11-1-2015

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Recommended Citation

Jones AK, Heintz P, Geiser W, Goldman L, Jerjian K, Martin M, Peck D, Pfeiffer D, Ranger N, and Yorkston J. Ongoing quality control in digital radiography: Report of aapm imaging physics committee task group 151. Med Phys 2015; 42(11):6658.

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Ongoing quality control in digital radiography: Report of AAPM Imaging Physics Committee Task Group 151

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Quality control (QC) in medical imaging is an ongoing process and not just a series of infrequent evaluations of medical imaging equipment. The QC process involves designing and implementing a QC program, collecting and analyzing data, investigating results that are outside the acceptance levels for the QC program, and taking corrective action to bring these results back to an acceptable level. The QC process involves key personnel in the imaging department, including the radiologist, radiologic technologist, and the qualified medical physicist (QMP). The QMP performs detailed equipment evaluations and helps with oversight of the QC program, the radiologic technologist is responsible for the day-to-day operation of the QC program. The continued need for ongoing QC in digital radiography has been highlighted in the scientific literature. The charge of this task group was to recommend consistency tests designed to be performed by a medical physicist or a radiologic technologist under the direction of a medical physicist to identify problems with an imaging system that need further evaluation by a medical physicist, including a fault tree to define actions that need to be taken when certain fault conditions are identified. The focus of this final report is the ongoing QC process, including rejected image analysis, exposure analysis, and artifact identification. These QC tasks are vital for the optimal operation of a department performing digital radiography. © 2015 American Association of Physicists in Medicine. [http://dx.doi.org/10.1118/1.4932623]

Key words: quality control, digital radiography, repeat analysis, exposure analysis

1. INTRODUCTION

The American Society for Quality defines Quality Assurance (QA) and Quality Control (QC) as follows:[1]

Quality Assurance: "The planned and systematic activities implemented in a quality system so that quality requirements for a product or service will be fulfilled."

Quality Control: "The observation techniques and activities used to fulfill requirements for quality."

These definitions indicate that quality assurance is a proactive process that seeks to prevent defects in products or deliverables, e.g., medical images, while quality control is a reactive process that seeks to identify defects in products or

deliverables. The major focus of this report is quality control in medical imaging, that is, examining the deliverable, the medical image, and the process used to create it for deficiencies.

QC in medical imaging is often viewed as a series of regular (often annual), detailed evaluations of a piece of medical imaging equipment by a qualified medical physicist (QMP). However, QC should be viewed as an ongoing process that occurs on an image-by-image basis. The QC process involves key personnel in the imaging department, including the radiologist, radiologic technologist, and QMP. The radiologist administers and oversees the QC program, which is carried out by the radiologic technologist. The QMP consults with the radiologist in the design and implementation of the QC program, works with the technologist to triage problems, and carefully evaluates the imaging equipment on a regular basis for proper calibration, function, and compliance with applicable regulations.

Ongoing QC was inherent in the screen-film imaging workflow, where rejected image rates were calculated by counting rejected films. Improperly exposed films resulted in images that were too dark or light and were repeated out of necessity, and the rejected films counted. During the early years of the shift to digital imaging in radiography, ongoing QC was largely abandoned, owing to both a perceived lack of need and difficulty in performing ongoing QC with early digital imaging systems, which lacked standardized exposure indicators and tools for counting rejected images.

The initial work of this task group included reviewing historical data from QC programs offered by equipment manufacturers and other historical QC data, as well as performing specific QC tests on a frequent basis. Task Group 151 also worked closely with Task Group 150, whose charge was to outline a set of tests to be used in the acceptance testing and quality control of digital radiographic imaging systems, to design tests and avoid overlap in our efforts. No key *equipment performance characteristics* that varied on a time scale short enough to warrant ongoing testing by a radiologic technologist under the supervision of a QMP were identified by TG-151. However, it was noted that key *aspects of a QC program* were often lacking in imaging departments and in published recommendations and practice guidelines.

Therefore, the focus of this final report is the ongoing QC process, including rejected image analysis, exposure analysis, and artifact identification. These QC tasks are vital for the optimal operation of a department performing digital radiography.

2. REJECTED IMAGE ANALYSIS

Repeated and rejected images represent both unnecessary radiation exposure to patients and inefficiency in the imaging operation owing to wasted time and resources. Rejected images are inherent to projection radiography, where patient positioning and alignment are integral components of image quality. With screen-film imaging systems, the relatively narrow exposure latitude available for creating a clinically useful image sometimes necessitates repeated images owing to under- or overexposure of the film. Patient motion, positioning, and

artifacts unique to the image receptor technology can result in repeated images as well. Therefore, repeat/reject analysis is an integral part of a QA program for radiography. Repeat/reject analysis is mandated by the United States government for mammography[2] and is recommended for projection radiography by multiple organizations and accrediting bodies.[3–5]

In screen-film imaging departments, a Reject Analysis Program (RAP) relies on the physical collection of rejected images in containers, the contents of which are periodically sorted by reason for rejection and normalized by the total number of films consumed during the period to determine reject rates.[6] This system is often complicated by the time-consuming task of determining reasons for rejection "after the fact" and determining the total number of films consumed.[7]

During early clinical experience with digital radiography (DR), it was proposed that this new technology might eliminate rejected images and render any RAP obsolete.[8] However, imaging departments quickly realized that this was not the case[9] and that a RAP was still a vital part of a QA program. In fact, DR has made rejected image analysis more complicated, and ironically, may facilitate the repetition of images owing to the ease of acquisition, especially with cassette-less systems where no manual intervention occurs between receptor exposure and image readout. Physical evidence of rejected images no longer exists for tallying, and on many early digital imaging systems, radiographers can simply delete unwanted images, which are ultimately never accounted for.[9,10] Even if deletion is not an option, rejected images often simply reside in the system until they are removed to free space for more images.

