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Tracking patient radiation exposure: challenges to integrating nuclear medicine with other modalities

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Abstract

The cumulative radiation exposure to the patient from multiple radiological procedures can place some individuals at significantly increased risk for stochastic effects and tissue reactions. Approaches, such as those in the International Atomic Energy Agency's Smart Card program, have been developed to track cumulative radiation exposures to individuals. These strategies often rely on the availability of structured dose reports, typically found in the DICOM header. Dosimetry information is currently readily available for many individual x-ray based procedures. Nuclear medicine, of which nuclear cardiology constitutes the majority of the radiation burden in the U.S., currently lags behind x-ray based procedures with respect to reporting of radiation dosimetric information. This paper discusses qualitative differences between nuclear medicine and x-ray based procedures, including differences in the radiation source and measurement of its strength, the impact of biokinetics on dosimetry, and the capability of current scanners to record dosimetry information. These differences create challenges in applying monitoring and reporting strategies used in x-ray based procedures to nuclear medicine, and integrating dosimetry information across modalities. A concerted effort by the medical imaging community, dosimetry specialists and manufacturers of imaging equipment is required to develop strategies to improve the reporting of radiation dosimetry data in nuclear medicine. Some ideas on how to address this issue are suggested.

Keywords

Radiation exposure tracking; Cumulative patient dose; Radiation dose nuclear imaging; Effective dose

Introduction

Exposure of patients to ionizing radiation is an unavoidable epiphenomenon of most radiologic and all nuclear medicine procedures. This exposure is believed to be the source of a substantial proportion of the total annual collective radiation dose to the population worldwide¹, and the single largest source of radiation to the United States population.² Among radiologic and nuclear medicine procedures, the single procedure with the highest burden to the population in terms of radiation dose is myocardial perfusion scintigraphy.^{2,3} Radiation exposure can result in detrimental health effects to the individual undergoing the

procedure. Effects of radiation exposure can be tissue reactions (deterministic) or stochastic in nature.^{4,5} Concern over these effects has prompted efforts to minimize exposure from medical procedures to levels “as low as reasonably achievable”⁵ without affecting diagnostic information.*

Historically, an individual’s cumulative lifetime radiation dose from medical procedures was generally very low. The health concern from radiation was focused at the population level rather than at the individual undergoing a medical procedure. Population-level risk could be roughly assessed with information on the number of procedures per capita, and the “typical” dose for each type of procedure. However, over the past two decades there has been increasing use of procedures with higher doses (on the order of two digits of mSv of effective dose), and a rise in the number of patients undergoing multiple procedures in short periods of time.^{6–8} The result is a considerable number of individuals³ subjected to cumulative doses at levels where there is epidemiologic evidence for increased risk of cancer.⁹ This marks a shift to a focus on radiation protection for individuals in addition to populations, whereby it is now desirable to track an individual’s cumulative radiation exposure (number and type of examinations) and doses.¹⁰ Although there is some controversy about the desirability of tracking patient’s radiation dose histories, most radiation protection authorities support this idea, which fosters a data-rich environment for radiological protection efforts^{8,11,12}. This is expressed in a recent joint position statement involving several international and regional organizations.¹³ In any event, the focus of this paper is not to debate the virtues or lack thereof of tracking radiation exposure, but rather to focus on issues pertaining to accounting for nuclear medicine exposure in dose tracking.

Radiation Burden from Medicine

Although exposure to ionizing radiation can result in detrimental health effects, the risks incurred as a consequence of undergoing nuclear medicine or radiologic procedures must be balanced with the substantial benefits such procedures can provide. The potential benefits of these procedures are typically well understood, although not necessarily easily quantified.¹⁴ Understanding the risks associated with an approach to diagnostic testing, however, requires knowledge of the cumulative radiation burden.

