THE EVOLUTION OF QUALITY CONTROL SERVICES FOR RADIOLOGY EQUIPMENT OF HAMAD MEDICAL CORPORATION IN QATAR FROM 2005 TO 2021

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Abstract— **Hamad Medical Corporation (HMC) is the public health provider in the state of Qatar with 15 hospitals spread around the country. The Medical Physics Section (MPS) of HMC is the sole quality control (QC) service provider for all diagnostic equipment installed in HMC hospitals. In this article, the evolution of the MPS during the last 17 years of its operation is presented.**

Archives and QC reports from 2005 and onwards, were revisited to create an inventory of radiology equipment present in all HMC hospitals, QC control equipment present in MPS and QC protocols and methods used for acceptance and routine QC for radiology equipment.

The work was divided in four different periods 2005-2009, 2010-2014, 2015-2019 and 2020-2021, since the significant changes that took place during 2009, 2015 and 2000 are considered turning points for the evolution of MPS QC services. Emphasis is given in those changes in QC protocols and radiology and QC equipment which advanced the potential and efficiency of MPS in a higher level, leading to the official accreditation of MPS as a QC provider from MEFOMP organization.

The story of MPS is presented as a paradigm of the challenges that medical physicists worldwide, have faced in the past and will face in the future, to achieve the goals that promote both the essence and the appearances of the clinical medical physicist profession in radiological imaging: being knowledgeable, visible, useful and indispensable.

Keywords— **Medical Physics, Diagnostic Radiology, Quality Control, Accreditation.**

I. Introduction

Hamad Medical Corporation (HMC) is a governmental organization which constitutes the major health service provider in the state of Qatar. Starting from with three hospitals in the early 1980's, HMC gradually grew to 15 hospitals in 2020, which cover the whole range of medical specialties, medical personnel and medical equipment required to fulfill the health service needs of people residing in or visiting Qatar.

HMC has invested greatly on the radiology equipment since medical imaging is essential for diagnosis of a wide spectrum of pathological conditions. Apart from ultrasound and magnetic resonance imaging (MRI) equipment, the rest radiology equipment uses ionizing radiation, and therefore involves a certain risk, not only for the examined patients but also for the medical personnel using this equipment.

Due to the adverse effects of ionizing radiation which manifest mainly in high doses but may also appear in low doses (though the probability of occurrence is much lower), the operation of equipment using ionizing radiation should comply with certain requirements that have been issued by specialized international organizations, like ICRP and IAEA. These requirements are reflected in the national radiation protection laws and regulations of each country and Qatar is not an exception (Qatar Radiation Protection Law, Decree Number 31 of 2002 and Minister of Municipality and Environment Decree Number 4 of 2003 on the Executive Regulations for Law No.31).

In response to these requirements, the radiation safety services of HMC grew from a small Radiation Protection Unit at the Radiology (the name changed to Clinical Imaging) Department in 2000, to a fully functioning Radiation Safety Section within the Occupational Health and Safety Department in 2010, which was recently renamed to Medical Physics Section (MPS). MPS oversees the operation of all medical equipment using ionizing radiation in all HMC hospitals, while the last few years has extended its application field to lasers, MRI and ultrasound equipment as well.

The main purpose of MPS is to ensure that the operation of radiology equipment complies with national and international regulations. That is, in all radiology examinations the irradiation of the patient should be minimized as much as possible, while maintaining the image quality to the level required for the radiologist to perform a reliable diagnosis.

For this purpose, the MPS has developed a quality assurance (QA) program that is comprised by an initial extensive quality control (QC) test performed in every radiology equipment installed in HMC hospitals

(acceptance/commissioning QC) and periodical QC tests carried out thereafter (routine QC), during the whole time that this equipment is operational. The commissioning QC is very important to certify that the installed equipment is operating within specifications and that also meets the respective national and international requirements regarding safety and performance standards [1,2]. This means that several parameters must be directly measured or indirectly calculated, to ensure that they are within certain limits [3,4].

Additionally, some other parameters must be measured, the values of which will serve as baseline (where specific limits do not apply), to monitor in subsequent QC tests the performance of the radiology equipment and detect any significant deviations from its baseline performance [2,4]. It is well established that regular service and QC testing is the only way to assure that the radiology equipment is operating properly during its whole lifetime [5]. While regular service may prevent but cannot eliminate the occurrence of occasional malfunctions, routine QC is the only way to document that the performance of the radiology equipment adheres to the criteria related to both patient safety and image quality [6,7].

