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Quality Assurance for kV and MV In-room Imaging and Localization for Off- and Online Setup Error Correction

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Abstract

In-room radiography is not a new concept for image guided radiation therapy (IGRT). The rapid advances of technology, however, have made this positioning method convenient, and thus radiograph-based positioning has propagated widely. The paradigms for quality assurance of radiograph-based positioning include imager performance, systems integration, infrastructure, procedure documentation and testing, and support for positioning strategy implementation.

Introduction

While a large variety of volumetric imaging systems have been introduced recently, the vast majority of current image guidance involves the use of radiographic imaging information to drive verification of treatment. While imaging technology is evolving, the general problems of radiographic use for localization have been extensively studied, and thus quite mature guidance is available for proper quality assurance of technology and procedure for in-room radiography.

Many of the issues associated with megavoltage imaging were addressed by the American Association of Physicists in Medicine. In the report of task group 58[1], the general problems of gantry-mounted megavoltage radiographic systems for setup verification were elucidated. The report predates the advent of active matrix flat panel imagers (AMFPIs), by far the dominant current acquisition system for kV and MV radiographs in treatment rooms. Furthermore, most of the concepts of data integration needed to smoothly support in-room localization did not exist at the time of its writing. Nonetheless, this report serves as a valuable reference, which details many of the quality assurance considerations that are still relevant and which will be expanded on here.

The general quality assurance paradigm for radiograph-based setup error correction can be broken down into the following components: equipment performance (image quality, dose), systems integration (accuracy, calibration), and process implementation (infrastructure and protocol development and implementation).

Equipment Performance

The components of a radiographic localization system include: an imager, imager mount, image processing and display software, image alignment tools, and connections with an image and patient record database.

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This paper will focus on flat panel imaging systems since other systems such as camera-mirror and liquid ion chamber imagers have previously been reported in considerable detail[2–4], and their prevalence is expected to diminish steadily over time. The unique and essential component of an AMFPI consists of a two-dimensional grid of imaging pixels, each of which comprises an amorphous silicon photodiode coupled to a thin-film transistor (TFT). The pixels are addressed and read out by means of two orthogonal sets of control lines that extend to contacts on the periphery of the glass substrate on which the array is fabricated[5].

There are two possible read out modes for these imaging systems: radiographic and fluoroscopic. Early MV AMFPI systems tended to produce images with groups of consecutive rows of pixels at slightly higher signal levels than nearby rows, an artifact commonly referred to as banding. Such banding can occur due to variation in linac output (during fluoroscopic operation) or variable gain in the preamplifiers that receive the pixel signals from the data line. Modern, more sophisticated systems should reduce or eliminate such effects through methods such as frame averaging and application of image processing corrections based on previously acquired dark and flood frames. The presence of banding in images could be indicative of unusual variations in linac output (for fluoroscopic acquisition), lack of synchronization between imager operation and beam delivery, or problems associated with image processing (for either mode).

Image Quality

While phantoms have been designed for portal imaging, the most common form, a contrast-detail phantom (e.g., the “las vegas” phantom)[1,6,7] was developed in an era in which imager sensitivity and artifacts limited usefulness of images in resolving anatomical features. The dramatic improvement in image quality provided by AMFPI systems has limited the usefulness of these early phantoms, and currently source size and contrast limits imposed by Compton scattering heavily influence the degree to which anatomy can be resolved for purposes of patient positioning. Other phantoms were developed around the concept of contrast-to-noise ratio (CNR), as well as high-contrast spatial resolution[8]. These phantoms may be more applicable to modern megavoltage imaging.

A major factor in image quality related to detection of implanted radiopaque markers with megavoltage AMFPI systems involves the frequency of pixel defects. Typically, AMFPI systems have a number of isolated pixels, pixel clusters, and even one or more lines of pixels that are either completely non-responsive, or do not otherwise respond in a normal manner to incident radiation. Some of these defects may be transient, while others are permanent. Generally, these pixel and line defects are identified through acquisition of flood and dark fields during routine quality assurance. Once identified (e.g. in a bad pixel map), the imager software will typically fill in information for bad pixels using either a neighboring pixel/line value, or an average of surrounding pixels. In either case, the major impact of large pixel cluster defects, or consecutive line defects will be increased difficulty in localizing small implanted fiducial markers. Knowing the fraction of bad pixels and their relative locations in the imaging field can help determine the impact on marker localization.

Diagnostic AMFPI imaging involves much higher subject contrast information, and thus more common radiographic image quality phantoms may be appropriate. At present, the demands for low contrast detectability in patient positioning probably do not match those of diagnostic radiology, although more advanced image analysis tools may increase demands on image quality. It is likely that the most demanding component of in-room radiographic use, in terms of image quality, is cone beam CT imaging, discussed elsewhere in this issue. A recent, multiple institution review of early users of one of the commercial diagnostic systems documents early

experience, with summaries of some of the key components of the systems for radiographic as well as tomographic image guidance[9].

