a comprehensive quality assurance program.
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# I. BACKGROUND

## I.A. Introduction

The primary goal of radiation therapy is to deliver a tumoricidal dose while minimizing dose-limiting normal tissue effects. In recent years, advanced technologies such as intensity modulated radiotherapy (IMRT) and stereotactic body radiation therapy (SBRT) have allowed the delivery of higher doses to tumors while sparing adjacent radiosensitive structures. As these approaches are often accompanied by steep dose gradients, it is essential that the planned dose distribution be delivered as accurately as possible to maximize the benefit to the patient. This in turn imposes rigorous attention to accurate patient localization and motion compensation.

In order to improve irradiation accuracy, particularly when combined with highly conformal delivery techniques, several different technologies have been developed to image the patient daily and/or track the patient during treatment. Image guidance technologies (IGRT) include kilovoltage (kV) x-rays imaging, in-room computed tomography (CT), kV and MV cone-beam CT, and ultrasound. Imaging techniques such as these provide the ability to visualize the patient anatomy and to directly correlate the patient settings to the initial planned settings. Other technologies that do not use ionizing radiation have also been developed for the purpose of patient setup and monitoring, with the clear benefit that no additional dose is delivered to the patient from the localization procedure. As an added benefit, infrared, optical, and radiofrequency(RF) based technologies provide real-time feedback and can be used to monitor motion such as that due to respiration.

This report reviews concepts, clinical applications, and quality assurance for patient positioning, localization, and motion compensation that use nonradiographic technologies such as video and infrared cameras, surface texture map imaging, and radiofrequency tracking systems. These technologies are used for external beam radiation therapy, stereotactic radiation therapy, respiratory gating, and real-time patient monitoring. While some of these systems make use of implanted fiducials, the use of radiographic techniques for localizing these markers is outside of the scope of this report, which is limited to nonradiographic and nonultrasound systems. Several other AAPM task group efforts, listed below for reference, address QA issues associated with image-guided radiation therapy:

Task Group 104: The Role of In-Room kV X-Ray Imaging for Patient setup and Target Localization[1]
Task Group 135: Quality Assurance for Robotic Radiosurgery[2]
Task Group 142: Quality assurance of medical accelerators[3]
Task Group 154: Quality Assurance of Ultrasound-Guided External beam Radiotherapy for Prostate Cancer[4]
Task Group 179: Quality Assurance for image-guided radiation therapy utilizing CT-based technologies (not yet published)

Daily setup variation, interfraction, and intrafraction anatomical changes can create significant uncertainty with regard to radiotherapy localization. Generally, uncertainty in

location of the clinical target volume (CTV) is accounted for by adding an appropriate margin to create a planning target volume (PTV).[5] Tumors in the abdomen and pelvis tend to exhibit variability due to organ filling, while targets in the thorax or in the upper abdomen are most affected by respiratory and cardiac motion. Because extending PTV margins to account for setup and motion uncertainties frequently results in the irradiation of unacceptably large volumes of healthy tissue, minimizing uncertainty due to daily setup variation and inter- and intrafraction motion is highly desirable.

Interfraction motion, or more accurately, interfraction variation refers to changes in the patient setup from one fraction to the next. This may include changes in the patient's anatomy, such as variation in organ filling, changes in size of the tumor, weight changes, and differences in baseline breathing. There are several clinical approaches to minimizing interfraction variation. These include image-based techniques, stereoscopic x-ray imaging, volumetric (CT) x-ray imaging, and ultrasound imaging, as well as the nonradiographic methods covered in this report.[6–9] It is important to note that pretreatment image guidance offered by some systems, allows correction only at specific time points during the patient alignment process, and in general is not continuous. There have been many studies that address the effects of interfraction motion for various different clinical situations.[10–14]

In contrast, intrafraction motion refers to the motion of the patient and/or internal organs during delivery of a treatment fraction. A number of authors have investigated internal organ motion in a variety of tumor sites, including lung,[15] liver,[16–18] prostate,[19,20] and breast.[21–23] These studies indicate that internal anatomy can move significantly in time intervals corresponding to the duration of a radiation fraction. Other studies indicate that a tumor volume may deform or change from one fraction to the next or during a single fraction.[24–26] Recently, several reports have been published that describe the possible dosimetric impact of such motion for a variety of anatomical sites.[27–38] A summary of the management of respiratory motion is given in the report of AAPM Task Group 76.[39] The technologies outlined in this report are specifically designed to provide feedback on intrafraction motion during treatment. Systems based on video or radiofrequency technology typically have a fast update rate and therefore can be used to track intrafraction changes. Depending on disease location and individual patient motion characteristics, surface tracking technologies may or may not provide a good surrogate for internal motion; surface tracking has been shown to be a poor surrogate for prostate motion[40,41] and may or may not have an adequate correlation with targets in the thorax and abdomen, depending on individual patient characteristics.

## I.B. Theory of localization and tracking systems

The objective of several of the systems outlined in this report is to provide accurate three-dimensional information about the patient anatomy from two-dimensional input data (images). Derivation of 3D information from image data generally involves the addition of invariant geometry to the data, through *a priori* knowledge of the detector geometry and/or addition of known image features. Cyclopedian or monoscopic systems use feature-additive methods, whereas binocular or stereoscopic devices may rely upon the relative geometry of two sensors in deriving 3D scene information. This may be combined with other manipulation of illumination to improve feature identification in the 2D data set.

Photogrammetry is the extraction of three-dimensional information from data acquired by means of two-dimensional images.[42] The technology has been used for many years in radiotherapy to obtain surface contours, and now it is being used to register surface contours.[43–46] The current photogrammetry types used in radiation therapy are based on video or visible light, infrared, or laser detection.[47] The technologies of the cameras may be different, but the theory of operation falls in the following three categories based on the geometry of the systems: Stereo or binocular imaging which uses two cameras or receivers; Single Camera or cyclopedian/monocular imaging which uses a single camera or imager; or interferometry which can use either one or two cameras or detectors but relies on wave interference principals. There are several different clinical systems that fall in either the binocular or monocular camera configuration that may use fiducials or patterned light to aide in signal detection. Since currently no system uses interferometry in radiation therapy, it is not described.

In all cases, fundamental accuracy of 3D reconstruction from 2D data is limited by basic detector characteristics. These include light frequency response, pixel size, lens quality, and acquisition geometry. It should be noted that received pixel size and shape are dependent upon the acquisition geometry of a given scene, therefore ultimate resolution and distortion characteristics of an individual system will depend upon the geometry of the installed system.

The other major technology that is used in tracking is radiofrequency tracking. This technology uses a transponder and a receiver. The receiver accepts a signal from the transponder and is able to triangulate the position of the transponder based on the use of a specific geometry of the transponders. The theoretical basis of electromagnetic tracking is also described.

### *I.B.1. Stereoscopic (binocular) imaging*

When a pair of cameras is arranged such that they view a common scene in a fixed geometry, it is possible to reconstruct 3D scene information from the image pair. There are generally three steps to this process:

1. Identify spatially invariant or known features in the first image (feature extraction).
2. Locate corresponding features in the second image (feature correspondence).
3. Compute the 3D coordinates of the features using the triangles formed by the known locations of the cameras and the intersection of their respective projections into the common volume of view.

Steps 1 and 2 above can be computationally intensive, and various developments have resulted in development of

different measurement products. The features to be used must be clearly visible in both images. "Features" in this context may be native parts of the image scene, or may be added to the image in the form of fiducials or projected light. Feature extraction can be accelerated by manipulating illumination and/or through the use of emissive or reflective fiducials. Some stereoscopic systems, such as Free Track (Varian Medical Systems, Palo Alto, CA) and Exactrac (BrainLAB AG, Feldkirchen, Germany) utilize infrared illumination and retroreflective markers to produce very distinct, high-contrast features in each image that are readily distinguished from other image content. This permits simple signal processing algorithms to be used to quickly locate desired features in each image.

Structured light projection is another means of providing known features to an image for extraction. Here, a known pattern of light is projected onto the scene during image acquisition. The structured light pattern in the images then constitutes the features to be extracted. Examples of this form of photo generation are given in Siebert *et al.*[48] This technology is employed by VisionRT for use in surface tracking.