In this study the evolution of QC services in the radiology equipment of HMC during the period 2005-2021 is presented. The changes in X-ray equipment, QC equipment, personnel, QC protocols and QC methods are highlighted, along with the outcome of these QC services. The difficulties encountered during all these years, solutions applied, as well as, future challenges are discussed, from the aspect of Medical Physicists focused in the field of radiology.

II. Materials and Methods

The evolution of QC services of the MPS to the various HMC hospitals, can be roughly categorized in 4 different periods: 1st) 2005- 2009, 2nd) 2010-2014, 3rd) 2015-2019 and 4th) 2020- 2021. This evolution was driven by two major factors. The first was the rapid increase in the number of radiology equipment installed in HMC hospitals, which was combined with the establishment of many new hospitals. The second was the gradual replacement of analogue radiology equipment by digital in the existing hospitals and the installation of digital units of advanced technology, like angiography units, CTs and digital mammography systems in the new hospitals, right from the start.

The replacement of film/screen systems by digital detectors in both general and dental X-ray systems had a large impact on our QC program. Some QC tests were abolished, like dark room and wet-processor tests requiring the use of sensitometer and densitometer [2,8]. Others like Automatic Exposure Control (AEC) tests, which were mostly based on measurement of optical density (OD) of processed films with the densitometer, had to fully reshaped since OD of digital printed films was no longer associated with incident air-kerma [4,9]. The installation of advanced technology radiology equipment in HMC hospitals had also a big impact on QC services. The establishment of a QA program for these systems, required additional training of Medical Physicists and new QC equipment, and introduced a whole new chapter of QC tests regarding the evaluation of image quality. In the following sections are presented some informative data on the X-ray equipment installed in HMC hospitals and the QC services offered by the MPS of HMC during these four periods.

III. Results

1st period: 2005 - 2009

During this period, only 5 hospitals established up to that time under HMC: Rumailah Hospital (RH) established in 1957, Hamad General Hospital (HGH) established in 1982, Women's Hospital (WH) established in 1988m, National Center for Cancer Care and Research (NCCCR) established in 2004 and Al Khor Hospital (AKH) established in 2005. Most of the radiology imaging equipment installed in these five hospitals was analogue, using screen/film systems as image receptors. The type and number of units installed and overseen by the MPS are shown in Figure 1. QC was performed every six months in 56 out of 93 units (60%), and it was limited to general radiography systems, mobile X-ray units and dental periapical units. Regrettably, no acceptance or routine QC tests were performed in CT, fluoroscopy systems (stationary or mobile C-arms) and mammography units, due to lack of staff, training, and appropriate QC equipment. During this period, the available staff for performing QC tests was 2 medical physicists (MPs).

As can be seen in **Table 1**, during this period the available equipment was rudimentary; just two multifunction meters for measuring high potential (kVp), dose and dose rate (i.e. air-kerma and air-kerma rate) and exposure time, one set of aluminum filters for determining X-ray beam quality via the half-value layer (HVL), and one set of tools for checking the light and radiation field coincidence and the beam verticality. Two more instruments were available, a sensitometer and densitometer for QC tests related to dark rooms and wet film processors (e.g. film sensitometry, dark room light isolation, safelight evaluation etc.). The number of wet processors and dry printers that were under surveillance during this period can be seen in **Table 2**, while the available staff for performing QC tests is shown in **Table 3.** The QC tests performed during the period 2005-2009 [10-14] are listed in **Table 4** in comparison with the QC test performed in the period 2010-2014 [15-17]. Despite the shortage of staff, 112 QC tests per year were performed in X-ray units plus the QC tests in 10 wet processors that were performed daily. It must be mentioned that after 2010, the printer QC tests were gradually reduced, since diagnosis was shifted from view boxes and films to diagnostic monitors, and currently QC is performed in only one dry printer, monthly.

