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FULL PAPER

Benefits and limitations for the use of radiation dose management systems in medical imaging. Practical experience in a university hospital

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Objectives: Radiation dose management systems (DMS) are currently used to help improve radiation protection in medical imaging and interventions. This study presents our experience using a homemade DMS called DOLQA (Dose On-Line for Quality Assurance).
Methods: Our DMS is connected to 14 X-ray systems in a university hospital linked to the central data repository of a large network of 16 public hospitals in the Autonomous Community of Madrid, with 6.7 million inhabitants. The system allows us to manage individual patient dose data and groups of procedures with the same clinical indications, and compare them with diagnostic reference levels (DRLs). The system can also help to prioritise optimisation actions.
Results: This study includes results of imaging examinations from 2020, with 37,601 procedures and 286,471 radiation events included in the radiation dose structured reports (RDSR), for computed tomography (CT), interventional procedures, positron emission tomography-CT (PET-CT) and mammography.
Conclusions: The benefits of the system include: automatic registration and management of patient doses, creation of dose reports for patients, information on recurrent examinations, high dose alerts, and help to define optimisation actions.
The system requires the support of medical physicists and implication of radiologists and radiographers. DMSs must undergo periodic quality controls and audit reports must be drawn up and submitted to the hospital's quality committee.
The drawbacks of DMSs include the need for continuous external support (medical physics experts, radiologists, radiographers, technical services of imaging equipment and hospital informatics services) and the need to include data on clinical indication for the imaging procedures.
Advances in knowledge: DMS perform automatic management of radiation doses, produces patient dose reports, and registers high dose alerts to suggest optimisation actions. Benefits and limitations are derived from the practical experience in a large university hospital.

INTRODUCTION

This study presents the methodology behind a homemade dose management system (DMS) called DOLQA (**D**ose **O**n **L**ine for **Q**uality **A**ssurance) and reports the results obtained after several years of experience during the transition period from analogue to digital radiology[1–5] in a large university hospital in Madrid (San Carlos University Hospital, SCUH) as a close cooperation between the medical physics experts (PME) radiologists and radiographers.

The automatic registration and management of patient doses in order to optimise digital imaging systems and quality assurance programmes has been, and it is still, a challenge.

In their 2004 report on "Managing Patient Dose in Digital Radiology",[6] the International Commission on Radiological Protection (ICRP) highlighted of the need to take into account the work of the DICOM (Digital Imaging and Communication in Medicine) committees, and involve clinical specialists, medical physicists, and radiographers to ensure that imaging capability and radiation dose management are integrated, because quality control requires new procedures and protocols. Later, in the ICRP report 135 on "Diagnostic Reference Levels (DRL) in Medical Imaging",[7] the ICRP suggested to take advantage of automated reporting of radiation-dose-related quantities to improve the use of these tools for optimisation.

In "Radiation dose management systems-requirements and recommendations for users from the ESR EuroSafe Imaging initiative"[8] co-authored by the European Society of Radiology (ESR), R. Loose et al, set out the main criteria for DMS contained in the European Directive 2013/59/Euratom. The Directive requires that all medical radiological equipment in use is kept under strict surveillance regarding radiation protection. The optimisation principle shall apply to individual doses and be consistent with the medical purpose of the exposure. Information relating to patient exposure should form part of the report of the medical radiological procedure, and a system for recording and analysing accidental and unintended exposure must be implemented.[9]

The EuroSafe Imaging initiative presented a second "Call for Action" in 2018,[10] which included the promotion of DMSs to help establish and use local, national, and European DRLs and recommended the implementation of clinical audits to improve the quality of patient care. DMS are excellent instruments to audit and introduce corrective actions when appropriate. The AAPM (American Association of Physicists in Medicine) also published recommendations on this issue.[11]

In this study, we describe how we use a homemade DMS to improve radiation protection and several quality aspects by automatic registering and managing the relevant dosimetric data for the imaging procedures. The dosimetric data are analysed for individual patients, different X-ray systems, and at the hospital level. We report the advantages (and limitations) of using DMSs.