Establishing correspondence of features from one image to the other is usually accomplished through various search and correlation algorithms. One means of speeding the correspondence process is by taking advantage of the epipolar geometry of a camera pair. This concept is illustrated in Fig. 1.[49] The epipolar plane is defined by the centers of the cameras and the point of interest. This plane can be calculated from the pixel of the point of interest in the first image and the cameras geometry. The correspondence pixel in image 2 must be along the line created by the intersection of the epipolar plane and the plane of the camera, known as the epipolar line. Calculating the eipoloar geometry allows for a faster search of the image of Camera 2 by limiting the search to this line. Although fast, this method is subject to "ghosting" where a single marker can erroneously appear as multiple markers because each marker in 1 image corresponds to a line in the other image. This issue is avoided by using markers in predefined geometric arrays.[48,50–52]

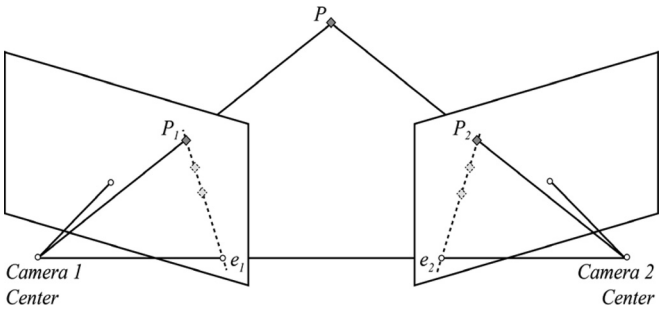


FIG. 1. Illustration of the principle of epipolar geometry in stereo correspondence. In order to calculate the 3D location of a point P three steps are needed: (1) Identify the pixel coordinates of P in Camera 1 ($P_1$), (2) search the image of Camera 2 to find the corresponding pixel coordinate of P image 2 ($P_2$) and (3) project and compute the 3D location of P from the coordinates of $P_1$, $P_2$, and the known camera geometry. Epipoles ($e_1$ and $e_2$) are defined at the intersection of each image plane and the vector between the camera centers. The epipolar plane is the plane containing the camera centers and point P. The search for the correspondence pixel $P_2$ can be limited to the line created by the intersection of the epipolar plane and the image plane of Camera 2. Sensor systems that restrict correspondence search to the epipolar lines can exhibit "ghosting" of features along the reduced search vector due to correspondence uncertainty (Ref. 49).

### I.B.2. Monoscopic (cyclopedian) imaging

Systems using a single camera typically add features to the scene as a source of geometric data for 3D determination. An example in radiation therapy is the C-Rad system in which a laser light provides geometric features in the acquired images. A mirror and galvanometer can be used to project a laser line into a field of view in a pseudo-raster pattern. The stepping galvanometer allows the line to be projected at known angles and times. A camera in a known geometry with respect to the laser line acquires an image of the field of view with a single horizontal line projected across it.[53,54]

Feature identification is now reduced to performing a search for the brightest pixel in each column of the image. The apparent displacement of the laser line from its location in the reference plane may then be combined with the known geometry of the camera and laser projector to compute the height of the reflective surface from the reference plane. This process is repeated at the camera acquisition frame rate in synchronization with the stepping of the galvanometer. Spatial resolution in this type of system is dependent upon the camera resolution and the accuracy of the galvanometer/mirror used to project the laser line. Temporal resolution is dependent upon camera acquisition rate and length of field of view. Higher temporal resolution may be obtained by stepping/acquiring over a truncated length of the field of view (FOV).

### I.B.3. Radiofrequency tracking

Patient alignment and tracking based on RF devices uses different principles than those based on camera technology and operate in the electromagnetic spectrum with frequencies lower than those of visible light. The principle of operation is that a coil is embedded into a small device that can be implanted in a patient, placed on a patient, or attached to an instrument. In order to obtain the coordinates of the coil, a pulse of RF radiation is focused at the coil and as it resonates, an RF signal is given off by the coil. This signal can be detected by an RF detection system and the coordinates determined by triangulation.

Tracking devices using radiofrequency waves can be very accurate, but they are also known to experience interference in the vicinity of any other magnetic fields or metal objects. Another disadvantage is that the magnetic field of such small devices is relatively weak, and therefore, the working volume is quite small. A major advantage of RF tracking systems is that the small devices can be implanted in or near the tumor, thereby eliminating the need for internal–external correlation models. Other advantages include a low latency, resulting in fast response times, and, like surface tracking technologies, the ability to receive information on multiple points (transponders) simultaneously.

### I.C. Commercially available non-radiographic localization/tracking systems

Several systems that use the theories and technologies described above are now commercially available for localization and real-time monitoring and tracking of radiotherapy patients.[55–57] In this section, the specific implementation and operation of these commercial nonradiographic localization technologies is described. In some situations, the commercial systems may be used in combination with radiographic or ultrasound imaging. In this case, QA of IGRT systems is addressed elsewhere, notable the reports of various task groups listed in Sec. I A. Additionally, some localization systems provide integration with radiation delivery systems, for example, to gate the treatment beam or track a tumor using a moving MLC or couch, with the latter two still being under development.[58–62] Physicists must be aware of how these systems integrate in order to develop a thorough QA program. This report also addresses the QA aspects of the localization capabilities of the equipment. Dosimetric quality assurance is discussed in the report of TG 142 and related documents.

#### *I.C.1. Infrared systems [BrainLAB's ExacTrac system/ Varian free track (SonArray), Varian RPM]*

Free Track (Varian Medical Systems, formerly Zmed) is a stereoscopic optical (infrared) tracking system that allows submillimeter patient positioning and real-time tracking of patients during treatment.[55,63] The stereoscopic nature comes from two cameras that focus at targets on the patient or on a device such as an ultrasound probe. The infrared (IR) tracking system has been employed predominately in the treatment of targets within the brain as a complement to stereotaxy systems.[64] This system is minimally invasive and employs a bite block connected to an optically reflective plate. The bite block is affixed to the upper palate and maxillary dentition of the patient. It is important to note that the relevance of the IR tracking to internal cranial and skull-base targets is a function of the bite block's stability and reproducibility. The system consists of two IR-sensitive stereoscopic CCD cameras and is capable of operating using either active IR emitters or passive reflectors. Software within a localization package recognizes the fixed arrangements of reflectors attached to the patient bite block and their relationship to the planned isocenter. The user console displays the three translations and three rotations required to align the patient. An interface to the treatment machine can be used to terminate the radiation beam based on a selected tolerance set by the user.[63,65–67] Infrared detectors have also been attached to other equipment in the room to provide localization of imaging equipment. This is the case for SonArray™ from Varian where the infrared markers are attached to an ultrasound probe for ultrasound image guidance.

ExacTrac x-ray 6D is a localization system that utilizes stereoscopic x-rays for image-guided radiation therapy in combination with an infrared stereoscopic subsystem and a robotic couch capable of correcting rotations about two axes. The system can be deployed with all components fully integrated, or with specific components used independently. The infrared subsystem can be used to localize the patient prior to imaging, and to monitor the patient's position during treatment. The x-ray component is used to determine the final position, based on either internal anatomy or implanted markers. The required couch translations and rotations determined by the imaging component are guided by the infrared system, based on markers (IR reflectors) attached either to the couch or to the patient. For the purposes of this report, only the operation and QA of the infrared components are discussed. The reader is referred to the reports of Task Groups 104 and 142 for more information on QA of the x-ray system.[1,3]

Another use of infrared cameras is in the management of respiratory motion (e.g., Exactrac system, Varian RPM system) for tumors in the thorax and abdomen.[56,68,69] A breathing signal is generated from the infrared camera system by visualizing the motion of one or more reflectors placed on the patient surface. This signal is electronically coupled to the linear accelerator and can be used to facilitate gating. QA frequency and both geometric and dosimetric tolerances in phantom-testing scenarios, for beam delivery with gated radiation are discussed in TG142.[3]

The Cyberknife system uses three infrared cameras as well as infrared reflectors for both tracking and for positioning. The QA objectives of this report are applicable to the camera configuration of the Cyberknife system; however, the camera tracking is not sold as an independent device that could be added to another system. The reader is referred to the report of AAPM Task Group 135 for more information about QA of the Cyberknife system.[2]

The primary reason camera systems have been successful is that they require minimal equipment and have a rapid update rate to facilitate real-time marker tracking. When properly implemented, these camera systems are also very accurate for remote patient monitoring. A disadvantage of infrared camera tracking is that it requires infrared reflectors to be placed on a device or on the patient. One area of concern in the use of infrared reflectors is that a direct line of sight between the reflector and the camera must be maintained. With other equipment in the room, it is possible for one or more of the reflectors to be obscured or partially obscured, which might lead the system to erroneously report a location. All systems have safeguards for determining whether a reflector is partially obscured, and for reporting to the user that the system is unable to track due to a blocked reflector. Another disadvantage is that infrared light systems can only address external patient motion, which may be different from the motion of internal organs of interest to the treatment, as discussed in Sec. I A.

The BrainLAB infrared system and the Varian Optical Tracking system provides a signal to move the Varian couch from outside of the room. The Varian RPM and BrainLAB ExacTrac gating systems can hold the beam if the patient moves and during gated operation. For both Varian and BrainLab, the remote motion based on the infrared signal is FDA cleared. For configurations of Exactrac on other linear accelerator couches, there is currently no remote couch

motion; however, in the future, if an interface to the couch is provided by the linear accelerator vendor, this could be possible and should be checked at installation by all vendors involved and the physicist.