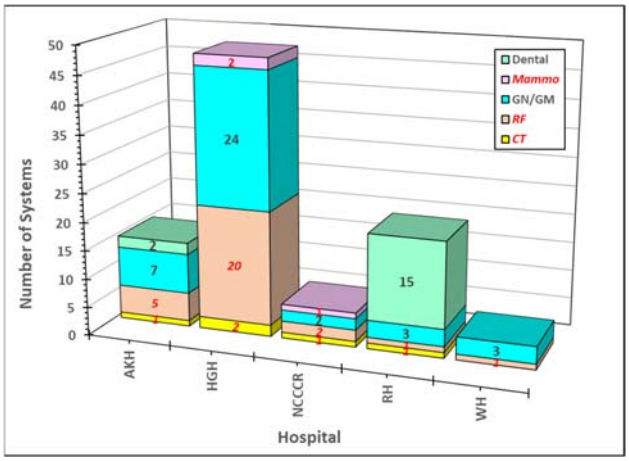

Figure 1 The type and number of the various X-ray modalities distributed in the Clinical Imaging Departments of the 5 HMC hospitals during the period 2005-2009. Units that are not included in QA program have their labels shown in *red italics*.

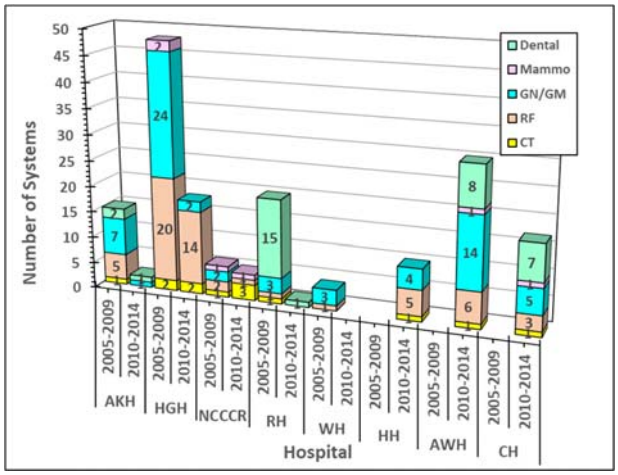

Figure 2 The type and number of new X-ray modalities distributed in the Clinical Imaging Departments of the 8 HMC hospitals during the period 2010 – 2014.

2nd period: 2010-2014

With the inauguration of new HMC hospitals and the installation of new modalities in the existing hospitals, the need to improve and advance the MPS services to meet the international standards became a necessity. As shown in **Figure 2**, during this period three new hospitals were added: Heart Hospital (HH) in 2011, Al Wakra Hospital (AWH) in 2012 and the Cuban Hospital (CH) in 2012, where additional cardiology and mammography departments were created.

Furthermore, a total of 83 new X-ray units of various types were added: 57 in the new hospitals and 26 in the existing ones and the equipment installed in all new hospitals and departments was fully digital, in view of the substantial image quality improvements that digital flat panel detectors offer. However, in most of the existing HMC clinical imaging facilities, the transition from analogue to fully digital occurred gradually. Due to the larger inventory of general and mobile radiography equipment, many of these systems were still being used during this period, but screen/film images receptors and wet chemical processors were replaced by computed radiography (CR) systems and dry printers, that allowed images to be digitized without having to replace the X-ray units.

During this period a significant increase in staff number took place with an increase in number of MPs to 5 (see **Table 3**) while new QC equipment was also made available (see **Table 1**). Both Barracuda and RaySafe Xi were procured as complete systems for multiparameter measurements on all X-ray modalities, capable of simultaneous measurement of tube potential (kVp), incident air kerma (IAK) and incident air-kerma rate (IAKR) per second or per pulse, exposure time for radiographic, fluoroscopic and mammographic systems in addition to measurement of HVL (not applicable for mammography) and recording waveforms. Both sets of instruments were also equipped with software to record the measurements and extract them in worksheets. Cu sheets were used for simulating the X-ray beam attenuation from thin (1 mm Cu), medium (2 mm) and large (3 mm Cu) patients in both radiography and fluoroscopy, while the Leeds TOR CDR phantom which was added last in the equipment, could be used for image quality assessment in both radiography and fluoroscopy.

At the beginning of this period, new QC protocols, shown in **Table 4**, were applied for general radiography, mobile radiography and dental intraoral equipment. Regarding the general X-ray systems, it can be seen in **Table 4** that the basic addition was the automatic exposure control (AEC) QC tests. While image quality was still not monitored (it was added in the 3rd period), the functionality of the AEC in terms of incident air kerma to the image receptor was the first step for connecting QC tests with clinical practice, as far as the dose to the patient is concerned.