Dose

In general, a modern AMFPI should permit MV radiography with 3 monitor units, or less. Averaging of multiple frames may be employed, with potential advantages of reduced noise and (in fluoroscopic mode) equalization of exposure, and thus background contrast, across an array. The cost of averaging is increased dose, as well as the potential for movement-related blur. *It is important to keep the purpose and value of the image in context, so that excess dose is not given to the patient in search of images that may be more aesthetically pleasing, and yet may not provide any added useful information for setup verification.*

The doses for radiographic localization using diagnostic x-rays are far lower than for MV imaging, and thus dose may be considered negligible by some users. However, it is important to not simply accept this fact and ignore imaging doses, since increased frequency of imaging, as well as potential developments in treatment monitoring through fluoroscopy, may result in very high (skin) doses over time. This point was recently addressed by AAPM task group 75 (report pending)[10]. It is recommended that techniques be established and related exposures measured at the time of commissioning a diagnostic radiographic localization or monitoring procedure.

Systems Integration

The usefulness of radiographic imaging in the setup verification process is highly dependent on the systems developed around the imager. The components that contribute to a typical system consist of an imager, control software, imager positioning system, possible source positioning system, image display and analysis software, and connections to patient information and treatment control systems.

The proper design and interaction of these systems need to be understood to develop a functional, and useful system for treatment verification. One example is related to the imager (and source) positioning systems. Room-mounted x-ray sources and detectors have the advantage of a fixed geometric relationship to isocenter. With these systems, relatively simple quality assurance checks can be performed to insure that this relationship is maintained. Gantry-mounted imaging (and X-ray) systems need arms to position the system in a state that projects through isocenter. Due to the weight of the gantry and subsystems, the position of the detector (and source) relative to isocenter may change as a function of gantry angle, and may or may not be reproducible on multiple positionings[11]. This variation needs to be explored upon acceptance and commissioning of a system. The next best thing to a system that maintains a perfect relation to isocenter is one in which the varying relationship is reproducible, characterized, and integrated into software so that it does not negatively impact the relative measurement of position in the treatment room. Geometric phantoms are typically used to establish the relationship of isocenter to its projection. In addition to absolute checks, relative checks (e.g. kV vs MV, anterior versus lateral projections) should be evaluated. In fact, an absolute check may be difficult, as standard quality assurance typically ensures that the lasers indicate isocenter to within 2 mm. A room with isocenter maintained to stereotactic specifications may have a mechanical “standard” for isocenter that has tighter specifications, and which may aid in imager calibration. Of note, the focal spot of a linear accelerator has also been shown to potentially move, thus further complicating positioning accuracy[12].

Software tools should include an infrastructure for proper image display and analysis. Image display tools may include enhancement. For megavoltage imaging, there is limited subject contrast between bone and soft tissue. Typically applied enhancement algorithms include edge

enhancement and histogram equalization. Excessive use of these methods may in fact obscure anatomy, due to the high noise content, structured noise/artifacts (e.g. from the treatment table, masks, etc.), and potential for excessive contrast enhancement (e.g. from adaptive histogram equalization) to confound the accuracy of subsequent position measurement[13].

Image analysis may include a series of measurement tools for estimating the distance of anatomic landmarks from the field edge or isocenter. The most critical infrastructure in this area is the availability of image alignment tools. The ability to align the reference model of the patient to the sampled anatomy from a portal or other localization radiograph is critical for efficient on-line or off-line setup verification. While numerous automated alignment tools have been investigated, such methods have generally only worked robustly for fixed anatomy or simplified surrogate anatomic features such as implanted markers. Overall, manual alignment tools such as template or image overlay matching, are very valuable to the infrastructure for position verification[3,14–22].

The process of verification involves two steps: establishment of the room coordinate system relative to the image(s), and establishment of the patient position relative to the same image (s), and thus, to isocenter. Routine quality assurance should maintain the known isocenter position, as well as ability to measure known offsets, in a simplified phantom. It is advisable to test this relationship at several gantry angles, especially those at which image alignment is routinely performed. The advance of complex treatments using multiple beam angles has made portal-based positioning very complex, and thus a very popular paradigm involves localization through a pair of orthogonal radiographs, (e.g. an anterior and lateral projection). For such localization, a treatment portal may not be available, and thus the relationship to isocenter may not have a ready secondary check provided by the shaped field border. One option is to expose the (megavoltage) images with a square or rectangular field of a known size. In this manner, the projection of the field borders may serve as a secondary check of the isocenteric coordinate system. Database integration is quite common with modern in-room imaging systems. The major issues are storage and labeling of images, and ability to archive information.

The chain of treatment verification

Outside of the equipment and tools available at the treatment unit, the overall process of patient positioning from simulation forward through treatment needs to be evaluated and optimized to permit efficient and accurate use of radiographic images for positioning and verification.