### *I.C.2 Optical systems (AlignRT and C-Rad sentinel)*

AlignRT (Vision RT, London, UK) utilizes real-time 3D surface imaging techniques in combination with high speed tracking technology to determine the position of a patient in three dimensions. AlignRT utilizes stereoscopic video images in combination with patterns it projects onto the patient to dynamically capture and reconstruct maps of the patient's surface. Two or more camera pods are mounted in the treatment room and optionally also in the simulation room. Each pod contains one camera that projects a pattern on the patient and cameras to image the reflected pattern. Cameras can acquire single frame or continuous images at a rate of 7.5 frames/s. Three-Dimentional matching software is used to align the image captured on the treatment day with a reference image and to calculate the couch translations needed to correct a patient's position. Reference images can either be generated based on the CT body contour or obtained with the system when the patient is positioned correctly. The AlignRT system provides a signal that can be sent to an interface box or card to move the Linear accelerator couch from outside of the room(depending on Linac vendor and installation configuration). It can also hold the beam if the patient moves and during gated operation. The system was reported to be highly stable and to detect predefined shifts with an accuracy of less than 1 mm and rotational correction around the vertical axis less than 1° in phantom.[50,52] Initial applications of this device have included respiratory-gated treatment for radiotherapy of breast cancer.[70,71] The system has also been evaluated for respiratory gating in thoracic and abdominal tumor sites and in patient alignment for prostate cancer.[50,72] In such applications, the real-time 3D datasets are matched with corresponding reference images, obtained in the desired respiratory phase at the time of CT simulation. Another published application of this system has been for tracking and aligning the head for high-precision radiosurgery treatment.[73]

A limitation of this system is that it only tracks the surface and an additional system may be necessary to determine correlation between the alignment of the patient and the alignment of the internal target. Another limitation is that the cameras are sometimes unable to gather signals on low reflective surfaces such as hair and clothing. For most patients, the entire area of interest should be uncovered so that the skin is exposed. For head and neck or brain patients, where masks are traditionally used for immobilization, partial masks, which expose significant portions of the face, can be employed. While such masks are likely less immobilizing, it has been reported that patient positioning can be assured through monitoring with the AlignRT system. Also these masks are more comfortable to the patient.[73]

The current AlignRT system can be interfaced with some treatment machines. An interface provided by the linear accelerator vendor allows the couch translations from the remote localization system to be sent to the treatment couch for remote couch control. The correct application of these translations can then be checked with the AlignRT system. A gating interface to stop the treatment beam if the patient moves beyond a set limit, as determined by AlignRT, is also available, and also sends the signal to an interface provided by the linear accelerator vendor. For each install, the user will need to verify with their linear accelerator vendor and their localization system vendor the availability of such interfaces, and receive recommendations on installation and testing.

For localization purposes, 3D scanning lasers can be used to image the surface of a patient and to compare this surface with a reference surface. An example of a laser positioning system is the Sentinel laser alignment system (C-Rad AB, Uppsala, Sweden, marketed by Acceletronics, Inc Extan, PA). This device utilizes a laser scanning galvanometer and a video camera, which are installed in a single ceiling-mounted package. The scanning laser passes over the patient's surface and the apparent deformation of the laser line is used to render the surface. The patient's surface position is then compared to a reference surface to determine the patient's offset.[54]

This system is FDA approved, but is relatively new and therefore there are few publications on its clinical use. This device was reported to be accurate for aligning surfaces and for surface tracking in moving phantoms.[54] A contour from the CT scan can also be used as a reference surface for aligning the patient at the treatment machine. Current limitations are its limited connectivity with treatment planning systems and its limited connectivity to the linear accelerator where calculated alignment shifts may not be able to be automatically employed. Additionally, as this is a surface tracking system it may not be adequate for targets within the body unless coupled with a device capable of imaging internal anatomy.

### *I.C.3. Radiofrequency systems*

Radiofrequency signals have been used in radiology and surgery for a number of years. These devices typically consist of an RF transponder at the end of a cabled system or an array of RF detectors ("Flock of Birds").[74–80] These devices have traditionally been limited to either surface detection or have been used to track instruments inserted into the body such as the SuperDimension RF guided bronchoscopy device (SuperDimension, Inc., Minneapolis, MN), or the MicroPos system (Micropos Medical AB, Gothenburg, Sweden) that is designed to place an RF device into a catheter that is left in place during a radiation procedure.

The Calypso 4D localization system (Calypso Medical Technologies, Seattle, WA) utilizes radiofrequency signals for wireless localization and tumor tracking during radiation therapy. It is currently approved by the FDA for use in prostate or post prostatectomy radiotherapy. The system operates by detecting alternating current (AC) from electromagnetic markers (Beacon$^{TM}$) or transponders. The transponders are

approximately 8 mm in length and 2 mm in diameter, and consist of an AC electromagnetic resonance circuit encapsulated in glass. They are inserted into the prostate gland or prostatic bed under ultrasound guidance similar to a needle biopsy. For other body applications under investigation, the transponders can also be inserted into other areas of interest, or alternatively attached to the surface of or to other devices used in radiotherapy such as a bite block.

An array of source coils positioned a short distance above the patient produces an oscillating electromagnetic field. Energy from this field induces a resonance inside the transponder circuit, and the decay of the resonant signal is detected by a second array of receiver coils. Both the source and detection coils are mounted within the same panel, which is coupled to a console inside the treatment room. Typically, three different transponders, each with different resonating frequencies, are used; therefore, the signal emanating from each transponder can be uniquely localized by triangulation. The beacons' coordinates and the plan isocenter are initially identified on a treatment planning CT, and the offset between the planned isocenter and the intended isocenter is reported by the localization system at a frequency of 10 Hz.

The Calypso console, which contains the in-room controls and has an arm to suspend the panel over the patient, is positioned near the treatment couch and locked into place. Three infrared cameras mounted on the ceiling of the treatment room track infrared markers on the panel surface. The location of the panel relative to the linac isocenter is defined through a calibration procedure. Therefore, the position of the transponders relative to the panel and the position of the panel relative to the isocenter are known at all times. The panel is left in place during irradiation and its radiation attenuation has been reported to be negligible, but should be verified by the user.[81] Through a graphical user interface in the treatment machine control area, the Calypso system displays real-time graphs instantaneously highlighting shifts in position that exceed a user-specified threshold. Interface modules with radiation delivery system to shut off the beam if the target moves outside of user-specified parameters as well as to transfer couch shift values to the treatment machine are available. Several studies have described in detail the clinical use of this system as well as the sub millimeter localization accuracy that can be achieved when employing these systems for real-time intrafraction patient and/or organ motion tracking.[33,56,82,83]

Another RF based localization device is RayPilot (Micropos Medical AB, Gothenburg, Sweden). At this time it is undergoing testing and is not FDA cleared in the U.S. This system is a wired device and uses a catheter, surgically implanted in the prostate, as a conduit for an RF transmitter. The patient is placed on a special couch top plate that powers the RF transponder and can detect the location of the device within the patient in real-time.[84]

A potential issue with any implanted markers, such as those used with RF based systems, is marker migration away from their locations at simulation. The Calypso system mitigates the issue by assessing the position of multiple markers relative to each other.[82]

Another limitation is the relatively small field of view or operating range (in the case of Calypso, approximately 20 cm), thus use in very large patients is a contraindication for the Calypso system. Finally, the Calypso panel must be positioned prior to each treatment, which requires additional setup time.

On September 19, 2011, Varian Medical Systems, Inc., and Calypso Medical Technologies, Inc., announced they signed a definitive agreement under which Varian will acquire Calypso.

As with the infrared and video systems, integrations between a radiofrequency tracking system and the linear accelerator for remote motion or for gating control will rely on the linear accelerator vendor for both the couch control interface and the linac beam control interface. The user should check with both the linear accelerator vendor and the localization vendor to determine if such an interface exists and to receive appropriate testing for such an interface.

### *I.C.4. Other systems*

A list of all FDA cleared and commercially available systems available at the time of this writing is provided in Table I. These systems follow the principles outlined in this report and are briefly described above. The remaining sections will outline QA principles that are common to all nonradiographic systems that are used for localization. While attempts have been made to cover all technologies that can be used for localization and tracking, it is foreseeable that additional nonradiographic localization devices may be available in the near future. One such device is the Navotek system that uses an implanted radioactive marker in combination with an add-on radiation detector/localization device for tracking the implanted marker. Several publications describe the device and its use in prostate localization.[85–87]

While no specific descriptions about future products can be given at this date, the basic principles of quality assurance for nonradiographic localization and positioning systems as described in the report should be applicable to other localization devices.

## II. SYSTEM SPECIFICATION, SITE PREPARATION, AND INSTALLATION

An essential feature of the devices discussed above is that they are compatible with the treatment delivery process. For such systems, it is important for the radiation therapy team to determine how and why the equipment will be used both for clinical and research purposes prior to the purchase so that appropriate specifications, installation, and quality assurance processes can be developed. This team should be lead by a designated qualified medical physicist (QMP).