It must be stressed, that with screen/film image receptors, high or low patient doses would manifest as over- or under-exposed films respectively, something that was no longer valid with digital image receptors, either flat panels or CR cassettes. In digital systems due to the wider dynamic range and auto-adjusting of window width and level, the IAK to the image receptor does not affect the image "blackening" but only the noise.

Table 1 Equipment available for QC measurements over the years

1st period: 2005-2009	2nd period: 2010-2014	3rd period: 2015-2019	4th period: 2020-2021
Victoreen X-Ray Test Device, Model 4000M+, Fluke	RTI Barracuda multi-function meter	Fluke RaySafe X2 X-ray Measurement System: CTDI, kVp, Dose & Time	Fluke RaySafe DXR+ Tool: X-ray/Light field alignment
Gammex 330 Digital: kVp, Dose & Time Meter	Fluke RaySafe Xi X-ray: kVp, Dose & Time measurement System	Nested CT Dose Phantom Kit for Pediatric/Adult Head and Body Model 76-424-4156: CTDI measurments	Gammex-Sun Nuclear Modular DBT™ Phantom: image quality evaluation in 2D mammography and tomosynthesis
Gammex Model 115A / 115H: Half Value Layer Attenuator Set	Cu sheets (3 × 1 mm) for simulating patient attenuation	18-220 ACR Mammography Accreditation Phantom: image quality evaluation in 2D mammography	Leeds CBCT-161 Phantom: image quality evaluation in Dental CBCT (including automatic evaluation software)
Gammex Model 161B / 162A: Collimator and Beam Alignment Test Tools	Leeds test objects, TOR CDR, contrast-detail phantom	Leeds test objects, TO CDRH: R/F & X-ray image quality evaluation	Leeds PIX 13 phantom: beam alignment and image quality R/F testing
X-Rite 331C: Portable Transmission Densitometer			Iba Primus A Phantom: beam alignment and image quality R/F testing
X-Rite 334 Battery Operated Dual Color Sensitometer			Leeds TOR DEN digital Phantom; dental intra oral and panoramic image quality evaluation
			Gammex Mercury 4.0 phantom; QC for CT AEC
			* Quart Nonius Digital Electronic Ruler; measuring radiation beam slice-width and field edges
			* Gafchromic films XR-M2 and CT2: measuring radiation beam slice-width
			* Software for automatic evaluation of CT ACR, Leeds and iba Primus A phantoms

* Denotes equipment that has been ordered but has not been yet made available due to delays in tenders.

Table 2 Number of medical image printers installed in HMC hospital over the years

Type	1st period: 2005-2009	2nd period: 2010-2014	3rd period: 2015-2019	4th period: 2020-2021
Wet processors	5	-	-	-
Laser Printers (dry)	-	10	22	10

Table 3 Number of Diagnostic Radiology Medical Physicists and Assistants over the years

Staff	1st period: 2005-2009	2nd period: 2010-2014	3rd period: 2015-2019	4th period: 2020-2021
Medical Physicist	2	5	7	10
Assistants	2	3	3	5

The higher the IAK the lower the noise and the better the image quality, something which means that the radiologist would never complain but rather prefer "over-exposed" images [1, 2, 9]. On the other hand, radiologist would complain in the case that the noise was too high, something that would force the radiation technologist to increase exposure factors to an extent that could not be predicted. This was the reason why the addition of AEC tests was considered mandatory.

The new QC procedure not only enabled an indirect way of routine and systematic monitoring of radiation dose to the patient but also helped in the implementation of follow-up actions when IAK values to the image receptor were too high (i.e. > 5μGy on the image receptor and/or >10 μGy on table) or too low (i.e. < 2μGy on the image receptor and/or < 4μGy on table). Since most of the AEC systems had not been adjusted or have been adjusted for use with screen/film systems, the AEC function of most of the general X-ray machines initially failed in one or more of the AEC QC tests. These problems were rectified soon by informing the respective clinical imaging departments and contacting the company responsible for the service. The next most often failures observed were those regarding the exposure time accuracy, which were also corrected without any delay by the servicing company.