2.A. The continued need for rejected image analysis

The adoption of digital imaging, and specifically soft-copy interpretation, has forced radiology departments to develop innovative RAP. Early methods used for RAP included manual collection of data from acquisition stations,[11,12] manual tagging of rejected images by a QC radiologic technologist (RT),[10] manipulation of examination and demographic information in rejected images along with the use of routing tables to segregate rejected images,[9] and extraction of information from the Digital Imaging and Communications in Medicine (DICOM) header.[13] Most of these methods involved manual collection of data and were subject to similar problems, including lack of RT compliance,[9–11] intentional circumvention of the program,[10] accidental deletion of data,[12] and false negative or false positive results.[13] Recently, several studies have described sophisticated server-based RAPs that automatically collect, parse, and analyze data from many different acquisition systems spread throughout an institution.[14–17] This type of RAP avoids many of the difficulties associated with manual data collection and analysis.

It is likely that a number of causes have contributed to the demise of rejected image analysis in digital imaging departments, including a reduction in the number of images rejected owing to exposure errors, abandonment of programs owing to a perceived lack of need in digital imaging, the lack of physical evidence for collection, and the general difficulty of performing rejected image analysis on digital imaging systems,

especially in high-volume departments. Whatever the reason for the abandonment of rejected image analysis, many authors have made clear the continued need for rejected image analysis programs.[9,14–16] Consider the fact that 281 000 000 projection x-ray examinations were performed in 2006 (Ref. 18) in the United States. These exams accounted for 73% of all radiographic and nuclear medicine procedures, excluding dental, and 11% of the total medical exposure to the U.S. population. Assuming conservatively a reject rate of 8%,[10–12,14,16,19] it is clear that repeated images are a large contributor to, and perhaps the number one cause of, undue patient exposure in projection radiography. A study of repeat rates among 18 radiology departments determined that 14% of patient exposure in projection radiography was due to repeated images.[19] These concerns are in line with the as low as reasonably achievable (ALARA) principle and are especially relevant in light of recent initiatives in the medical imaging community, including pay for performance,[20,21] image gently,[22] and image wisely.

2.B. Performing rejected image analysis

In digital radiography, the rejected image rate in its simplest form can be calculated as the ratio of the number of rejected images to the total number of images acquired. In screen-film imaging departments, the rejected image rate also includes wasted films,[23] which contribute to increased costs but not to increased patient exposure, the focus of this report. It is important to note that it may not be possible to identify and track images that are repeated but not rejected.

2.B.1. Rejected image analysis in screen-film departments

Radiology departments using screen-film receptors should abide by all of the recommendations outlined in this report, keeping in mind that thresholds for corrective action may require adjustment owing to the increased probability of exposure errors when using screen-film image receptors.

2.B.2. Data collection

Data should be collected daily if accessible remotely, otherwise it should be collected on a monthly basis to prevent accidental loss.

2.B.3. Data analysis

A RAP can be a powerful tool for practice improvement and QC, but only if the maximum amount of useful information is extracted from the available data. Simply calculating the overall rejected image rate is likely to be insufficient for identifying and correcting practice problems. After calculation of the overall rejected image rate, the data should be stratified by body part and view, clinical area, and technologist. Stratification of the data will allow for identification and correction of practice problems, including problematic views or struggling technologists. The ability to stratify rejected image rates into these categories would require the stratification of examination

totals, which is discussed in more detail later in this report. Collected data should be analyzed on at least a quarterly basis, but preferably on a monthly basis. Corrective action, when taken, should be documented as part of the rejected image analysis program. It is suggested that limits for corrective action be both positive and negative, e.g., for a target rate of 10%, investigation and possible corrective action would be triggered at ±2%, i.e., for a rate less than 8% or greater than 12%. This strategy considers the fact that abnormally low rejected image rates can signal poor compliance with the analysis program or acceptance of poor quality images.

2.B.4. Corrective action

Corrective action should be taken when rejected image rates fall outside predetermined thresholds, which should be set by the administrator of the program in conjunction with a radiologist and the QC technologist. It is important to realize that rejected image rates will vary based on practice and setting. Differences in rejected image rates of a factor of three have been demonstrated between different types of hospitals.[24] One would expect a lower rejected image rate for a commonly performed view such as a PA chest as compared to a seldom-performed, technically challenging view such as facial bones, and this has been demonstrated.[14,16] The presence of trainees will also impact the rejected image rate. All of these factors must be considered when determining thresholds for corrective action.

A review of the literature revealed that repeated image rates hovered around 10% in screen-film departments, with approximately 45% of images repeated owing to exposure errors, which are expected to be greatly reduced in digital imaging.[9,11,12,23,25–27] Rejected image rates in digital departments have been reported to range from 4% to 8%.[10–12,14,16] Therefore, this task group recommends that 8% be used as a target for overall rejected image rate, and 10% as a threshold for investigation and possible corrective action. As mentioned previously, this rate should be adjusted to reflect the operator's clinical practice. Repeated image rates in pediatric imaging departments have been reported to be approximately 3%–5%,[7,9] and the task group recommends that a target of 5% be used in pediatric imaging, and 7% as a threshold for investigation and possible corrective action. When rejected image rates are stratified—for example, by technologist, view, or clinical area—the threshold for investigation and potential corrective action should be determined based on clinical practice. For example, target rates for trainees may be set higher than those for staff, or target rates for an area performing only chest radiography may be set lower than an area performing a variety of views.