Most add-on localization systems are calibrated to isocenter by using the room lasers as the reference system. The accuracy of the add-on localization system is therefore dependent upon the accuracy of the in-room laser localization system. It is important that the specification, purchase, and installation process include an *a priori* evaluation and definition of the room reference coordinate system (i.e., in-room lasers

TABLE I. Currently available localization systems covered in this report.

| | Type of camera | Device name | Company | Components | Contact |
|---|---|---|---|---|---|
| Stereoscopic camera systems | Infrared cameras | Exactrac | BrainLab | Infrared cameras (x2), body markers (IR markers), Video camera phantoms (IR calibration, alignment, and QA) | www.Brainlab.com |
| | Infrared camera | Varian Free Track (Formerly Zmed) | Varian | Infrared camera (x2), passive/active IR markers, motion phantom | www.varian.com |
| | Infrared camera | DynaTRAC | Elekta—Medical Intelligence | IR camera system (3 cameras) on mounting bar, workstation, camera calibration device, Isocenter calibration device, patient repositioning spheres | www.medint.de |
| | Video camera with speckle pattern | Align RT | Vision RT | Video camera, projection camera, tracking system (inside room/outside room) | www.visionrt.com |
| Single camera based system | Scanning laser | Sentinel | C-Rad | Laser scanning device, lasers, camera, and computers | www.c-rad.se |
| | Infrared camera | Varian RPM | Varian | Single infrared camera with passive marker for breathing monitoring | www.varian.com |
| Radiofrequency systems | Also uses Infrared cameras for RF signal/receiving panel | Calypso | Calypso Medical | Beacons and RF panel, Infrared cameras (x3), tracking system (overlay, computers), operator console, phantoms (IR calibration, alignment and QA) | www.calypso.com |
| | | MicroPos | RayTrack | RF guided system with couch overlay reference | www.micropos.ab |

and machine isocenter), which should be done under the supervision of a physicist similar to the process of acceptance testing a linear accelerator. The combined patient setup accuracy should conform to the recommendations of TG142 of 1 mm for SRS and SBRT and within 2 mm for conventional treatments. For older linear accelerators, it may be necessary to arrange with a machine service engineer or consultant to modify the linear accelerator such that the isocenter meets the desired goal and to align the lasers per desired specifications prior to installation of the add-on localization system. If the isocenter cannot be made to meet the specification, the goals of the purchase of the add-on localization system should be reconsidered.

An important installation-specific issue for systems utilizing room mounted cameras is the mounting stability of any in-room equipment, which may require fabrication and mounting by third party contractors. Temperature may play an important role because thermal expansion and contraction can affect the mounting hardware and cause a drift of the system's identification of the machine isocenter. Similar problems can arise from natural disasters such as earthquakes or other stresses on the building. Architects, engineers, and vendor representatives must coordinate with the radiation oncology team so that the required modifications are achieved without interference with other facility or treatment services. This team typically manages compliance with construction and safety codes, but additional consideration may be necessary to fulfill local building and safety requirements. It is appropriate for the physicist to evaluate the installation documents to be certain that no parts of the nonradiographic localization system will interfere with radiation delivery or shielding. Individuals from the institution's facilities management/physical plant group will also need to verify that proposed installation is compliant with other electrical, emergency, and safety regulations.

If the localization system includes an electronic interface to the treatment machine, for example, for remote couch control, radiation gating, radiation tracking, or other capabilities, it is necessary to establish compatibility of both systems and to verify correct performance. The add-on localization system and the radiation delivery machine may not interface directly, but may communicate via the facility's record and verify (R&V) system or other third party interface. This may require support from the R&V vendors and should be considered in the planning process and for purchase. The localization systems will ultimately determine treatment parameters, such as couch position; quality assurance procedures should include documentation of these parameters. Prior to clinical use, a process describing the clinical use of the localization system should be developed. For example, R&V tolerance tables for couch parameters may be changed by use of the localization system. For all connections of the localization device to the linac or to other computer systems, the physicist should work with the vendors of the localization device, the linac, and any other involved system vendors, along with department or hospital IT personnel, to establish these connections following their guidelines and to ensure that adding the localization equipment will not violate any service contract.

Because patient specific information is required for add-on localization systems, it may be necessary for the system to access the local area network. It is essential that information systems specialists at the facility be involved to ensure that the proper outlets, data ports, servers, and network security (e.g., firewall) are available prior to installation. As part of systems' communications, a conformance statement from the vendor should be provided to assist in setting up mechanisms for data transfer between the localization system, imaging devices (e.g., CT), treatment planning, and record and verify systems. Finally, systems should provide a mechanism for archive and retrieval of patient data. Ideally, all data should be transferred to a central electronic record for permanent storage. Additional safeguards for the use of computers that are to be used for patient alignment should be managed through the facility's information technology department to insure that they are well-protected against the threat of virus or malware using antivirus software and if possible all USB ports be secured and internet access limited to further minimize the risk.

One other area of concern when preparing installation of add-on equipment is to negotiate a schedule for training. As new technologies are implemented into a clinical setting, it is often difficult to have staff stop treating patients to attend training; however, it is extremely important that all members of the staff who may use the equipment are fully trained on the proper equipment operation and possible clinical situations. This training should include a discussion of clinical support where the vendor may be consulted and provide follow-up training sessions for advanced techniques. Specific areas of training and documentation that are necessary include (1) proper startup/shutdown of equipment, (2) calibration of equipment, (3) operating procedures, (4) QA procedures, (5) possible failure modes of the equipment, and (6) possible failure modes of the localization process using this equipment.

## III. ACCEPTANCE TESTING AND COMMISSIONING

As with all equipment that is used clinically, it is important to perform a thorough evaluation both with regard to the individual components of the new equipment and to the impact of its use within the overall practice of patient care. There are many different types of components and equipment that can be used for nonradiographic localization, thus each user may need to adapt specific tests as necessary based on their equipment and their unique clinical use. While vendor specific tests typically focus on operation, this report focuses on application and QA.

It is important to note that with all of the systems described in this report, system tolerance is often specified as the accuracy of the system in matching treatment and machine isocenter. Claims of submillimeter accuracy, while representative of phantom studies, do not fully describe all sources of uncertainties encountered in clinical practice. Other uncertainties present in the treatment process, including imaging and calculation errors, must be included in consideration of the overall patient treatment and localization accuracy.[88]

The common link between all of the devices covered in this task group report is that they are referenced to the machine radiation isocenter. As already mentioned in the preinstallation section, it is recommended that the physicist, along with in-house or field service engineers responsible for the radiation equipment, verify the tolerance for the treatment machine isocenter, including both measurements of mechanical isocenter and radiation isocenter, their coincidence, as well as the laser alignment to radiation isocenter. Proper documentation of the machine isocenter should include star shot films for collimator, couch, and gantry run out, and/or results of a "Winston-Lutz" type test, in which beams-eye images of a ball placed at isocenter are analyzed as a function of gantry, couch and collimator angle.[89] The accuracy of couch readouts should also be consistent with the criteria in TG142, dependent upon the procedures in which the equipment will be used. For standard treatment, accuracy should be 2 mm and for SBRT or SRS treatments accuracy within should be within 1 mm. These indicators are important, as they will be used when verifying the accuracy for localization using the add-on localization equipment.

***Recommendations: The accuracy of the machine isocenter should be checked in accordance with TG-40, TG-142 and the user's acceptance test documents for their specific linear accelerator. Additionally, if lasers, light field, couch digital readouts, or any other machine components are used to define the reference of a peripheral localization device with regard to the linear accelerator, this shall be established before installation and checked at minimum at the frequency recommended by TG142 and more often if deemed necessary by the QMP for accurate use of a specific localization device.***

### III.A. Acceptance testing

For most new equipment, the vendor will provide the user with an acceptance procedure that will define operation and limitations of the equipment. It is important to keep in mind that acceptance tests demonstrate only that the equipment is working as per the specific purchase contract between the facility and the vendor. As stated in Sec. II, the radiation therapy team, lead by the physicist, and the vendor should agree upon a set of acceptance tests prior to purchase so that this process will adequately illustrate the device works as anticipated. In some cases, the acceptance test document is specifically a vendor document and may not be adapted. In these situations, it is recommended that the physicist be familiar with the various tests recommended in the commissioning section of this report and negotiate for support from the vendor in conducting part of the commissioning if the acceptance does not cover these. This also applies to situations where the vendor does not provide an acceptance procedure at all or a rudimentary procedure that only insufficiently demonstrates the needed capabilities of the system.

The acceptance test process should include tests to illustrate the safe operation of the localization system along with basic localization accuracy. Localization accuracy describes the ability of the system to position a target point at the

radiation isocenter. Accuracy evaluation should be customized to the type of treatments that are desired. For example, for SBRT treatments, the localization device should be capable of positioning a point within a phantom to within 1 mm of the radiation isocenter. Reproducibility is measured in terms of the standard deviation for repeated localizations. Three or more measurements are necessary to assess reproducibility.

Some localization systems, particularly those that provide gated treatment, integrate with the beam delivery of the linear accelerator. In these cases, it is important that the safety features and interlocks of the linear accelerator are not compromised. The physicist should utilize the acceptance test to become more familiar with the equipment operation and should be familiar with the vendor supplied user manual, which should indicate possible warning messages and safe use of their equipment. The use of these manuals along with discussions with the vendor and the installation team can be useful to help to develop the QA process for additional tests specific to the users situation that are necessary to prevent any misuse of the equipment or failures in the equipment that may not be detected in the machine specific QA that is outlined in this report.

Additional tests include testing compatibility with other equipment. This includes communication between the localization device and treatment planning systems, the record and verify system and the linear accelerator. The vendor should provide guidelines for basic communications testing. More details regarding testing of coordinate systems are included in the commissioning test descriptions in the Sec. III B. The other major component for compatibility is to determine the workspace issues for the add-on equipment, and if there is potential for collisions or limitations of use under certain circumstances (such as a camera blocked at some gantry angles.) This also is referred to as limit testing and is further described in the commissioning test section.