A very important step in the implementation of radiograph-based (or any other) image guidance is an end-to-end test. This process will permit debugging and documenting all steps from simulation through planning and treatment-based positioning. While mechanically engineered phantoms are useful for these tests, an anthropomorphic phantom may further elucidate factors such as patient size and image quality and their impact on protocols for positioning.

Positioning strategies

The paper by Yan et al in this issue delves deeply into the concept of adaptive therapy. This is a very powerful philosophy for managing the impact of variations on treatment. Prior to wide-scale adoptions of the concepts presented therein, simpler paradigms, such as on-line and off-line adjustment, can still lead to significant improvements in position. These paradigms require process implementation (and thus process QA), may not be completely supported by various software platforms, and have tradeoffs in accuracy versus effort that need to be explored.

On-line adjustment

The prevalent use of radiograph-based guidance is for on-line adjustment. Simply put, this involves acquiring radiographs, comparing them to reference information (radiographs, DRRs, reference anatomic templates, reference CT volumes for 2D–3D matching), and using the measurements from these comparisons to adjust the position of the patient immediately. On-line adjustment can be applied to all measurements, or with a threshold (i.e. adjustments will not be made for transformations below threshold values). The reasons for applying a threshold are twofold: 1) adjustments and potential subsequent verification may take time/dose, and 2) error in measurement and correction may, at some level, negate the benefit of adjustment in the first place. While theoretical studies have begun to elucidate this cost-benefit relationship, a practical threshold for current radiograph-based positioning is likely in the 2 to 3 mm range. This can be demonstrated by repeating the end-to-end test with an anthropomorphic phantom, and plotting the range of resulting position variations (image-based positioning versus an absolute reference marked on the phantom).

On-line adjustment reduces systematic as well as random error. If no threshold is applied, it is expected that the final error is a combination of errors in measurement and correction, as well as subsequent patient movement. While outside the scope of this paper, immobilization becomes a key concept in IGRT, and one that needs further exploration and optimization.

Off-line adjustment

Off-line adjustment is primarily aimed at reducing systematic errors. It is important to note that these errors arise not only from mechanical and calibration differences between CT scanners and linear accelerators, but from the random variation of patient position as well. This is easily seen by noting that the patient is typically not at his/her “average” position at simulation, as the random component of their position is sampled each time they are immobilized.

There are a number of off-line strategies. A common strategy is the no-action-level (NAL) strategy[23]. In this strategy, the average position after a small number (3–5) of fractions is corrected. It has been shown that the mean position of a patient can be estimated with reasonable accuracy after a small number of measurements, for a majority of patients. It is important, however, to have some check, even with reduced frequency, in place to catch outlying patients. In addition, a less accurate estimation of random error can be made in the first 3 to 5 measurements. If random error is unexpectedly large, then a decision can be made to switch to on-line localization on a case-by-case basis. It is especially in these instances that a more global philosophy guiding imaging and adjustment decisions is needed, and where adaptive strategies have significant advantages.

Implementation of off-line strategies is very cumbersome with existing software platforms. Very few information systems permit tracking of position over multiple fractions and combining this information, and thus outside tools such as custom software, spreadsheets, and hand-entered forms are used. This challenge requires significant attention be paid to process quality assurance, and represents an area in which significant infrastructure changes should occur in the future.

QA guidelines

While specific guidelines are beyond the scope of this paper, a few brief summary points can be made. The QA program for radiograph-based positioning (kV and MV) should include the following:

1. Commissioning/acceptance tests:
  - a. Image quality and dose
  - b. Imager positioning accuracy and reproducibility
  - c. Safety systems (e.g. collision interlocks)
  - d. Software tools for image display, analysis, archival, and review
  - e. End-to-end test of positioning
  - f. Documentation of processes for use (SOPs)
2. Routine quality assurance
  - a. Image quality, especially extent of masked bad pixels/lines
  - b. Accuracy (distance to agreement) of isocenter
3. Positioning strategies
  - a. Departmental review of protocols and training
  - b. Development of ancillary tools for documenting protocol-based positioning (e.g., forms, spreadsheets)
  - c. Periodic review of frequencies of adjustments, accuracies of resulting positions, and guidance for future patient/protocol selection

Summary

Radiograph-based image guidance has gone through a rapid period of expansion after nearly 2 decades of slow development. This has been fueled by dramatic improvements in image quality and software infrastructure. The quality assurance paradigms for this IGRT implementation, while reasonable in some areas, have otherwise been ill-defined (e.g. process QA for positioning strategies) or outpaced by technology (e.g. image quality for MV radiography). The development of end-to-end tests, as well as the involvement of a broad cross section of staff involved in these procedures, especially for initial process development, documentation, and feedback, is crucial to safe and effective implementation of radiograph-based positioning. While small, dosimetric issues from using these systems cannot be ignored.

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