The task group also recommends the adoption of a lower threshold rejected image rate for investigation and potential corrective action. An unusually low rejected image rate can signal poor compliance with the analysis program or acceptance of images with marginal or poor image quality. It has been proposed that there is a baseline repeat rate of 5%, below which radiographic quality is sacrificed and further reduction is not cost-effective.[9] This baseline number may be lower in digital radiography, as several authors have found rejected image rates of less than 3% in certain clinical areas.[11,14,16] As with the upper threshold for investigation and potential corrective action, the lower threshold should be set considering clinical practice, as some views or clinical areas may be characterized by lower than typical rejected image rates. The task group recommends that a lower threshold of 5% be used as a threshold for investigation and possible corrective action unless clinical data indicate this threshold should be lower.

2.B.5. Record keeping

Rejected image rates, including stratified rates, if applicable, should be analyzed and documented at least quarterly, but preferably monthly, and kept for the greater period of one year or the length of time required by applicable regulatory agencies. Also, any corrective action taken in response to abnormally low or high rejected image rates should be documented, along with the results of the corrective action.

2.B.6. Standardized reasons for rejection

Standardized reasons for rejection should be included in all RAP programs, and the option to add additional user-specified reasons should also be available. Standardized reasons for rejection should include the following:

1. Positioning
2. Exposure error
3. Grid error
4. System error
5. Artifact
6. Patient motion
7. Test images
8. Study canceled
9. Other

Also helpful would be the ability to subdivide the reasons listed above. As an example, suggested subdivisions of the standardized reasons are listed below.

1. Positioning
   a. Rotation
   b. Anatomy cutoff
   c. Incorrect projection
   d. Incorrect marker
2. Exposure error
   a. Overexposure
   b. Underexposure
3. Grid error
   a. Cutoff
   b. Decentering
   c. No grid
   d. Grid lines
4. System error
5. Artifact
   a. Detector
   b. Foreign object (jewelry, clothing, etc.)

c. Contrast media
d. Table/support/x-ray tube
6. Patient motion
7. Test images
8. Study canceled
9. Other

2.B.7. Collection and storage of data

Collecting certain data and demographic information is necessary for a RAP to be useful. Table I lists data that are required for a functional RAP ("required") and data that would make a RAP simpler and more useful ("optional"). For example, a technologist can be linked to a study via the accession number, but this requires that data from the radiology information system (RIS) be incorporated into the program, making the process more complex. A system that requires a technologist to log in or enter an ID before beginning a study, and links this information to that study, would be simpler.

Data should be stored locally in hard disk memory until downloaded by the program administrator, at which time it can be deleted. Data should be collected daily if accessible remotely, otherwise it should be collected on a monthly basis to prevent accidental loss. Also, data should be downloaded prior to any equipment service event to prevent its loss.

The calculation of rejected image rates also requires a denominator equal to the total number of images acquired during the analysis period. Ideally, this information would also be available on the acquisition station and would not require the information to be retrieved from the RIS. The ability to stratify the number of acquired images by body part and view would make the information more useful for rejected image analysis.

2.B.7.a. Other useful information. The inclusion of additional information not required in Sec. 2.B.7 is encouraged. Examples of additional information include examination of technical factors or downsized copies of rejected images stored in the local database. These images could be compared with the reason for rejection as a quality control measure on the rejected image analysis data. This feature itself could be further enhanced by the inclusion of the reason for rejection either as an overlay or burned into the pixel data. Such additional information adds value to the RAP and may be useful as an educational tool.

2.C. Access to data

After collection of data, the administrator of the RAP must be provided with access to the stored data. The data should be retrievable from the database in a suitably delimited, cross-platform format such as comma separated value (CSV) or extensible markup language (XML). In addition, the administrator should be able to select data from a specified date range for download or export. Implementation and administration of large-scale RAPs is very difficult if the only means to download data is external storage, e.g., CD or USB memory. Therefore, the task group strongly recommends that these data also be accessible remotely through hospital networks. This can be accomplished in several ways, including using file transfer protocol (FTP), shared folders, or digital dashboards.[28] Storing and providing data in this manner would facilitate server-based systems that collect, archive, and analyze RAP data from many different systems. This feature will be especially vital to participants in efforts such as the American College of Radiology's General Radiology Improvement Database,[29] which includes rejected image rates as one of its metrics. Information security and patient privacy must be carefully considered when making such data available over hospital networks. Information that is not accessible over hospital networks should be downloadable to USB or CD memory.

2.D. DICOM

It would be advantageous to use or modify an existing DICOM structure to accomplish the goals outlined in this report. It has previously been suggested that DICOM should be preferred owing to its wider acceptance by vendors.[30]

TABLE I. Data stored for rejected image analysis.

Field	Function	Required/optional
Acquisition station/digitizer	Can identify specific stations with problems	Required
Accession number	Links study to technologist through RIS	Required
Exam date and time	Allows temporal sorting of data	Required
Body part	Allows sorting of data by body part	Required
View	Allows sorting of data by view	Required
Exposure indicators (EI)[a]	Allows exposure analysis/troubleshooting	Required
Reject category	Allows reject analysis	Required
Technologist ID	Alternative method of linking technologist and study	Required[b]
Reject comments	Further clarifies reason for rejection–free field	Optional
Technologist name	Allows sorting of data by technologist name	Optional
Technique factors	Troubleshooting	Optional
Thumbnail image	QC of reason for rejection	Optional

[a]The target EI and DI should also be included, if available.
[b]Optional if separate user names are provided for each technologist who uses the system.

Two intriguing possibilities exist within DICOM: modality performed procedure step (MPPS) and the structured report (SR).

2.D.1. MPPS

MPPS involves the transfer of information between a modality and another system, such as the RIS.[31] Typically, this transfer happens at the beginning and the end of a procedure, but it may also occur after each image instance is created. Information passed may include patient demographics and information about events that occurred during the procedure. Fields for additional information such as radiation dose exist currently in the MPPS report. Data for rejected image analysis could be included by altering the MPPS report to include fields for the total number of images acquired, the number of images transferred to picture archiving and communications system (PACS)/permanent storage, and the body part and view for each image acquired. This information would be sent to RIS or another selected system upon the conclusion of the study. The information could be extracted from RIS and analyzed, or analyzed in RIS, depending on the level of sophistication of the RIS. MPPS may not be ideal as a vehicle for rejected image analysis, however, owing to its lack of widespread use and difficulty in achieving system-wide integration.