Finally, for each device, the manufacturer is required by the FDA (or other regulatory agencies if outside of the U.S.) to provide written documents on adequate direction for safe use of the equipment. The physicist should be aware of the possible hazards as well as safety features of the equipment prior to commencing with commissioning. Safety features may include automatic shut off, collision detection equipment, and the availability of backup power systems for data recovery. The physicist should also use the list of possible equipment or process failure modes compiled during the acceptance test process to develop additional procedures to ensure the safety of the patient as well as of the radiation team. Specific examples of safety hazards with the use of these peripheral devices are collisions due to add-on equipment, electrical hazards, trip or other mechanical hazards due to added cabling and wiring. Most of these hazards will be installation-specific and will not be applicable to each user; therefore it is important to work with the facilities department at each institution as well as the vendor to determine the hazards and to address any possible concerns.

***Recommendations: Acceptance testing should evaluate the localization capabilities and should include some quantifiable measure of the localization accuracy and reproducibility following vendor guideline or those described in Sec. III B. The vendor must be able to demonstrate localization consistent with the recommendations of TG 142, within 2 mm for conventional delivery and within 1 mm for SBRT or SRS treatments. Safe operation of the equipment must also be demonstrated. Proper functionality of the localization system interface to the linear accelerator and other computer equipment should be demonstrated. The vendor and physicist should work together to develop a list of possible failure modes and ongoing system checks and maintenance as these can be machine and facility dependent and can also depend on the specific version of the software and or hardware that is installed.***

## III.B. Commissioning

The commissioning of a localization system requires the radiation oncology team, lead by a designated QMP, to determine all parameters necessary to utilize the equipment in a clinical situation. This includes measuring the system accuracy, determining system limitations, and developing operating procedures and QA schedules. Some of these tests will be completed as part of the acceptance test with the vendor; however, in most cases, the acceptance test is at the discretion of the vendor and may not satisfy all clinical recommended quality assurance. For example, with respect to communications, the vendor may only agree to test basic communications between their system and the other computer systems within the department while this task group recommends testing various patient configurations (prone/supine) and data transfer combinations as part of the commissioning. Commissioning of the localization system should include evaluation of the following:

1. Integration of Peripheral Equipment
    a. Communication with Record and Verify Systems
    b. Integration with the Linear Accelerator
    c. Determination of localization Field of View
2. Spatial Reproducibility and Drift
3. Static Localization Accuracy
    a. Localization Displacement Accuracy
    b. End-to-End Assessment
4. Dynamic Localization Accuracy
    a. Spatial Accuracy
    b. Temporal Accuracy
    c. Dynamic Radiation Delivery (gating/tracking)
5. Vendor-Recommended Assessment
6. Documentation
7. Standard Operating Procedures

The radiation oncology staff should feel comfortable requesting vendor guidance and participation in conducting these tests and in requesting that other tests, deemed necessary for safe and effective use, be added to the acceptance tests. Vendors should provide technical assistance and participation in response to reasonable requests.

*Description of tests*: Since all tests of equipment should be performed at the time of the commissioning of the system, the detailed descriptions of the tests are outlined in this section. Section IV lists the tests that the task group recommends for ongoing daily, monthly, and annual QA but the reader is referenced back to Sec. III for the description and design of these tests.

### III.B.1. Integration of peripheral equipment

Testing of equipment compatibility in an integrated, multivendor environment is essential. This section will discuss the software integration and hardware integration separately.

*III.B.1.a. Communication with electronic medical records systems.* The peripheral devices described in this report employ a database to store patient information. This typically includes patient name, plan information, and either a scan of the patient surface or the location of internal or external fiducials and their coordinates relative to the isocenter. Direct communication between the treatment planning system and the peripheral system, if available, can avoid transcription errors. Not every system allows direct DICOM transfer of the localization data from the treatment planning system or simulation. Some systems communicate using the record and verify system as a link between the treatment planning system, the localization system, and the treatment delivery device. Whether the data entry is manual, via DICOM transfer, or by some other electronic means, the radiation team, upon commissioning, must confirm the correct orientation and spatial geometry of the data. This is particularly important given that a standard convention for coordinate systems has yet to be developed. When establishing a link between different systems, each aspect of the data transfer should be checked individually for data integrity as described below.

Phantom tests covering a representative variety of clinical scenarios should be performed to verify relationship/transformation between different coordinate systems. This may involve the use of vendor-provided phantoms, but in many cases these can be inadequate, and the physicist may need to adapt existing phantoms. This is performed by acquiring CT images of a phantom in different treatment positions and selecting a representative target within the phantom (i.e., isocenter) and applying other superficial marks on the outside of the phantom at those coordinates. The coordinates for the phantom and the representative isocenter can be transferred to the localization system to ensure that the coordinates of the representative target and the superficial marks represent the correct location of the phantom relative to the room isocenter. Different patient orientations would include CT scans with the phantom identified as headfirst supine, headfirst prone as well as feet first supine or any other orientation that may be used clinically. If necessary, markers can be added to a specific location on the phantom to indicate orientation (for example, superior, anterior, right side). Also, some systems use units of cm while others use units of mm; this should be checked by looking at relative distances between multiple points or isocenters in a phantom. It is common for treatment planning systems to use coordinates of the CT scanner, which may differ from the coordinates of the treatment machine. For example, in CT coordinates, the Z dimension is typically aligned with the couch movement or the patient's superior/inferior axis, which at treatment machine corresponds to the movement direction of the Y jaws (assuming the collimator in neutral position) and is typically labeled as such. This testing should be done whenever the localization system, simulator, or the R&V system is upgraded, as any of these could lead to a change in coordinate systems.

*III.B.1.b. Integration with the linear accelerator.* It is of utmost importance that any add-on localization equipment does not adversely affect radiation delivery by attenuating the radiation beam or by any other means. Any potential changes in the delivered radiation must be measured. This includes, but is not limited to, add-on couch tops, immobilization devices, and any other device that may attenuate or alter the beam. For example when using the Calypso system there is a specific couch top in place, the attenuation through which may be different than the standard couch top. AAPM task group 176 (in preparation) is charged with a thorough analysis of the impact of these devices.

In addition to physical components, there is remote possibility that electronic devices used in the add-on localization systems could interfere with components within the linear accelerator. It is important for the physicist to discuss this with the accelerator vendor, and as always, properly evaluate the radiation delivery system after any service. Also, if the system is not used as recommended, by the vendor, the user should evaluate if specific protocols for off-label use need to be in place. Generally, the Institutional Review Board (IRB) should be consulted on any required forms and processes, as these tend to vary greatly between institutions. Guidance on off-label use can be found in the report of the AAPM Task Group 121.[90]

The radiation team should also be aware of potential issues that could arise when multiple combinations of add-on equipment are used in the same treatment room, such as an add-on MLC, robotic couch tops, and other localization systems. This may require the support of several different vendors in order to verify that all add-on equipment combinations have been tested together, and if not, to get the help of the vendors to design tests to be performed to insure all equipment will work together.

Radiation delivery with the add-on localization equipment or combinations of added equipment should include operating both the linear accelerator and the localization equipment with radiation measurement equipment in place (phantoms/films) to ensure that the radiation delivery system operates without triggering machine interlocks and delivers the prescribed dose. This should also include testing that in the event the radiation is terminated due to the localization system (either manually or automatically), that the radiation is carried out as intended when the beam is resumed. This test should be performed using representative delivery techniques for patients (i.e., arc, IMRT, static field, or gating).

In some instances, there may be a possibility of the radiation or linear accelerator interfering with the localization

equipment. For example, for video based systems, some cameras may be blocked when certain gantry or couch angles are used. Partial obstruction of an infrared marker may cause the system to report a location different than the true location. For RF localization systems, magnetic or metallic objects, especially oscillating ones such as a motor, in the treatment room may add radiofrequency noise that introduces error into the localization system. Additionally, use of an add-on microMLC for stereotactic procedures may create a situation where MLC motors are closer to the RF detection equipment than originally measured, causing a similar issue. To evaluate possible interference or obstructions, one should plan to deliver several different plans to a phantom while using the localization system to test both the radiation delivery and localization system under different combinations of gantry, couch, and MLC settings. This is to ensure that the equipment does not interfere with each other and to identify operating limits and possible collision areas. The process should be repeated anytime a new treatment technique using the equipment is introduced in the clinic. Essentially, every piece of localization equipment that is introduced for patient treatments should undergo a complete end-to-end test (described in Sec. III B 3 b) to ensure that a problem is not overlooked.

In addition it needs to be considered that over longer period of exposure to ionizing radiation in the treatment room, accumulated radiation damage can eventually affect the performance of the localization system. This applies in particular if the treatment room is for total body irradiation and or total skin irradiation. These procedures can produce significant scattered or direct radiation to these devices, as well as neutrons from photon beams with energies greater than 10 MV.