Our DMS is currently used in 3 Autonomous Communities in Spain – Madrid, Aragon and the Basque Country – and the system will be part of a regional project in Latin America and Caribbean countries (OPRIPALC) for paediatric interventional radiology.[12]

DOLQA is not a commercial system – it has been developed under Spanish and European research programmes. We hope that our experience and results will improve the use of DMSs in general, and contribute to an understanding of the benefits, the support requirements, and the limitations of these systems.

METHODS AND MATERIALS

The current version of our DMS has been adapted for use in X-ray systems that have DICOM Radiation Dose Structured Reports (RDSR), but it can also manage image headers and secondary capture with optical character recognition (OCR). In these cases, OCR errors may be produced and missing dose information when only DICOM headers are analysed. This version was launched in 2019, but for some X-ray systems it has been possible to include information on procedures performed before 2019, when the RDSR information was stored in the PACS (Picture Archiving and Communication System) of the networked hospitals.

Currently, 16 large public hospitals and about 20 additional mammography centres in the Autonomous Community of Madrid (6.7 million inhabitants) are connected to the DOLQA system. The system receives and manages the information almost in real time, and can show the tables and graphs updated for all the procedures. The modalities included in the system are: Computed Tomography (CT), Interventional Radiology (XA), Positron Emission Tomography with CT (PET-CT) and mammography (MG).

INSTALLATION, CONNECTION AND ACCESS TO THE DMS

The DMS can be installed in a central server of any hospital, or in the central server of the local Health Authority when several hospitals are involved. Connection to the imaging modalities (X-ray systems) may be achieved directly with a DICOM node and a dedicated personal computer, or preferable via the hospital's PACS. It is important to follow local privacy rules to restrict user access to some data.

Access to the system needs to be authorised by an administrator, and to maintain confidentiality as it is limited to the hospital's own data, except when searching for an individual patient. In this case, authorised users can access the full patient repository (and dosimetric data) together with all previous imaging procedures archived in any of the networked hospitals. These data may be useful for the application of the justification criteria for new procedures and for patient information, according to national and European regulations.

DATA AVAILABILITY AND MANAGEMENT

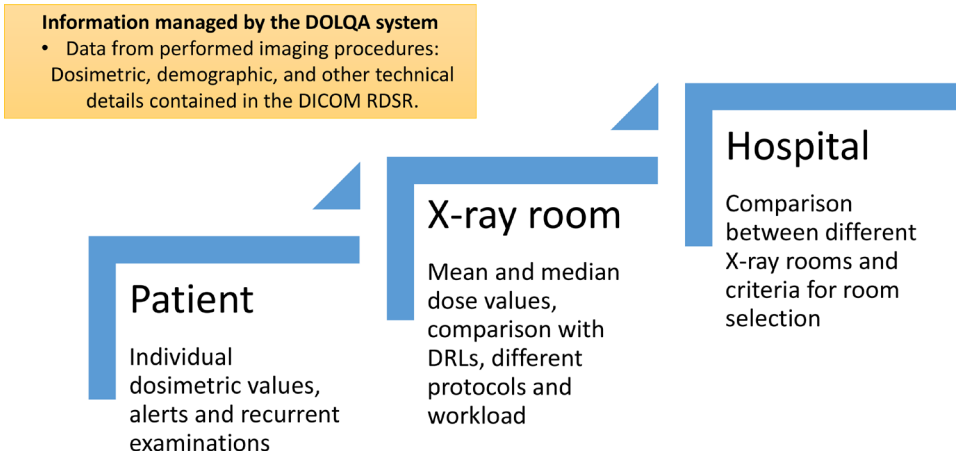
At the SCUH, the CT, PET-CT and MG systems connected to the DMS send their RDSR to the hospital's central PACS. The DOLQA receives the information from the PACS. The interventional systems are, in our case, also directly connected to the DMS for an early detection of studies with high skin doses.