2.D.2. DICOM SR

Radiation dose information generated during computed tomography[32] and fluoroscopy[33] procedures has been incorporated into a DICOM SR. A SR could be used to log and store information essential to the performance of rejected image analysis. For example, an instance could be created for each image acquisition, and would include information such as body part, view, and image archival status at the conclusion of the study. In addition, the SR would contain data on both archived and rejected images. The format of the SR could be designed to make extraction of useful information as simple as possible. It is likely that analysis software would be developed that would facilitate analysis of the data, and that current RIS vendors would adapt their systems to include features for analyzing rejected image data, if a rejected image analysis SR was defined.

3. EXPOSURE ANALYSIS

The end goal of any projection radiography study is to produce an image that is suitable for interpretation by a radiologist, i.e., a *diagnostic* image. A diagnostic image must necessarily possess several qualities, including proper patient positioning, a lack of significant artifacts, and the appropriate exposure to the image receptor. The European Commission has published guidelines on what constitutes a quality projection radiograph.[34] Achieving the appropriate exposure to the image receptor is quite challenging in screen-film imaging. Patients span a wide range of sizes and shapes, and film has narrow exposure latitude within which adequate contrast can be gener-

ated. A film provides immediate feedback about the nature of the exposure—a dark film indicates an overexposure, while a light film indicates an underexposure. A film that is sufficiently under- or overexposed lacks contrast and must be repeated, and appropriate corrective action can be taken based on the appearance of the film.

Digital radiography, on the other hand, provides both benefits and drawbacks for patient dose and image quality, particularly related to image receptor exposure. The much wider dynamic range of digital image receptors is more forgiving of exposure errors, and images can be produced with a wide range of receptor exposures, spanning three to four orders of magnitude. Lack of attention to this wide dynamic range gives rise to a phenomenon known as *dose creep*.[35,36] Because the final grayscale appearance of a digital image bears little relationship to the exposure delivered to the image receptor, overexposed images are difficult to identify and, in fact, are more pleasing to radiologists owing to reduced noise levels compared to properly exposed images. *Exposure indicators* (EI)[37–39] were introduced in an attempt to combat dose creep and reverse the trend. An EI provides feedback to the operator about the exposure used to create the image and, in some cases, how the receptor exposure relates to the target exposure. If displayed on a PACS or overlaid on a printed film, the EI provides feedback to the radiologist and facilitates radiologist oversight. The EI is also indirectly related to patient dose.

3.A. Assessing patient dose in digital radiography

From a QC perspective, radiation dose resulting from radiographic imaging can be considered in one of several different ways. Routine quality control tests performed on an annual basis—such as measuring x-ray output, half value layer (HVL), and assessing automatic exposure control (AEC) calibration—provide some information that relates to patient dose. However, these tests provide no information about typical or actual patient doses.

A second way to gather information about patient dose is to measure patient doses for specific examinations. Phantoms representing specific body parts, specific patient sizes, and specific radiographic projections are available for this purpose.[40–43] These phantoms can be used to perform measurements in standard geometries[40] under AEC or using manual exposures. Quantities of interest include the incident air kerma ($K_{a,i}$) and the air kerma-area product (P_{KA}).[44] Drawbacks, including the fact that such phantoms are bulky, may not accurately represent a "normal" patient considering the increase in average patient size in the United States,[45] and that the number of patient body parts, sizes, and radiographic views represented by existing phantoms cover only a small fraction of the possible combinations. Patient doses resulting from manual exposures can be calculated for any size patient based on known technical factors, including kVp, mAs, any added filtration, and source-to-image distance (SID) using measured data, including x-ray output, as a function of kVp and the HVL. These dose metrics can also be used to estimate effective dose (E) through the application of conversion factors[46–48] or by using commercially available software such as pcxmc, a Monte

Carlo program for calculating patient doses in medical x-ray examinations.[49]

While measuring or calculating "typical" doses on a regular basis is useful, one might be more interested in examining actual patient doses throughout the year so corrective action can be taken quickly when problems are identified. However, frequent use of the techniques discussed thus far is not practical, as a QMP (Ref. 50), whose expertise is required to make such measurements, may not always be available. The advent of digital radiography initiated a rapid increase in the amount of information available that is related to an imaging study. The National Electrical Manufacturers Association (NEMA) and American College of Radiology (ACR) DICOM standard has been the driving force in the availability and standardization of much of this information, and the International Electrotechnical Commission (IEC) and the American Association of Physicists in Medicine (AAPM) have also played major roles in this effort. Several metrics can be used to perform ongoing exposure analysis in projection radiography, and these are discussed in Secs. 3.A.1–3.A.3.

3.A.1. The EI

An EI for digital radiography has been described independently by the IEC (Ref. 39) and AAPM Task Group 116.[37,38] Details regarding the implementation of each EI can be found in the respective references. The IEC implementation of the EI is the one most likely to be adopted by manufacturers of digital radiography equipment. Therefore, this report will use the IEC definition of the exposure indicator throughout.