*III.B.1.c. Determination of the localization field of view.* Most localization systems will have a finite field of view around the isocenter within which the system can perform. Some limitations are due to the detection device range or the arrangement of the cameras in the room. It is essential that the radiation team is familiar with this field of view so that they know how much motion can be detected or possible scenarios when the accuracy may be compromised or the localization system may not work. Field of view limitations may limit the use of the system to only certain couch and gantry angle combinations. System descriptions will generally include information on the localization space. Measurements to determine the area where the localization system will work should be performed to verify the manufacturer provided data. This can be done by moving a phantom from the isocenter while the localization system is on to determine the distance from isocenter at which the localization system fails to detect the phantom. After localizing a phantom, the couch can be rotated about the isocenter and the gantry rotated to different angles to determine if the field of view will allow use at various different treatment scenarios. Clinical workflows using localization systems usually require the therapist to set the patient as close to isocenter as possible using conventional methods while using the localization system to make minor adjustments and/or track the patient position.

***Recommendations: It is recommended that initial checks of data transfer include transfer of data from the simulation, treatment planning and record and verify system in different patient orientations (head first, feet first, prone, supine, etc.). Both input and output data transfer should work as expected (i.e., coordinates, units and axis transfer to the correct coordinates, units, and axis). Phantom delivery of representative patient treatment plans should be performed to radiation measurement equipment with and without the localization system turned on to verify that the localization device does not change the radiation delivery (within 1% dose) and radiation does not change the localization (within 1 mm). The localization field of view should be measured and documented.***

### III.B.2. Spatial reproducibility and drift

Patient positioning systems that use optical or radiofrequency mechanisms can be susceptible to spatial drift. Testing procedures specific to optical systems can be found in the literature.[63,67,91–93] Rigidly fixing a test pattern in the camera's field of view, and then sampling the position of the test pattern at time intervals immediately following power on to the camera can evaluate spatial drift of a camera. Figure 2(a) graphically depicts the thermal drift from the time an infrared camera is switched on through 100 min. It can be observed that the 3D targeting position as determined by the

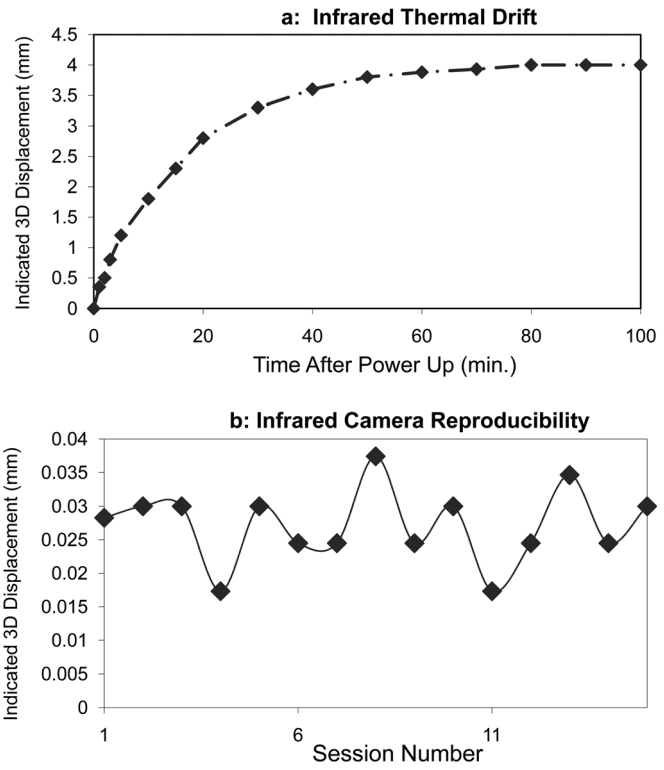


FIG. 2. Thermal drift and reproducibility measured using a commercially available infrared camera system. (a) Thermal drift: Measurement of 3D displacement of a fixed target due to camera drift from initial startup monitored for 100 min. (b) Reproducibility: Measurement of 3D displacement of a fixed target with multiple readings. Vertical axis is the absolute location reading (mm) for a fixed target and the horizontal axis are multiple readings. The displacements in this example vary between 0.01 and 0.04 mm.

camera system drifts more than 4 mm over the first 80 min. If the system is calibrated to the radiation isocenter during this warm-up period the accuracy of the overall system will be affected. Neither camera calibration nor clinical use should be performed unless power has been supplied to the camera for a minimum of 90 min. Some systems have an interlock or a warning to prevent the use of this system in this warm-up period; however, this is not true for all systems, so it is important to add a warm-up time to the procedures for use of systems that demonstrate a thermal drift.

After this initial system warm-up, the reproducibility of the system can be evaluated by continuing to sample the position of the test pattern or phantom at fixed temporal intervals. Figure 2(b) shows the results of repeat measurements taken at 10-min intervals after the camera has stabilized. The duration and magnitude of this initial instability is camera dependent and should be tested independently at each site prior to clinical use.

***Recommendation: Building on the corresponding tests during acceptance, stability testing should be performed during commissioning of a localization system by monitoring and recording a test pattern device at initial startup of the equipment for at least 90 min or until sufficient stability is achieved. Safeguards or procedures should be developed to prevent use during this time. Reproducibility can be measured by monitoring this same device for an additional 60 min after establishing stability. This test should be done at least annually or after equipment changes or per manufacturer specifications.***

### III.B.3. Static localization accuracy

*III.B.3.a. Localization displacement accuracy.* The localization displacement accuracy of any localization system needs to be checked over a range that covers all clinical shifts to be expected for the system. When assessing this range it should be considered that it is sometimes necessary to treat multiple target areas, or to align to different locations than isocenter to check patient setup.

Couch readout QA should have already been performed following TG142 guidelines so that couch indicators can be used to compare the shifts that are applied while using the add-on localization system. If the couch readouts are not accurate enough for use in testing the localization system they should either be brought to within tighter specifications or an accurate motion phantom may be necessary for this test. The phantom should be positioned at a fixed distance away from the isocenter and then shifted back to isocenter using the localization system. The offsets that are checked should cover a reasonable clinical range. For example shifting a breast patient from the breast tangents to the supraclavicular isocenter could be about 10 cm, while other patients may almost always be aligned to isocenter within 3 cm. If possible, our recommendation is that at least 10 cm shifts from isocenter or between two isocenters be checked in all directions. To verify the accuracy of the couch shift to position a target, orthogonal MV portal verification images should be taken of a known target within the localizer phantom. This is similar to the localization test but includes the accuracy of the couch motion to the treatment isocenter.

Some systems have the ability to detect and correct for both rotational and translational deviations. Testing of rotational compensations should be performed if this will be used on patients. Robotic couchtops can usually be adjusted to specific angle of pitch, roll, and yaw and these values should be verified with a digital level. If this type of couchtop is going to be used for treatment it can be used to introduce different angles to a static phantom in order to test the localization system ability to detect and correct for the angle corrections. A phantom that is on a platform with angle corrections could also be used. For devices such as Calypso that only use a few points, an angle correction could be simulated by moving one of the three transponders within a phantom (to known geometry). Currently, most centers do not apply angle corrections using a 6D couch, however, angle detection in localization is helpful in indicating if the patient is rotated in one or more dimensions on the couch and should be repositioned and relocalized.

*III.B.3.b. End-to-end localization assessment.* After system characteristics have been evaluated, commissioning tests should focus on the localization system accuracy. Overall system accuracy is best measured using an end-to-end target test. For this test a phantom that has embedded radiographic markers visible on both CT and kV or MV imaging is typically used. Several commercial phantoms exist for this purpose, and it is also possible to modify existing anthropomorphic phantoms, or plastic slabs for this purpose. For surface tracking systems, some plastics may not be usable due to their reflective properties. Soft plastic mannequins can be used and phantoms with appropriate surface coloring to approximate a patient should also work. Some commercial localization systems may come with a phantom that can be used to evaluate the entire localization process. To perform the test, the phantom may be marked with some exterior visual cues for initial setup. A treatment planning CT scan is performed under similar conditions as for patients. For localization systems that use specific points identified in the CT image, the targeting uncertainties are directly related to the CT slice thickness and field of view, so a high resolution (small slice spacing $< 2$ mm) CT with a small field of view should be used to determine the coordinates of markers and the isocenter for the phantom. The procedure should also be performed using the CT protocols that will be used clinically to compare the localization accuracy under clinical conditions. This may show that the clinical procedure will require a small slice thickness CT scan through the area of interest in order to achieve the level of accuracy required for a particular treatment. The CT scan is then sent to the treatment planning system where an isocenter can be defined relative to the location of the hidden target. At the treatment machine, the phantom is positioned arbitrarily relative to the isocenter but within the operating range of the imaging system to be tested. Using the nonradiographic localization system in the treatment room, the couch is moved to restore the hidden target to the isocenter or to its planned location relative to isocenter. At this point, orthogonal MV verification

images acquired with a small radiation field can be used to identify target localization accuracy relative to the machine's radiation isocenter. The testing process described is oftentimes called a hidden target test and can therefore be used to complete the localization end-to-end testing.