At the beginning of this period QC was still limited in X-ray and dental units. However, gradually fluoroscopy systems were incorporated in the QA program. Fluoroscopy is a modality used for dynamic examinations and can be found in various configurations, like over-couch and under-couch systems with radiographic capability or in C-arm configuration, stationary or mobile, like angiographic systems used for complex interventional procedures. Fluoroscopy systems are mainly used by radiologists, but also by cardiologists specialized in interventional cardiology procedures and by many other medical practitioners, such as gastroenterologists, orthopedicians, urologists and neurosurgeons, performing a wide range of diagnostic or therapeutic fluoroscopy guided procedures. Due to the dynamic nature and the complexity of some of these procedures, fluoroscopy can result in relatively high radiation doses which may lead to the occurrence of deterministic effects, like temporary or permanent skin injuries [5, 6]. For this reason, initially the focus of the fluoroscopic QC protocol was on the operational characteristics related to patient exposure.

In analogy to IAK on image receptor in radiography, when the IAK rate (IAKR) in fluoroscopy drops below a certain point, the radiologist will notice that the fluoroscopic images will become excessively noisy and this will hinder diagnosis. To increase the IAKR, an increase in exposure factors is required, which inevitably will result to an increase in the patient dose. So, it is essential to adjust and maintain the IAKR at such a level, that diagnosis is feasible and a further increase in IAKR will provide little improvement in image quality which is disproportional and does not justify the increase in patient dose. The inclusion of image quality tests in the fluoroscopy QC protocol (and later in the radiography QC protocol) was made feasible around 2013, when the Leeds TOR CDR contrast/detail phantom was added in the QC equipment. By the end of this period the QC protocol for fluoroscopy systems and mobile C-arm units - briefly described in **Table 5-** had been formulated [30].

By the end of the 2nd period 157 (99 X-ray and dental, and 58 fluoroscopy units) out of 176 systems (90%) were included in the QA program. During this period, the focus was on setting acceptable performance limits based on the existing international QC protocols [15-17,30], while on the practical side, any failed QC test identified was communicated to the service engineers along with the suggested course of actions that was expected to resolve the problem. The success of every repair performed by the service personnel was documented by follow-up QC tests.

3rd period: 2015-2019

By the end of the previous period, a 90% of the radiology equipment installed in HMC hospitals was included in the QA program. However, this was not satisfactory since two crucial modalities had been still ignored: CT and mammography! Justifiably and undoubtably CT is considered the flagship of the diagnostic equipment involving ionizing radiation. Currently, CT examinations are responsible for more than half of the collective population dose due to medical exposures. Therefore, though image quality is always of primary concern, the patient dose in CT has come in focus during the last years. The QC protocol for CT scanners is described in **Table 6** and as can be seen the QC tests are focused on both image quality and patient doses, though only a limited number of clinical protocols are evaluated (adult & pediatric head, adult and pediatric abdomen & adult HR chest) [8,31,32].

Table 4 QC tests performed in general radiology (GN), mobile (GM) and dental intraoral (DI) units during the periods 2005-2009 and 2010-2014 [11,12,18-20].

Period	2005-2009			2010-2014		
PERFORMED QC TESTS \ Equipment type	**GN**	**GM**	**DI**	**GN**	**GM**	**DI**
1. Beam Geometry Evaluation						
1.1. Source-to-image distance indicator accuracy	×	×	×	✓	✓	×
1.2. X-ray & collimator light field alignment	✓	✓	×	✓	✓	×
1.3. Alignment of image and X-ray field center	×	×	×	✓	✓	×
1.4. X-ray beam perpendicularity	✓	✓	×	✓	✓	×
2. Generator and tube QC tests						
2.1. kVp accuracy	✓	✓	✓	✓	✓	✓
2.2. kVp reproducibility	✓	✓	✓	✓	✓	✓
2.3. kVp independence of mAs selection	×	×	×	✓	✓	×
2.4. Tube output (O/P) vs kVp	×	×	n/a	✓	✓	n/a
2.4. Tube O/P linearity	✓	✓	✓	✓	✓	✓
2.5. Tube O/P reproducibility	✓	✓	✓	✓	✓	✓
2.6. Tube O/P comparison large & small focus	×	n/a	n/a	✓	n/a	n/a
2.7. Exposure time accuracy	✓	n/a	✓	✓	n/a	✓
2.8. Exposure time reproducibility	✓	n/a	✓	✓	n/a	✓
2.9. Half Value Layer	✓	✓	✓	✓	✓	✓
3. Automatic exposure control (AEC) QC tests						
3.1. Relative response of AEC chambers	×	n/a	n/a	✓	n/a	n/a
3.2. AEC reproducibility	×	n/a	n/a	✓	n/a	n/a
3.3. AEC response (image receptor dose)	×	n/a	n/a	✓	n/a	n/a
3.4. AEC density control evaluation	×	n/a	n/a	✓	n/a	n/a
3.5. AEC kVp selection compensation*	×	n/a	n/a	✓	n/a	n/a
3.6. AEC thickness compensation*	×	n/a	n/a	✓	n/a	n/a