The EI is widely available and is in the process of being standardized as vendors implement the IEC standard. With this standardization, meaningful comparisons can be made between different equipment, including equipment from different manufacturers. Although the EI describes the dose to the image receptor, which is only indirectly related to patient dose, meaningful QC can still be performed despite this limitation.[16,52,53]

The EI provides an indication of the exposure to the image receptor and a deviation index (DI) that compares the indicated receptor exposure to the target exposure. This allows radiologic technologists to make adjustments to technical factors for repeated images, and it will also allow for determination of the approximate image receptor dose for each radiograph. While the relationship of receptor dose to patient dose depends strongly on kVp, patient size, x-ray field size, and other factors, the DI will indicate the appropriateness of the receptor dose and, therefore, can be used to identify dose creep. This use of the DI for this purpose requires that the target exposure is both known and appropriate for the examination. DICOM correction item 1024 contains specifications for the "Exposure Index Macro" to be included in the DICOM header of digital radiography images.[51]

3.A.2. DICOM dose information

The DICOM radiation dose information module,[54] which is part of the DICOM header, contains data that can be used to estimate the patient dose resulting from a projection radiograph. The availability of this information may vary from vendor to vendor, and perhaps vary even within the same product line or different software versions from the same vendor. The configuration of the radiographic equipment also impacts the availability of such information. For example, a digital radiography system in which the generator is fully integrated with the imaging system will be capable of populating certain fields in the radiation dose information module related to the technical factors used, while a cassette-based computed radiography system in which the generator and other x-ray-producing equipment are completely separate from the imaging system will be incapable of automatically populating the same fields.

3.A.2.a. Entrance dose. The "Entrance Dose" [tag (0040,0302)] or "Entrance Dose in mGy" [tag (0040,8302)], as specified in the DICOM radiation dose module,[54] refers to the air kerma at a fixed location resulting from a radiographic exposure. While this value is more closely related to patient dose than the EI, sources of inaccuracy remain, primarily in determining the location of the entrance surface of the patient with respect to the location at which these metrics are reported. The incident air kerma ($K_{a,i}$) decreases with the inverse square of the distance between the focal spot and the entrance surface of the patient. If the fixed location used to report the $K_{a,i}$ is located at the entrance surface of the patient, this quantity may represent patient exposure. However, to the extent that the entrance surface of the patient deviates from the fixed location at which the $K_{a,i}$ is reported, the estimate will be inaccurate. In addition, the $K_{a,i}$ does not completely describe the radiation dose to the patient because changes in the x-ray field size also cause variations in the radiation dose delivered to the patient, even for the same $K_{a,i}$.

3.A.2.b. Kerma-area product (KAP). The "Image and Fluoroscopy Area Dose Product" [tag (0018,115E)], as specified in the DICOM radiation dose module,[54] refers to the product of the x-ray field size and the air kerma. This quantity is more commonly referred to as the dose area product (DAP), KAP, or air kerma-area product (P_{KA}).[44] This tag can be populated with either a calculated value of P_{KA} or a measured value of P_{KA}. A P_{KA} meter can be installed on the collimator of most radiographic systems to facilitate measurement of the P_{KA}. The P_{KA} meter will report measured P_{KA} values, but the inclusion of these values in the DICOM radiation dose information module still depends on the system architecture, as discussed in Sec. 3.A.2. P_{KA} can also be calculated by multiplying the measured or calculated air kerma at some point along the central ray by the measured or calculated x-ray field size at the same point. P_{KA} is a desirable quantity for ongoing exposure analysis for several reasons. First, P_{KA} is invariant along the x-ray source-image receptor axis, therefore the P_{KA} is known at the precise location of the entrance surface of the patient. Second, the P_{KA} accounts for all factors influencing the amount of radiation striking a patient during a projection radiography examination—namely, the output from the x-ray tube and the size of the x-ray field. For these reasons, P_{KA} is the most desirable quantity for performing ongoing exposure analysis, as problems with both the equipment, such as low HVL or poor AEC calibration, and practice, such as improper

collimation, can be identified and corrected. The effective dose (E) can also be calculated from the P_{KA} using published conversion factors.[47,48] Therefore, P_{KA}, if available, is the preferred quantity for performing ongoing exposure analysis.

3.A.2.c. The DICOM SR. Radiation dose information generated during computed tomography[32] and radiography/fluoroscopy[33] procedures has been incorporated into a DICOM radiation dose structured report (RDSR). The RDSR contains information that is useful for ongoing exposure analysis, including dosimetric quantities for both individual performed procedure steps as well as totals for an entire study. Ideally, the RDSR would be modified to include dose information for rejected or repeated images. A detailed description of the information contained in the DICOM RDSR can be found in DICOM Supplement 94.[33]

3.A.3. Other sources of data

If none of the aforementioned data are available, other strategies can be used in an attempt to track patient exposures. One such strategy is to collect the technical factors used to acquire radiographic images, including kVp, mAs, and source-to-patient distance. The $K_{a,i}$ can be estimated from the technical factors used to acquire a radiograph by using a lookup table (LUT) created for each radiographic system using measured output values. Also, some manufacturers may display certain dosimetric quantities, some of which may be proprietary, on the acquisition workstation. A QMP can help in determining which of these quantities may be useful for ongoing exposure analysis.

3.B. Collecting dose information

The method(s) used to collect data for analysis will vary in complexity based on the end user. A small facility with a single radiographic system may choose to manually record dose information in a paper or electronic log, while large institutions distributed over several sites separated by long distances may choose to use a separate server to extract and archive dose information. Methods for collecting information are outlined in Secs. 3.B.1–3.B.6.

3.B.1. Manual collection and recording of data

Manual collection of data is likely the most efficient method for a single site with few radiographic systems and no RIS. The radiologic technologist performing an imaging study can record selected dose metrics in a paper or electronic log at the imaging station. Manufacturers may display dose metrics other than the EI at the acquisition station. This facilitates manual collection of dose information by a radiologic technologist.

3.B.2. Modality performed procedure step

Fields for radiation dose information exist currently in the MPPS report in a structure similar to the radiation dose information module. Data for exposure analysis are, therefore, already included in the MPPS report, and this information can be sent to the RIS or another network node upon the conclusion of the study. MPPS would be more useful for ongoing exposure analysis if dose information for rejected or repeated images was included in the MPPS data. MPPS may not be ideal as a vehicle for exposure analysis, however, owing to limited deployment, lack of widespread use, and difficulty in achieving system-wide integration.