***Recommendations: A full end-to-end test from CT through treatment should be done upon acceptance and annually thereafter or whenever major equipment changes occur. Frequency may be increased upon vendor recommendation. A localization accuracy test with a previously scanned phantom should be performed monthly and can be referenced to the acceptance end-to-end test. The localization accuracy should be within 2 mm of isocenter for standard dose fractionations and 1 mm for SBRT and SRS treatments in following recommendations from TG-142. Additionally, the ability to accurately use the localization system to move a target a known distance should be evaluated on acceptance and monthly thereafter, as well as after any equipment change, and more frequently as recommended by the vendor. Recommended accuracy is within 2 mm over a 10 cm range in all directions for standard dose fractionations and 1 mm over 10 cm range for SBRT and SRS treatments in following recommendations from TG-142.***

### III.B.4. Dynamic localization accuracy

*III.B.4.a. Spatial accuracy.* For localization systems that can be used for real-time patient (or target) tracking, it is important to evaluate whether the indications of motion are both temporally and spatially accurate. Systems may have different modes of operation for real-time monitoring than when initially localizing the patient, this test should be performed independently from the evaluation of localization accuracy.

Ideally, one would be able to evaluate spatial tracking accuracy using a phantom that can be programmed to move reproducibly and precisely to certain locations at specific times. The accuracy during tracking is the difference between the phantom's programmed location and the localization system measured location. A step pattern works very well for this type of motion measurements. For example, programming a phantom to move $\pm 1$ cm and stay at each location for 5 s would give the user time to evaluate the accuracy with which the localization system reads the 1 cm offset. This is illustrated in Fig. 3. This is relatively new technology and there are a few reported results in the literature.[83,94] More information on 4D phantoms specific to respiratory motion measurements can be found in the AAPM report of Task Group 76 on respiratory motion management.[39,72,95–97] Currently, there are several commercial systems with programmable phantoms that have either plates or various other devices that move and can be programmed to move to match different patterns. The task group would recommend discussing with the localization device vendor to determine if a motion phantom is provided with their system or to get recommendations for a phantom. Without the use of a programmable 4D phantom, this test can be simulated by manually moving a phantom by predefined amounts using the treatment couch indicators or a precision stage to compare to the set phantom location to those indicated by the localization system.

*III.B.4.b. Temporal accuracy (latency).* System latency and time (frequency) of tracking should also be evaluated. Most vendors will give specifications for the frame rate, or frequency at which the system can update the localization data. Systems reviewed here typically operate with frame rates between 5 and 30 Hz. A test should be designed that will determine any delay between the time a patient moves and when the localization system identifies the motion. This test would most easily be performed using a programmable motion phantom.[39,83] The recommendation is that this test be performed with the aide of a field service engineer onsite. The criticality of this test will depend on the proposed application of the technology. The TG 142 report on linac QA gives some guidance about the temporal accuracy and specifies that it should be within 100 ms of the expected value.[3] More results on latency testing for the Calypso System can be found in the report by Santanam *et al.*[98]

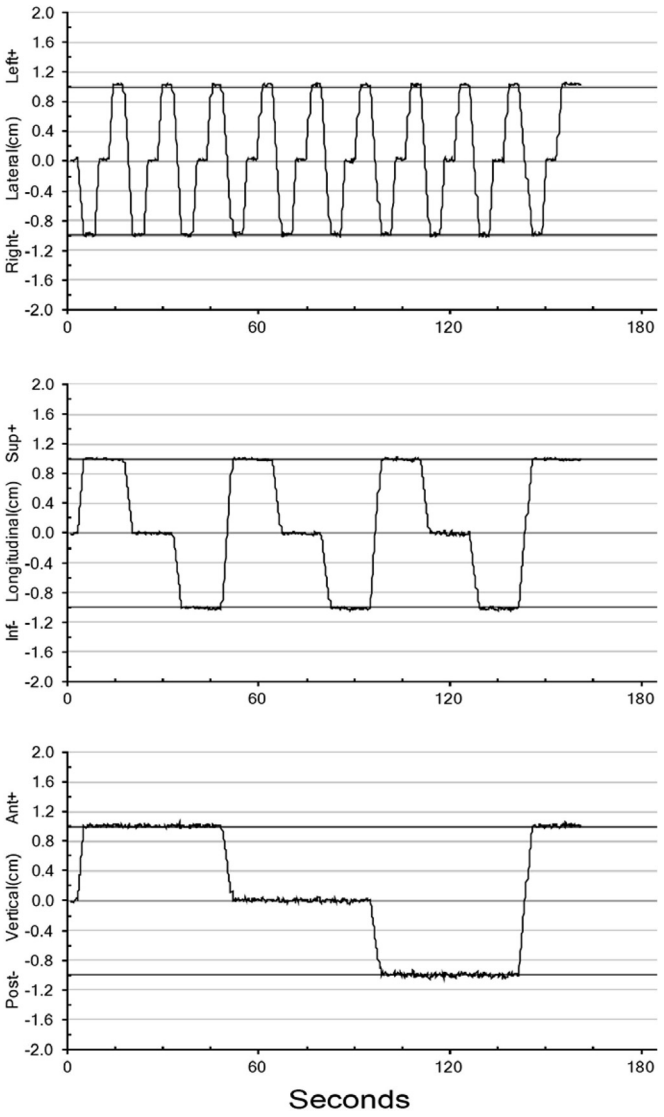


FIG. 3. Tracking report while moving a phantom 1 cm in each of the three orthogonal directions.

*III.B.4.c. Dynamic radiation delivery (gating or tracking).* The rapid update rate that can be achieved with optical or RF localization devices make them ideal for use in applications to gate the radiation delivery or track the radiation around the moving target. As was mentioned in Section III A., some of these systems can be configured to interface with the linear accelerator in such a way that radiation delivery or MLC motion can be tied to the motion as tracked by the localization device. As this is a complicated process, there are many challenges in establishing a QA program, however, the key components of radiation delivery must be checked as part of any quality management program.[99] The linear accelerator maintains the usual safeguards for the electronics and radiation monitoring and requires specific keyed safeguards in order to engage the radiation beam. The peripheral localization systems can only be used to disable the beam or to "hold off" the beam when the patient moves outside of a specified location as registered by the localization system. The functionality of the beam-hold mechanism should be tested on installation by using a motion phantom or a couch that can be moved from outside of the treatment room. A selected threshold of motion within the typical patient motion range (1–5 cm) should be selected such that radiation will be terminated outside of this range. The TG 142 report on linac QA gives guidelines for radiation delivery while in a gated mode and requires this to be within 2% of radiation delivery without gating. A tracked radiation delivery should be tested in the same manner as a gated delivery. These measurements would consists of using a radiation detector capable of accurately measuring dose (film, ion chamber, diode, etc.) mounted onto or in a motion phantom that can be made to move to simulate the tumor motion and can provide a surrogate for the tracking system. This output should be within 2% of the nontracked output.[3]

***Recommendations: Systems used in real-time applications, such as those designed for gating ot tracking, must demonstrate end-to-end accuracy commensurate with TG-142 when operated in dynamic mode. A full end-to-end test from CT through to treatment should be done at commissioning and annually thereafter. Monthly tests can be referenced to the annual CT scan.***

#### *III.B.5. Vendor-recommended assessment*

This task group is focused on the safe use of localization systems to localize patients and the tests are designed to detect errors that would lead to a compromise in patient treatment. Additional QA may be recommended by the vendor to maintain the localization equipment. Some examples include checking battery life or check sums of hard disks, or cleaning routines for maintaining the equipment in a functional manner. The vendor may also be aware of certain components that undergo progressive decline in their ability to operate, such as various forms of cameras, and may be able to give recommendations as to how to predict a failure. The physicist is encouraged to consult vendor manuals along with this task group in designing a QA program.

#### *III.B.6. Documentation*

A record of all tests done at the time of installation should be maintained for the life of the equipment. A hardcopy or electronic record of subsequent quality assurance and training should be maintained for at least a year or longer and all service documents should be maintained for at least the life of the equipment.

#### *III.B.7. Standard operating procedures*

Procedures for the use of the localization system should be created and kept at a suitable location (in hardcopy and/or electronically). These procedures should include training guidelines for new personnel. As experience with the system grows, the procedures should be updated.

## IV. CLINICAL USE AND ONGOING QUALITY ASSURANCE

Proper operation of localization systems is as important as that of radiation delivery systems, as delivering the prescribed dose to the wrong location can be more detrimental to the patient than delivering an incorrect dose. Just as there are recommended schedules for quality assurance of dosimetric parameters,[100] it is prudent to verify the accuracy of localization and positioning systems with similarly scheduled frequency. This quality assurance monitors the safety, accuracy, precision, sensitivity, and reliability of the patient positioning system. In general, these tests will be similar to the tests described in the initial commissioning section.

### IV.A. Daily QA

A QMP should perform the following daily QA tests or delegate them to another member of the radiation therapy team, like a radiation therapist. If the tests are delegated, a QMP needs to review the test results in regular intervals. Also, if any of the tests fail, the QMP must be notified before the equipment is used clinically.

#### *IV.A.1. Safety*

Any interlocks on moving parts that could be in contact with the patient while in treatment position should be checked daily. Assure that ceiling and wall-mounted parts of the system are rigidly fixed to the wall or ceiling of the treatment room by visual inpection. It should also be checked that the field of view of rigidly attached cameras and detectors is free of obstructions.