The majority of the collective radiation dose to populations due to radiologic (x-ray based) and nuclear medicine procedures comes from a few imaging modalities. In the United States, computed tomography (CT) accounts for approximately half of this collective non-radiotherapy medical dose to the population, with mean effective doses for different procedures typically ranging from 2 to over 20 mSv.^{2,15,16} Tracking of radiation dosimetry data to a patient from CT and other radiologic procedures has benefited from efforts to develop standardized indices and structured dose reports. Such information, for example the volume CT dose index (CTDI_{vol}) and the dose-length product (DLP), is currently incorporated into the DICOM header – a useful mechanism for communicating dosimetry data with tracking programs, such as the IAEA’s Smart Card/SmartRadTrack.^{8,12}

A second major medical source of radiation dose to populations, where individual patient dose is high, is fluoroscopic-guided interventional procedures, which may be performed by cardiologists, interventional radiologists, vascular surgeons, or other specialists.² The mean effective dose for these procedures can range widely, from <1 to nearly 100 mSv.¹⁵ Such procedures account for one seventh of the collective non-radiotherapy medical dose to the US population. Importantly, in addition to stochastic effects, these procedures have the

*In this paper, the term “exposure” is used in a qualitative manner and the magnitude of exposure is expressed as dose, which is a quantitative term. Also, the term “radiologic” is used for x-ray based imaging.⁵

potential for tissue reactions (more commonly known as deterministic effects, but currently the nomenclature preferred by the International Commission on Radiological Protection [ICRP] is tissue reactions) that cannot be ignored for long-duration fluoroscopy procedures.^{17,18} The dosimetric quantities for such procedures, such as kerma area product (KAP) and cumulative air kerma at the Interventional Reference Point, are well standardized and are provided by recent fluoroscopy units, thus offering the potential to achieve communication and tracking of fluoroscopy dosimetric quantities, as in CT.

The third major medical source of collective population radiation dose is nuclear medicine. Diagnostic procedures employing radionuclides account for approximately a quarter of the medical radiation burden in the United States.² Approximately 75% of this radiation comes from myocardial perfusion scintigraphy, where effective dose estimates as high as 40mSv have been reported, depending on the radiopharmaceuticals used and the protocol.^{14,19,20} Moreover, the problem of multiple testing with high cumulative radiation doses appears to be particularly significant for patients undergoing myocardial perfusion scintigraphy; one study demonstrated that in a series of 1097 patients undergoing myocardial perfusion scintigraphy, 31% had cumulative effective doses, both from myocardial scintigraphy as well as from all other medical imaging and intervention procedures, of at least 100 mSv.⁷

Unlike for most higher-dose x-ray based procedures such as CT and interventional fluoroscopy, widely accepted standardized dosimetry reports are lacking for nuclear medicine procedures, and specifically are not part of the DICOM header, rendering it difficult to incorporate radiation dosimetry information from nuclear medicine procedures into dose tracking strategies. Therefore, there is potential for significant misestimation of cumulative radiation doses to an individual undergoing a nuclear medicine procedure in addition to other radiologic procedures. This may be especially concerning among some cardiac patients, who may undergo numerous “high dose” diagnostic and interventional procedures in addition to myocardial perfusion scintigraphy.⁷ In the next section we will describe three unique features of nuclear medicine, beyond the lack of standardized dosimetry reports (and in fact likely causal of this lack of standardization), which create challenges in incorporating radiation doses from these procedures into comprehensive dose tracking strategies.

Measuring, Monitoring, and Reporting Radiation Exposure: Nuclear Medicine versus Other Radiologic Procedures

Several fundamental qualitative distinctions exist between nuclear medicine and other imaging modalities, which pose challenges in terms of having an integrated approach to measuring and recording radiation exposures between modalities. The most notable difference is in defining the strength of the source of the radiation. The magnitude of exposure and absorbed doses for each class of procedures are affected by a large number of parameters. Radiologic procedures use external radiation fields generated from an x-ray tube. Parameters affecting the magnitude of exposure and radiation doses from radiologic procedures include the output intensity and energy spectrum of the x-ray beam, the size of the radiation field, the distance between the subject and the x-ray tube, the parts of the body irradiated, absorption of x-rays within the body and the length of time the subject is irradiated. In contrast, the source of exposure for nuclear medicine procedures is the ingested, injected, or inhaled radiopharmaceutical. Doses from nuclear medicine are dependent on the type of the radiopharmaceutical used, the level of administered activity and the kinetics of uptake and clearance from each organ.¹⁹ It is due to these features that different standards of measurement have been adopted for nuclear medicine and for radiologic procedures. The standard measurement for radiation exposure in nuclear medicine is the radiopharmaceutical’s administered activity—the number of decays per second

(Becquerels). Estimates of exposures from radiologic procedures are Air Kerma-based (i.e. energy released per unit mass in a volume of air).