3.B.3. Use of the RIS to extract and archive data

If the DICOM RDSR is available, it can be sent directly to a server where dose data can be extracted, archived to a database, and sent to RIS via HL7. If MPPS is used to transfer dose information, such information can be sent to the RIS. The information could be extracted from the RIS, parsed, and analyzed, or it could be analyzed in the RIS, depending on the level of sophistication of the RIS. The RIS can also be used to assist in manual collection of exposure analysis data. Technologists may enter relevant data into designated fields within the RIS, where it will be stored in a database, facilitating extraction and analysis of data. However, manual data entry is not preferred, as it is prone to errors.

3.B.4. Use of a separate server to extract and archive data

As an alternative to the use of a RIS to extract and archive dose information, a separate server can be configured as a network node on the hospital network. A DICOM storage process can be started on the server so that image data or radiation dose reports can be received from other DICOM network nodes. Image data can be sent in parallel to both the server and other necessary network nodes. Dose information can be extracted, parsed, and archived to a database on the server.

3.B.5. Use of a commercial dose aggregation system

Recently, a number of commercial dose aggregation systems have been introduced to the market. These systems use one or more of the strategies discussed in this section. For example, they can be configured as a DICOM network node to which dose information, including secondary capture images or RDSR, can be archived and subsequently processed. Alternatively, DICOM query/retrieve can be used to download these same data that have been archived on a PACS system.

3.B.6. Other methods

Manufacturers of radiographic equipment may provide alternative methods for extracting dose information. Most commonly, EI are recorded in a database for each exposure instance. These data can then be downloaded to external memory such as CD or flash memory for analysis.[16]

If manufacturers of radiographic equipment implement the radiation dose report, it is likely that analysis software would be developed that would facilitate analysis of the data, and

that current RIS vendors would adapt their systems to include features for exposure analysis.

3.C. Analysis of dose data and corrective action

Data collected as part of an ongoing exposure analysis program can be analyzed in many ways. Reference levels for specific radiographic views have been published,[34,55] and National Council on Radiation Protection Report 174 provides updated reference levels and achievable levels for specific radiographic views.[56] Also, some states have set upper limits on patient exposure for certain radiographic views.[57] However, if these limits are based on very specific patient dimensions, they may not be useful for ongoing exposure analysis. The National Evaluation of X-ray Trends (NEXT) through the FDA Center for Devices and Radiological Health (CDRH) collects and publishes information about doses for specific procedures on an annual basis.[58]

Median dose metrics should be compared to achievable levels when available. Comparisons of other descriptive statistical parameters can be made to normative datasets as they are published. Also, exposure data can be analyzed with control charts to identify special-cause variation, and the root causes of these instances can be investigated, documented, and corrective action taken, if necessary. Any cases exceeding diagnostic reference levels should be investigated, and the findings and any corrective action taken should be documented.

Stratification of exposure analysis data will likely provide additional information that is useful for quality control and quality improvement. Variations in patient exposures for the same body part and view may occur between technologists, radiographic equipment, or clinical area. Equipment or practice problems can be identified early, before they lead to the formation of habits. It was recently demonstrated that technologists adjusted their manual techniques over time in response to equipment that was poorly calibrated.[16] Also, specific technologists or certain radiographic views may be problematic, and additional training can be offered to improve patient care and operational efficiency.

This task group recommends that exposure analysis information be stratified by technologist, body part and view, and equipment or room so that maximum benefit can be derived from the data. Stratification by body part and view will also allow for comparison of exposure data to reference levels and regulatory limits. When stratifying data by body part and view, care must be taken to ensure that technologists are selecting the correct body part and view within the protocol selection interface. This task group recommends that exposure analysis data be analyzed monthly, and at a minimum quarterly. Longer intervals between data analysis provide more opportunity for patients to be overexposed and habits to be formed by technologists. Data should be maintained for the longer of a period of one year or that required by applicable regulatory agencies. Exposure data should be reviewed longitudinally over time to identify and correct dose creep if it is occurring. This task group recommends that one year's worth of data be viewed at a time, with the most recent month or quarter replacing the oldest month or quarter.

3.C.1. Corrective action

Corrective action may be required if patient doses exceed reference or regulatory levels, or if certain technologists or equipment consistently deliver higher doses to patients for the same body part and view. Any corrective action taken, and the results of the corrective action, should be documented.

3.D. Quality control of dose metrics

Periodic QC should be performed on the dose metric(s) chosen for ongoing exposure analysis. The type of QC performed will depend on the chosen dose metric(s). For example, if an external KAP meter is used, the calibration of the meter should be verified on a routine basis by a QMP. Similarly, if a calculated P_{KA} or entrance dose is used, this should be verified periodically. Finally, if the EI is used, its calibration should be verified periodically. Addressing these calibrations and QC methods is beyond the scope of this document. Guidelines for verifying the EI have been published by AAPM Task Group 116 (Refs. [37] and [38]) in a report that is freely accessible, using a beam quality that is achievable by clinical medical physicists. This task group recommends that DAP meters used for exposure analysis meet the performance standards set forth by the International Electrotechnical Commission.[59]

4. ARTIFACT IDENTIFICATION

The radiologic technologist is the first person to view an acquired digital radiograph. The performing technologist, after deeming an image acceptable, may send the image to a QC technologist for further review. After reviewing the image for diagnostic quality—including proper patient positioning, appropriate exposure, and freedom from significant artifacts—the QC technologist sends the image to PACS and marks the study as finished so it appears in the queue of the reading radiologist. Considering the substantial and vital role played by the RT in this process, it is critical that he or she is trained in and comfortable with artifact identification and triage. The RT should be able to identify common artifacts in digital radiography and to follow a simple fault tree when an artifact is identified, including deciding whether or not to acquire further patient images prior to contacting the QMP or service engineer. A simple fault tree is provided in Fig. 1. The fault tree should identify the actors in the process as well as actions to be taken in the event of an image artifact, perhaps differentiated by artifact severity. The fault tree should be developed with input from a QMP. Appendix A of the supplementary material[60] contains images illustrating a variety of artifacts, some of which are unique to digital radiography.