#### *IV.A.2. Static localization*

Based on the importance of these parameters, the agreement between the localization system isocenter and treatment machine isocenter should be evaluated on the days that the system is used. In order to comply with the time constraints of a morning warm-up, this procedure can be simpler than the hidden target test by using a small phantom with a target in a known geometry that can be set to isocenter as indicated by the room lasers. The phantom should be

recognized by the localization system as being within 2 mm of the isocenter when it is positioned based on the lasers. Since these systems may be used to monitor patient motion, for tracking, or their readouts may be used to shift between two isocenters, a check of the localization systems ability to track patient motion should be performed by moving the phantom a known amount while monitoring the localizations indicators. For example, shift the phantom 5 cm (using ruler or couch readouts) and check that the localization system indicates 5 cm from isocenter (within 2 mm).

#### *IV.A.3. Documentation*

A record of the results of the daily QA should be created, signed by the operator and kept either electronically or in a binder at the machine. Alternatively, a system that provides a log of activity that includes an approval mark of the operator is sufficient as documentation.

#### *IV.A.4. Vendor recommended tests*

In addition to the tests described above, additional tests that are recommended by the vendor should also be performed. These may include tests of backup systems or basic software check sums or other internal QA that is part of the software or hardware.

### IV.B. Monthly QA

Monthly QA by or under the supervision of a QMP should include all tests performed daily with the addition of the following.

#### *IV.B.1. Safety*

For gated radiation delivery, verify that the beam control system is terminated when the localization system indicates the patient location is out of tolerance. (Sec. III B 4 c). This can be tested by using a simple motion phantom that can move the phantom out of a radiation-gated area and verifying that the beam terminates when this occurs.

#### *IV.B.2. Static localization accuracy (hidden target test)*

Before checking accuracy of the localization system, the accuracy of the machine isocenter should be checked in accordance with TG-40 and TG-142. Additionally if lasers, light field, or any other machine components are used to define the reference of a peripheral device to the linear accelerator this shall also be checked. A localization accuracy test (hidden or known target), which relates the localization system directly to the treatment isocenter, should be performed monthly and can be referenced to the end-to-end test performed annually. This can be accomplished by using films or portal imaging devices to verify alignment of a target with the treatment isocenter. This test is described in Sec. III B 3 b.

#### *IV.B.3. Dynamic localization accuracy*

If the device is left in place during treatment, the tracking accuracy of the system should be evaluated monthly following the procedure in the installation section.

#### *IV.B.4. Vendor recommended tests*

Any additional monthly tests recommended by the system vendor should be performed.

#### *IV.B.5. Documentation*

A record of the results of the monthly QA should be created, signed by the physicist and kept either electronically or in a binder at the machine.

### IV.C. Annual QA

In addition to the tests performed daily and monthly, the following tests should be performed annually by or under the supervision of a QMP.

#### *IV.C.1. System safety*

Systems should be tested to ensure that backup power and/or batteries are functional. All emergency-off buttons, if present, should be evaluated at least annually.

#### *IV.C.2. System integrity*

A visual inspection of all camera settings should be performed to verify that they match the values from the time of commissioning (some cameras have zoom, focus or other settings that should be recorded to match those from the time of commissioning). If the cameras are in a location of heavy traffic or are switched on and off routinely or possibly adjusted this should be performed more frequently.

#### *IV.C.3. Camera stability*

For all systems that use a camera of any type, a camera drift and reproducibility should be performed (as described in the commissioning Sec. III B 2).

#### *IV.C.4. Extended system performance*

Checks should include comparison of actual and predicted shifts over a range of distances likely to be encountered clinically. These should be conducted at various couch angles to mimic patient treatments. Checks should also span various IR configuration geometries and minimum number of markers needed for redundancy. Additional to the localization test performed monthly, an end-to-end test on the entire process should be performed annually.

#### *IV.C.5. Positioning accuracy*

Patient positioning system should be tested to autocorrect for known displacements of the test phantom. Differences between actual and detected shifts in the three dimensions establish translational accuracy. Similar tests can also be performed for angular displacements if applicable.

#### *IV.C.6. Evaluation of gating or tracking capabilities*

For evaluation of gating functionality, a motion phantom should be used that can move at specific increments and the

system set to shut of the beam when the signal is out of range. This can be correlated with image guidance software as necessary to design a test that best matches the clinical practice. The goal is to determine if the patient motion management system interfaces with the linac to turn on and off the radiation beam at the appropriate time. Additionally, the radiation delivered under gated conditions should be checked for dosimetric accuracy on an annual bases following TG142 guidelines.

#### *IV.C.7. Data transfer*

If the system is connected to the treatment planning system or the record and verify system, the integrity of the data transfer should be evaluated annually using a test patient data set. Test sets should include at least two different I patient/device configurations [head first supine (HFS), head first prone (HFP), etc].

#### *IV.C.8. Vendor recommended tests*

Any additional annual tests recommended by the system vendor should be performed.

#### *IV.C.9. Documentation*

A record of the results of the annual QA should be created, signed by the physicist and kept either electronically or in a binder at the machine.

### IV.D. Patient specific QA

The proper transfer of data to the localization system from treatment planning and correlation of the data to the record and verify system should be checked by the physicist and therapist team prior to the start of any new patient. This should include patient identification, medical record number, coordinates of any implanted devices and/or the isocenter from the treatment plan, patient orientation and treatment site. If there is any concern about collisions due to unique beam and couch combinations with the use of the localization systems, these should be checked on a patient-by-patient basis.

### IV.E. QA in special situations

In case of special situations, ranging from software upgrades and power outages to earthquakes and building vibration due to construction, thorough testing is needed before the system can resume clinical use. The tests need to be appropriate for the situation. When in doubt, repeating the commissioning procedure is recommended.

### IV.F. Time planning

While each installation for add-on localization equipment is unique to the customer and their institutions' equipment, it

TABLE II. Recommended QA and frequency.

| Frequency | Test | Method | Accuracy |
|---|---|---|---|
| **Daily** | Safety | Check interlocks and clear field of view for all mounted cameras | Pass |
| | Static localization | Daily QA phantom positioned at isocenter and can track movement to isocenter from offset | 2 mm |
| **Monthly** (in addition to daily tests): | Safety | Machine interface: Gating termination, couch motion communication | Functional |
| | Static localization | Localization test based on radiographic analysis (i.e., hidden target) | 2 mm/(1 mm SRS/SBRT) |
| | Dynamic localization | Motion table or manual couch motion of monthly phantom by known distances | 2 mm or less if manufacturer spec. |
| **Annually** (in addition to all monthly tests) | Safety | Test/reset buttons, backup power supply, and emergency-off switches | Pass |
| | | System mounting brackets (all cameras are secure) | Pass |
| | Integrity | Check camera settings if available | Unchanged from previous |
| | Stability (drift/reproducibility) | Drift Measurement (over at least 1 hour) | <2 mm over one hour |
| | | Reproducibility (localization repeated several times) | <1 mm after stabilizing |
| | Static localization (extensive) | Full end-to-end tests (with data transfer check of localization accuracy, etc.) | <2 mm of isocenter (1mm SRS/SBRT) |
| | | Translation and rotation auto correct over a clinical range of motion | <2 mm of isocenter |
| | Dynamic (gating system) | Using a motion phantom / check of gating system radiation dosimetry accuracy. | <2% (per TG142) |
| | Data transfer | From all systems in use | Functional |
| **Commissioning:** (in addition to monthly and annual tests) | Safety (integration) | Communications with EMRs/other systems | Functional |
| | | Integration with Linac (radiation and interference) | <1 mm change in localization<br><1% change in expected dose |
| | | Field of view | Per system spec. |
| | Stability (drift/reproducibility) | Drift measurement (over at least 1 hour) | Establish warm-up time |
| | | Reproducibility (localization repeated several times) | <1 mm after stabilizing |
| | Dynamic localization | Latency test and update rates | Per spec. |

will be important to plan to allocate physics resources to perform the recommended quality assurance. In general, based on the level of expertise of the authors of this report, the physicist should plan on spending at least 2–3 h for the annual QA and approximately 1 h for each monthly QA. One must keep in mind that if the equipment is used for SRS or for SBRT, this may take longer to achieve the more stringent requirements. Also, if gating or other linac interfacing is involved, there are additional tests required which will add additional time. For the purposes of allocating resources or for more specific time planning, the task group would recommend discussing the particular configuration of the installation with the vendor to obtain a list of users with a similar configuration to get an estimate of the time required for the quality assurance process.

## V. CONCLUSIONS/RECOMMENDATIONS

Nonradiographic patient localization and positioning systems have become important components within the radiation therapy process. Quality assurance of these systems is essential, as only proper operation and use ensures that the intended dose distribution is indeed delivered. The QA procedures presented in this report are designed to address currently available systems and to provide insight to adapt to new systems as they become available to the radiation therapy community. It is recommended that these QA procedures be carried out at the frequency indicated in Table II and every time following the replacement of components, cameras, and computers in order to re-accept and recommission the system.

## VI. DISCLOSURES

Twyla Willoughby has accepted honoraria from BrainLab and from Calypso, and has in the past had research funded in part by Calypso Medical.

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