Data are collected and processed automatically, and the DMS is configured to manage the information at three levels: patient, X-ray system and hospital (facility level). See Figure 1.

In addition to individual dosimetric data (patient dosimetric indicators and also occupational doses for interventional procedures in our DOLQA), the system can provide graphs and statistical analysis of groups of procedures carried out in different radiology rooms and over certain periods of time.

For occupational doses, if specific electronic personal dosimeters are available and worn over the protective apron, and electronic area dosimeters are located on C-arms (used as reference dosimeters) occupational doses Hp(10) may be managed in parallel to the patient doses. Electronic dosimeters communicate wirelessly with hubs installed at the interventional laboratory and it is possible to synchronise the occupational dose records with the information from the RDSR to create an occupational dose report (ODR). These occupational reports include information on occupational doses at the irradiation event level and the total value at the end of the interventional procedure. A comparison with the Hp(10) measured by the non-protected reference dosemeter at the C-arm, allows auditing the proper use of the ceiling suspended protective screen or other equivalent protection. It is

Figure 1. Three levels of information: patient, radiology room and facility.



also possible to audit the ratio between the values of Hp(10) and the P_{KA}. This may also be an indication on the proper occupational protection.[13–15]

The dosimetric audit can be performed for individual patients (with alerts, trigger levels or potential unintended exposures)[8,16–18] or for groups of procedures with the same clinical indications and compared with DRLs. This information can be used to produce patient dose reports, to decide if optimisation actions are necessary, and to report other factors related with image quality and local regulations (Figure 2). The system has the option of presenting some marked images (selected applying different technical criteria) for quality review by the radiologist through direct connection to the PACS, without the need to leave the DOLQA system. A registration and statistical analysis for the follow-up of alerts and trigger levels for patient doses is included in the DMS.

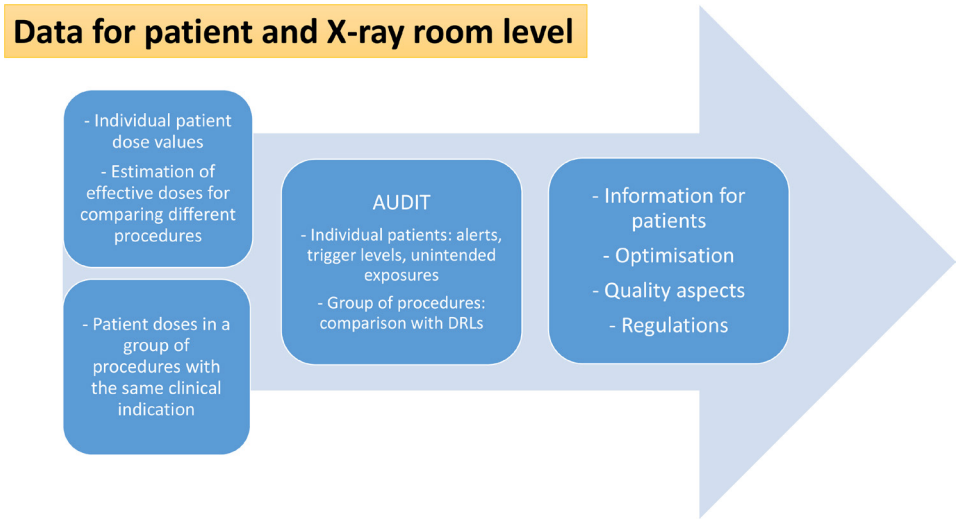
When high dose values are detected in some radiology rooms, an audit of patient dose data and occupational doses for interventional radiology[13–15] may be required to analyse the different radiation events occurring during the procedures, and thus determine the reasons for the high doses or identify certain technical parameters that would explain the poor image quality (*e.g.*, low compression force in mammography or pulse rate or pulse time in interventional procedures). Collimation may also be audited with the information contained in the RDSRs. With this analysis, optimisation actions may be suggested in many cases.