True patient doses from both radiologic and nuclear medicine examinations are affected not only by the source of radiation, but also by individual variations in body habitus. Patient doses in nuclear medicine procedures, however, are also affected by individual variations in biokinetics. For example, in a comprehensive study of Rb-82 dosimetry in 30 patients, including individuals both with and without disease, Hunter observed the coefficient of variation of organ residence times to vary, by organ, up to a maximum of over 50%.²¹ This resulted in organ equivalent doses varying with coefficients of variation in the worst case of over 100%; mean organ equivalent doses differed between men and women, and up to 91% between injections performed at rest and those performed with pharmacologic stress for selected organs.²¹ These patient-specific variations in habitus and biokinetics may result in differing absorbed doses between patients who receive identical exposures, e.g. two patients each receiving a CT scan of the same body region with the same scan parameters, or two patients each receiving the same activity of the same radiopharmaceutical. The additional variability introduced by the effect of biokinetics on dosimetry is another unique feature of nuclear medicine. Resultant of this is that while in x-ray-based imaging, standard reference quantities such as DLP or KAP are sufficient to estimate the effective dose to a standardized phantom, in nuclear medicine the reference dose quantity (activity) alone is of lesser value.

With respect to accounting for the parameters described above and providing an estimate of radiation dose, radiologic procedures have another advantage over nuclear medicine, which is due to another qualitative difference between these modalities. That is, with most radiologic procedures, radiation exposure to the patient is confined to the short duration of x-ray beam-on time and consequently the devices emitting the radiation, recording the image and measuring a radiation dose index can be directly integrated. This facilitates the relay of dosimetric information along with image information to the DICOM header and to a picture archiving and communication system (PACS). Specifically, this is the case for digital imaging modalities including CT, mammography, computed radiography, direct radiography, and, to some extent, fluoroscopy.²² This is not the case for SPECT and PET procedures, where patient radiation exposure begins prior to and continues beyond the imaging time. Consequently, the image recording device that communicates imaging information with the DICOM header cannot reflect patient doses throughout radiation exposure. Currently, such image recording devices, which are separate from the source of radiation exposure, may not even typically record administered activity, which could at least be used to provide an estimate of organ doses.

Integrating Exposure Data with Tracking Strategies: Overcoming Challenges in Nuclear Medicine

In the previous section we described a number of qualitative differences between radiologic and nuclear medicine procedures. Specifically, these procedures differ in 1) the radiation source and measurement of its strength, 2) the impact of biokinetics on dosimetry, and 3) the capability of current equipment to record dosimetry information. In order to integrate dosimetry information from nuclear medicine procedures with that from radiologic procedures, one must overcome these qualitative differences.

Differences in defining the strength of the radiation source and standards of measurement between the various modalities could be overcome by converting the information we could obtain to a common dosimetric quantity or quantities, not tied to a particular modality. The ideal dosimetric quantities are the true absorbed doses to each organ in the patient imaged. In clinical practice, this is virtually impossible, as determining these doses would require

knowledge of patient-specific biokinetics and habitus. For example, determination of patient-specific biokinetics would require extensive scanning of the patient beyond what is necessary for medical diagnosis, thereby placing undue stress on both the patient and medical resources. Thus, in practice, simplified estimates of these true absorbed doses are the best common quantities that could currently be reported, serving as surrogates for the true organ doses.

In addition to organ doses, the effective dose⁵ currently enjoys significant popularity. Three virtues of effective dose are that it is not modality-specific, that it is a convenient single quantity that can be cumulated over multiple procedures, and that it reflects, in a general sense, the overall radiation burden to a typical patient from a procedure. However, effective dose was developed for population-level dosimetry, not for measuring radiation burden to an individual patient, and thus its application to describing the dose to an individual patient is “off-label.” Specifically, effective dose is properly defined only for a non-obese “reference individual”, and the tissue weighting factors used to weight individual organ doses in its calculation are gender- and age-averaged, rounded figures.