4.A. Artifact check after detector calibration or detector drop

While artifacts are generally equally likely to appear at any time of the workday, two situations deserve additional attention—image receptor calibration and dropped detectors. Image receptor calibration may be performed either by a
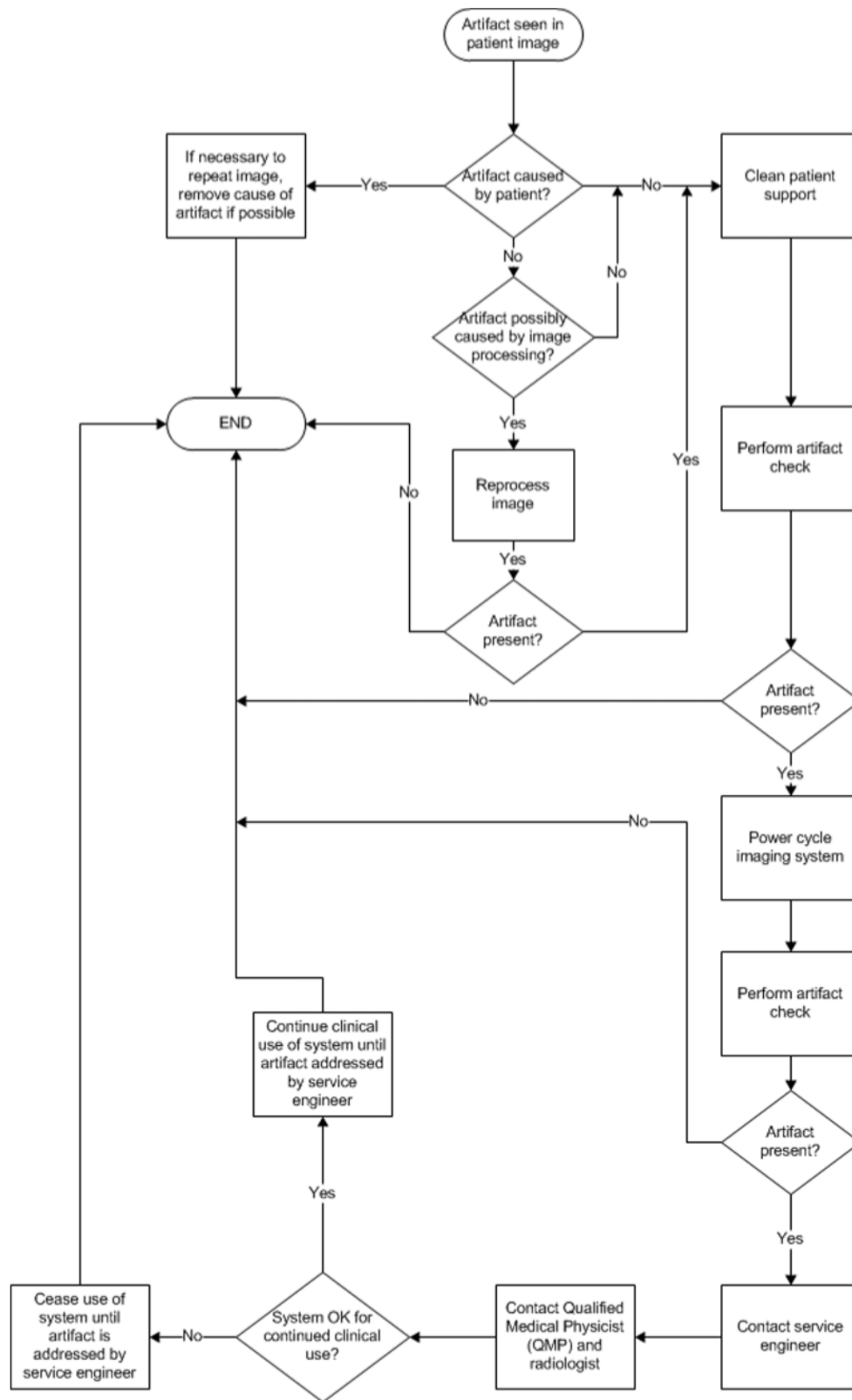
Fig. 1. Example fault tree for artifact troubleshooting.

member of the clinical technical staff (e.g., RT) or by in-house or OEM service engineers. A check for artifacts after calibration is important for two main reasons—the calibration files affect all future images acquired with the image receptor (until the next calibration), and detector calibration can "burn in" or make permanent (until the next calibration) any defects in either the x-ray production chain (e.g., collimator) or the image receptor itself. A check for artifacts after suspected damaged to the detector is important to verify proper functionality prior to patient use. In addition, many manufacturers

require detector calibration after a drop sensor is triggered. For these reasons, the task group recommends that the following check be performed immediately after detector calibration, a detector drop, or suspected damage to the detector, prior to the acquisition of patient images.