RESULTS AND DISCUSSION

The results and some automatic statistical analyses may be accessed in each of the four imaging modalities currently included in the DOLQA system. Using certain selection criteria, the results of all modalities can be shown (*e.g.*, date intervals, patient dose values, etc.) in graph or numerical form and the selected records can be exported to Excel files.

It is also possible to visualise the alerts generated during certain procedures, according to the previously selected criteria, *e.g.* high Air Kerma Area Product [P_{KA}] or Air Kerma at the patient entrance reference point [$K_{a,e}$] for interventional procedures, average glandular dose [D_G] for mammography, Dose Length

Figure 2. Flow chart of individual dose values and groups of procedures for audit and optimisation



Product [DLP] and Computed Tomography Dose Index (volume) $CTDI_{vol}$ for CT, or radioactive activity for the radiopharmaceutical used, and DLP for PET-CT.

Calibration or dosimetric correction factors (differences between the dosimetric indication of the X-ray system and the real value measured during the quality control) are also part of the DMS, together with the date and the medical physicist responsible for dose validations.

INFORMATION AT THE PATIENT LEVEL

The patient level is probably one of the most important practical aspects of any DMS. Ideally, a centralised database or dosimetric repository that allows access to all (or most) radiological data would be the best solution, but this is beyond the scope of many national health systems.

The DMS can manage individual patient dose data for all imaging procedures and details for the different radiation events. Interventional procedures are the most complex, and sometime involve more than 300 radiation events per procedure (fluoroscopy, cine, digital subtraction angiography [DSA], or cone beam CT [CBCT] acquisitions). For CT and PET-CT, the details of all series (radiation events) are also available, including the activity of the radiopharmaceutical used for PET examinations. For mammography, data from all the images obtained are automatically collected, including the calculation of the mean glandular dose.

In the case of patients who may undergo several procedures with different imaging modalities, our DMS can also provide a rough estimate of the effective doses and the equivalent time of background radiation.[16–18] This may be useful for patient information on the benefits and radiation risks of the imaging procedures.

X-RAY SYSTEM LEVEL ANALYSIS

The overall results for procedures performed with specific X-ray systems may be used to audit imaging practices as part of the hospital's quality assurance programme.

One of the main difficulties encountered in analysis and optimisation strategies is the different names of the clinical procedures used by the radiologists and interventionists at the hospital. This is still more critical when trying to manage patient dose data from several hospitals.

The most important information used to help optimise the full procedure and different radiation events in the four imaging modalities included in the DOLQA system is described in the next sections.

COMPUTED TOMOGRAPHY (CT)

During 2020, a total of 21,567 CT procedures were included in the SCUH DMS. The audit of DLP values indicates that 1% of the procedures had DLP values higher than 3,100 mGy.cm. Figure 3 shows the histogram.

CT procedures have a low number of radiation events in comparison with interventional procedures, except for a few examinations. A total of 44,349 radiation events were registered during 2020 (a mean of 2.1 radiation events per procedure).

The most relevant data collected for CT procedures are: date of the study, X-ray system, patient identification, age, gender, hospital, procedure identification code, procedure requested, procedure performed, number of radiation events, body part examined, acquisition protocol used, DLP, and estimated effective dose.

For radiation events, the following details are also included: acquisition protocol, irradiated area, kVp, mA, exposure time,

Figure 3. CT procedures. Distribution of DLP (mGy.cm). 1% of the procedures had DLP values higher than 3100 mGy.cm in 2020