While true patient-specific organ doses cannot be determined, there are however several frameworks in existence which enable estimation of radiation doses from nuclear medicine procedures that at least reflect the administered activity, and assume “typical” habitus and biokinetics. These include model-derived dose coefficients for many radiopharmaceuticals that are offered by organizations such as the Society of Nuclear Medicine’s Committee on Medical Internal Radiation Dose²³ and the ICRP^{24–26}, by the Radiation Dose Assessment Resource (RADAR) website²⁷, and by radiopharmaceutical manufacturers in product information sheets. Such dose coefficients can be multiplied by the administered activity to provide estimates of organ and effective doses. Dose coefficients from such models could be used to estimate and archive doses from individual procedures. While activity- and radiopharmaceutical-specific, these estimates would not reflect patient biokinetics and habitus, but they would at least provide a good starting point for more refined nuclear medicine dosimetric efforts. At the present, it is not clear for most radiopharmaceuticals how much difference patient- and clinical-condition-specific biokinetics makes, but that is a topic for future refinement. Future efforts will likely focus on developing methodology that can incorporate measures of patient habitus and biokinetics into dosimetric models. In the field of CT, such efforts have begun with the development of Size-Specific Dose Estimates that modify the standard volume CT dose index²⁸; similar methodologic advancement is needed for nuclear medicine, although this promises to be an even more challenging task due to the need to reflect variation in both habitus and biokinetics.

While in the future it may be possible to acquire accurate organ doses in a manner that accounts in some form for an individual’s habitus and biokinetics, currently one may only be able to apply simplified methods to estimate doses, such as those based on the collections of dose coefficients mentioned above. Although this may not be considered ideal, it does offer a way to integrate dose estimates from nuclear medicine procedures with those from radiologic procedures for an individual patient.

Parameters required to give some estimate of radiation doses to an individual during a particular procedure should be incorporated into nuclear imaging devices for each procedure, via a computer interface. This information could then be communicated in the DICOM header, and later be integrated with a dose tracking system. Professional organizations such as nuclear medicine societies have the responsibility to provide manufacturers with consensus on what dosimetry information industry should be incorporated into such a system, and how doses should be estimated. With this information a DICOM standard for nuclear medicine dosimetry could be developed. Numerous types of

data should be considered for inclusion in such a system to ensure the best possible dose estimates at the time of imaging, and to make possible updated dosimetry estimates when methodology advances. Such data elements could include patient demographics, measures of patient habitus, radiopharmaceutical administered, activity calibrated, date and time of calibration, mode of administration, conditions of administration (e.g. during exercise or pharmacologic stress), date and time of administration, date and time of imaging, system of dose coefficients used (e.g. ICRP Publication 106²⁶), and individual organ dose estimates. Moreover, as the nuclear medicine and nuclear cardiology communities push for lower dose protocols, residual radiopharmaceutical activity in the syringe may increase as a percentage of the calibrated activity. In some cases, this may cause a significant overestimate in patient doses when they are estimated using initially-calibrated activity, and thus, provision should be made for including residual activity and its date and time of measurement among the set of data elements in this dosimetry system.

Conclusions

Nuclear medicine in several ways lags behind x-ray based imaging procedures in incorporating radiation dosimetry data into the DICOM header. This creates difficulties in estimating cumulative doses and in integrating radiation exposure from nuclear medicine into tracking programs, which may be of particular importance for nuclear cardiology patients. Here we outlined some inherent features of nuclear medicine that create challenges to integrating nuclear medicine radiation dosimetry reporting with that of radiologic procedures, and suggested some ideas to begin tackling these challenges. Overcoming all of these challenges may require technology and knowledge beyond what is currently available. Concerted attention by the nuclear imaging community is required to address this concern, to improve the reporting of radiation dosimetry information in nuclear medicine, and thereby enable more comprehensive strategies for dose tracking and minimizing ionizing radiation.

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