4.B. Protocol for performing artifact check

The steps in the protocol are as follows.

i. Acquire one image using the gain calibration conditions (kVp, mAs, added filtration) used by the manufacturer of the image receptor. If the gain calibration protocol is not known, the TG-116 EI calibration protocol may be used. If neither the gain nor EI calibration conditions are known, the default conditions described below can be used.

ii. Acquire a second image using one-half (0.5) of the mAs used in step 1, with the other conditions identical.

iii. Either the for processing images should be reviewed or a test image processing protocol that applies minimal image processing should be used to create for presentation images that will be reviewed. The window level (WL)/center should be set to the mean pixel value in the image as measured using a region of interest (ROI) placed in the center of the image. The window width (WW) should be set to 10% of the WL. For example, if the mean pixel value in the image is 500, the WW should be set to 50. Image analysis may be performed at the acquisition workstation or on PACS. The RT should evaluate both images carefully for both large-scale and small-scale nonuniformities, including grid lines, dead pixels, and dead lines. Evaluation of the image for small-scale nonuniformities should be conducted while viewing the image at acquisition size (1:1 detector pixel to display pixel ratio), which will require panning to view the entire image, and may require viewing the image on PACS.

4.B.1. Configuring acquisition and image processing menus

Image acquisition and processing menus for performing the artifact check should be configured with input from the QMP and posted in the clinical area or installed on the acquisition station. Carefully labeling and saving the menus in a "Test" folder on the imaging equipment is preferred. The task group recommends that the exposure conditions listed in Table II be used if the gain and EI calibration conditions of the equipment manufacturer are unknown.

4.B.2. Training staff to perform the artifact check

A sufficient number of RT staff should be trained such that a trained RT is always available, regardless of shift and vacation coverage. The training session should address acquisition of images, analysis of images, simple troubleshooting techniques, and it should include a review of the fault tree of actions to be taken if the artifact check produces unacceptable results.

4.B.3. Troubleshooting

A toolbox of simple troubleshooting techniques should be provided to the trained RTs by the QMP. These techniques should include tests to isolate the cause of artifacts in flat field images to either the x-ray production equipment or image receptor. These techniques include looking for positive/negative duplications of artifacts [Fig. A29 (Ref. 60)]; rotating cassette-based image receptors or shifting the x-ray tube/collimator assembly or image receptor for cassette-less image receptors to cause movement of artifacts caused by the x-ray production equipment; and rotating the added filtration if the filtration is suspected to be causing artifacts.

5. TOOLS PROVIDED BY MANUFACTURERS

Many manufacturers of digital radiography equipment offer, in addition to software tools for performing rejected image and exposure analysis, hardware or software tools for performing QA of the imaging equipment itself. These tools may be provided with a digital radiography system at no additional cost, or they may be offered as an option at additional cost. Third-party companies may offer similar products. These QA tools are intended to identify deficiencies in the imaging equipment before they affect the medical image deliverable.

This task group evaluated QA programs from several manufacturers. While day-to-day variations in quality metrics were not observed, the programs did prove to be useful for long-term trend analysis. This task group recommends that QA programs provided by manufacturers at no additional cost be implemented, and that facilities consider purchasing QA programs provided at additional cost, or implement a similar program on their own.

One caveat to this recommendation is that the QA technologist will likely be the person responsible for performing

TABLE II. Default exposure conditions for artifact check.[a]

kVp	mAs for exposure 1[b]	mAs for exposure 2	Field of view	Anti-scatter grid	Added filtration
70	AEC center cell	0.5 × mAs for exposure 1	Fully expose detector	In	Filter provided by manufacturer for calibration (e.g., 20 mm Al). If no filter available, use suitable filter, e.g., 0.5 mm Cu.

[a]Factors not explicitly listed (e.g., focal spot size) can be set however desired.
[b]QMP may program the reported AEC mAs (exposure 1) and mAs for exposure 2 into an acquisition menu after they are determined initially.

the manufacturer's QA program. It may be difficult to train the QA technologist to run programs requiring that specific measured exposures be made, e.g., exposing a plate to 1 mR for a particular test. While charts detailing technique factors to be used can be provided for this purpose, errors in these exposures may be a source of failure unrelated to the imaging equipment.

6. ADMINISTRATION AND OPERATION OF A QC PROGRAM

All personnel in a radiology department play a role in patient care, and they should also play a role in the ongoing QC process. A successful ongoing QC program requires the combined efforts of many clinical staff, including the radiologic technologist, the QMP, the radiologist, and department administrators. The roles of the QMP, QC technologist, and radiologist are outlined below.

6.A. Role of the QMP

The rejected image analysis and exposure analysis programs outlined in this report should be designed and implemented by a QMP in accordance with the recommendations in this report. The program should be set up with the cooperation of a radiologist and the QC technologist, including the installation of corrective action thresholds and decisions on how the data will be stratified and analyzed. The decision of which dose metric(s) to use and how they should be collected and analyzed should be coordinated by the QMP. The QMP should participate in the analysis process, including reviewing data and analysis on at least an annual basis, and be available for consultation regarding corrective action when necessary.

6.B. Role of the QC technologist

The QC technologist is the person responsible for the day-to-day operation of a QC program. The QC technologist should ensure that all technologists involved in the radiography practice understand their responsibilities in the process. The QC technologist should manage the data collection and analysis, keep records, and perform other necessary administrative tasks. The QC technologist should perform quality control on the selected reasons for rejection and notify the QMP and radiologist of any problems or anomalies in the process. The QC technologist should work with the QMP to implement suggestions for correcting malfunctioning equipment and practice problems.

6.C. Role of the radiologist

The radiologist is the person ultimately responsible for the quality of the imaging practice. Therefore, the radiologist should participate in the design of the QC program and be available for consultation with the QC technologist and QMP when problems or questions arise. The radiologist should participate in the analysis process and in the implementation of corrective action when necessary. The PACS system should

be configured, if possible, to display the EI, P_{KA}, or other dose metric(s) used in the exposure analysis program as an overlay on patient images. This will allow the radiologist to contact the QC technologist when exceptional cases are identified. The ongoing role of the radiologist also includes identification of images of inadequate diagnostic quality that are archived to PACS instead of being rejected or repeated, as well as providing positive feedback where deserved. Tools for facilitating radiologist involvement in the QC process have been developed.[61]

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