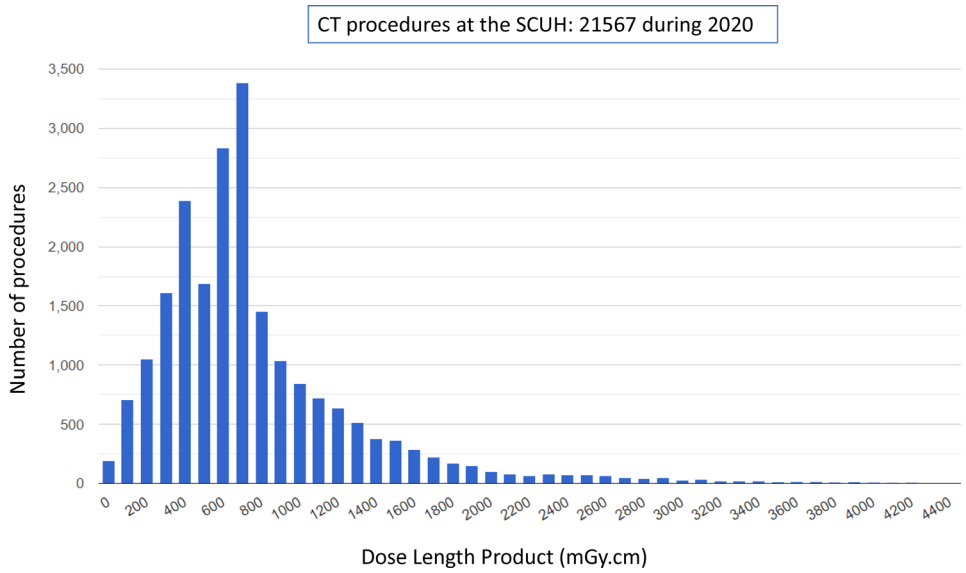
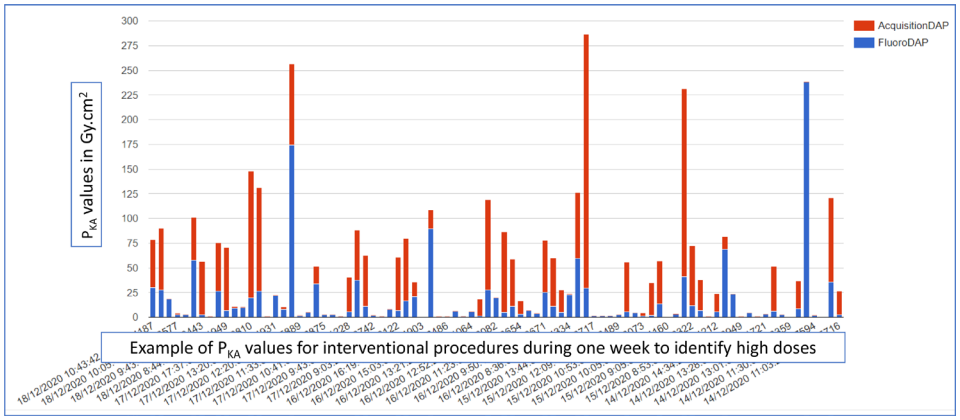


Figure 4. Example of patient dose audit (PKA values in Gy.cm^2) for interventional procedures in one week. High dose procedures are easy to discriminate together with the contribution of fluoroscopy and image acquisition.



exposure time per rotation, spiral pitch factor, mean value of CTDI$_{vol}$ and DLP for each event. Some CT systems are not including the values of DLP per radiation event.

INTERVENTIONAL RADIOLOGY (XA)

A total of 3,281 interventional procedures performed at the SCUH in 2020 were included in the DMS. Seven radiology rooms were involved, four for interventional cardiology, one for neuroradiology, and two for peripheral procedures.

For interventional procedures, the DMS can plot graphs using the P_{KA} and $K_{a,r}$ (for full procedures) for fluoroscopy and cine (or DSA or CBCT) recorded as "stationary" or "rotational" acquisitions, thus facilitating detection of high dose procedures (Figure 4). For individual procedures, it can also take P_{KA} and $K_{a,r}$ values to generate graphs with a timeline for all the radiation events.

In 2020, a search for interventional procedures with more than 500 Gy.cm^2 (one of the trigger levels for potential clinical follow-up)[18] yielded a total of 23 procedures (0.7% of all interventional procedures).

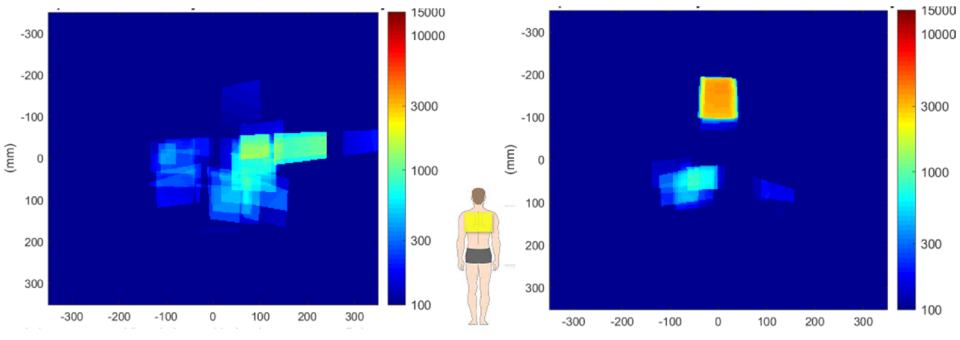
The most important data collected for interventional procedures in the DMS, in addition to the procedure identification code, are the P_{KA} and $K_{a,r}$ values (for fluoroscopy and stationary or rotational acquisitions – cine, DSA or CBCT-), the peak skin dose and the skin dose maps (if available for some of the procedures and calculated by a software module made by the Medical Physics Service of the Hospital, integrated into the DOLQA system) (Figure 5), the access (femoral or brachial), the number of radiation events, fluoroscopy time, stationary acquisition time and the number of images. Some of these data, such as the indication for the procedure, need to be introduced manually.

For the radiation events, the following data are collected: kVp, mA, acquisition mode, number of radiation pulses per second, pulse time, total radiation time, filtration of the X-ray beam, angulation and rotation of the C-arm, collimation, P_{KA} and $K_{a,r}$ values per radiation event.

POSITRON EMISSION TOMOGRAPHY WITH CT

In 2020, the total number of PET-CT studies found in the SCUH DMS was 4,064, with a total of 13,349 radiation events (3.3 events/procedure).

Figure 5. Skin dose maps for two interventional cardiac procedures with similar PKA and different Peak Skin Dose (PSD). Scatter radiation at the C-arm for these procedures is also indicated as personal dose equivalent Hp(10).



P$_{KA}$ = 287 Gy.cm^2, K$_{a,r}$ = 5142 mGy, PSD = 1530 mGy, C-arm ref. Hp(10) = 3.95 mSv (150720)

P$_{KA}$ = 279 Gy.cm^2, K$_{a,r}$ = 4689 mGy, PSD = 3749 mGy, C-arm ref. Hp(10) = 4.56 mSv (271120)

The most relevant data recorded for PET-CT procedures are, in addition to the procedure identification data, the irradiated area, the examination protocol, DLP, radiopharmaceutical used and activity (MBq). Effective dose is also estimated for CT and for PET.[16,17]

For the radiation events, the following data are collected: irradiated area, selected imaging protocol, kVp, mA, rotation time, spiral pitch factor, and mean $CTDI_{vol}$ per radiation event.

MAMMOGRAPHY (MG)

In 2020, the total number of mammography procedures found in the SCUH DMS was 8,989, with 32,474 radiation events (3.7 events/procedure).

The most important data recorded for mammography procedures are, in addition to the procedure identification data, procedure name, number of series, number of images, and clinical indication (diagnostic or screening).

For the radiation events, the following are also collected: laterality, projection, number of series, number of images, acquisition mode, kVp, mA, exposure time, anode material, filter, entrance air kerma, average glandular dose, compressed breast thickness, compression force and magnification factor.

Hospital level analysis

The hospital level analysis provides data on the workload and the impact of new X-ray technologies or image post-processing, in terms of patient dose for the different X-ray systems.

DOLQA AND ALERTS

Our DMS system shows a record of all individual alerts and the corresponding statistical analysis. Alerts are not only related to patient dose indicators.

In interventional radiology, alerts on trigger levels indicate the potential need for clinical follow-up of potential skin radiation injuries. At the SCUH, insufficient compression during mammography has also been identified as a frequent alert during 2020, and an optimisation action (retraining sessions with the team involved: radiologists, radiographers and medical physicists) has been implemented to correct the problem.

A total of 263 alerts were recorded at the SCUH in 2020: 97% mammography alerts, mainly due to low compression values, and 3% interventional radiology alerts for high $K_{a,r}$ values. The P_{KA} alert option was still not activated in 2020.

Alerts are registered in the system, and include the date, time, and the X-ray system involved.

Management of the DMS and optimisation actions

The DOLQA system allows to include manually, additional information on the demographic and other data of the imaging procedures. The possibility to do it automatically in the next versions from HIS/RIS and to improve a satisfactory mapping of the procedure names will be considered as part of the next updates of the system.

The DMS includes a table of correction factors for the dosimetric indicators, validated periodically by MPEs.

Once the imaging procedure has been completed, optimisation actions (or clinical follow-up) may be suggested on the basis of information from an individual patient (*e.g.,* patient dose indicators higher than alert or trigger levels) or a group of procedures (with the same clinical indications) if the median values of the patient dose indicators are higher than DRLs.

Image quality and an analysis of RDSRs showing abnormal compression force in mammography, high pulse rates in interventional cardiology, poor collimation, etc., may also indicate the need for optimisation actions.

CONCLUSIONS

The practical experience derived from the use of the DMS at the SCUH allows to derive the following benefits, requirements and limitations.

MAIN BENEFITS OF THE DMS

(1) Automatic transfer and registration of radiation dose indicators for the imaging modalities connected to the DMS.
(2) Alerts for high dose in individual procedures or in median dose values in groups of procedures with the same clinical indications (comparing with DRLs).
(3) Availability of patient dose reports, including estimates of effective doses and/or the equivalent time of background radiation (available from the Spanish Nuclear Radiation Authority, www.csn.es), and cumulative doses for recurrent imaging procedures.
(4) Availability of demographic, technical and geometrical factors included in the RDSR for optimisation actions, if appropriate.
(5) Generation of graphs showing high cumulative patient dose values over time, and registry of notifications and alerts for corrective actions.
(6) Periodic analysis of workload in the different radiology rooms.
(7) Evaluation of the impact on patient doses of new technologies, new operation protocols, and post-processing for different imaging protocols.
(8) Possibility to evaluate the impact of the complexity of some procedures by auditing patient dose values.
(9) Audit of radiation dose values for specific groups of patients (*e.g.,* paediatric patients, obese patients, etc.).
(10) Priorities for optimisation actions based on radiation dose values and frequency of the procedures.

DMS REQUIREMENTS

(1) Availability of medical physicists to manage the DMS and to promote the use of the system by other professional groups (*e.g.,* radiologists, other practitioners and radiographers).

(2) Good communication with radiology companies and the hospital's IT (Information Technology) services to obtain updates and to connect X-ray systems or PACS with to DMS.
(3) Periodic quality controls of the DMS to verify proper data transfer.
(4) The "study description" and some other personal patient data must be entered in the X-ray systems and in the DMS.
(5) Periodic reports for submission to the hospital's quality committees.

DMS LIMITATIONS

(1) The DMS "alone" cannot ensure compliance with radiation safety regulations.
(2) The DMS does not automatically suggest specific optimisation actions.
(3) Most of the dosimetric data in the DMS are related to X-ray beam output, and there are significant limitations to effective dose estimates.
(4) Some studies may not be registered in the DMS (*e.g.*, due to problems in the data transfer).
(5) Users may not enter all the demographic data and clinical indications for the imaging study and intervention.

Based on our experience, we can conclude that the DMS is a practical tool for the automatic registration and management of patient dose indicators, and helps comply with radiation protection regulations in medical imaging with ionising radiation. However, appropriate support is needed to make use of the information, to audit imaging practices, and to implement optimisation actions.

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