✓: Acceptance and routine QC tests, ×: QC tests not performed, n/a: not applicable

* In the 2020 revision these tests were merged to one, as the kV are adjusted according to the phantom thickness. Image quality QC tests (Low contrast sensitivity and spatial resolution) and display monitor QC tests were added for all modalities. KAP meter and exposure index accuracy test were also added for GN and GM units, as well as, the review of average KAP values in comparison to DRLs for GN.

Table 5 The fluoroscopy QC protocol established and applied during the 3rd period and differences with the latest protocol. The tests that refer to the radiographic capabilities of these systems have been omitted, as they are described in **Table 4** [21-29].

PERFORMED QC TESTS \ Period	2015-2019	2020-2021
1. Beam Geometry Evaluation		
1.1. Field size indicators versus actual exposed area	×	✓
1.2. Alignment of tube to image receptor	×	✓
2. Generator and tube QC tests		
2.1. kVp accuracy	✓	✓
2.2. Tube output (O/P) vs kVp	×	✓
2.3. Half Value Layer	✓	✓
3. Automatic exposure control (AEC) QC tests		
3.1. IAKR to image receptor	✓	☑
3.2. ESAKR* to standard patient** for all FOVs§	✓	✓
3.3. ESAKR to thin (1 mm Cu) and thick patients (3 mm Cu) for all FOVs§	×	✓
3.4. Maximum patient Entrance Surface Air-Kerma rate	✓	✓
4. Image quality		
4.1. Low Contrast Resolution	✓	✓
4.2. Limiting Spatial Resolution	✓	✓
5. Dosimetry		
5.1. KAP meter accuracy & Reference Air-Kerma accuracy	×	✓
5.2. Average Examination Doses	×	✓
6. Display monitor performance	×	✓

☑: QC tests performed in acceptance only, ✓: Acceptance and routine QC tests, ×: QC tests not performed, n/a: not applicable

*ESAKR is the entrance surface air kerma rate at the patient entrance surface and is equal to the IAKR multiplied by the backscatter factor (BSF) which increases with field size and beam HVL

**2 mm Cu are used to simulate the average patient attenuation

§ In the latest QC protocol routine tests are limited to a maximum of the 4 largest FOV selections

On the other hand, mammography is a very specialized and crucial examination for the early detection of breast cancer, and it is the first radiology examination that is performed in asymptomatic women in the context of screening programs [5,6]. Due to the low energy spectrum required to achieve the image quality necessary for confident diagnosis of subtle differences in breast structure associated with breast cancer, radiation dose to the breast is an issue. This fact combined with the radiosensitivity of the breast have set very high standards for the equipment and techniques that should be used to obtain optimum conditions in breast imaging. In view of these requirements, the QC tests should be thorough and focused on both breast dose and image quality and assure that all components of the imaging chain are operating properly. The QC protocol for mammography systems is described in **Table 7** [31]. It must be noted that the diagnostic workstations used in mammography have usually two medical grade high resolution monitors (of 5 megapixels or more) and their QC testing is most demanding compared to all other modalities.

Table 6 The CT QC protocol established and applied during the 3rd period and differences with the latest protocol [32,33].

PERFORMED QC TESTS \ Period	2015-2019	2020-2021
1. Technical and geometrical assessment		
1.1. Scout prescription and alignment lights accuracy	✓	✓
1.2. Table Travel Accuracy	✓	✓
1.3. Radiation Beam Width	×	✓
2. Generator and tube QC tests		
2.1. kVp Accuracy	×	☑
2.2. Exposure Time Accuracy	×	☑
2.3. Reproducibility (kVp, Time, Radiation output)	×	☑
2.4. Radiation Output Linearity	×	☑
2.5. Beam Quality (HVL)	×	☑
3. Image quality		
3.1. Artifact Evaluation	✓	✓
3.2. Water CT# accuracy and image noise	✓	✓
3.3. CT# Uniformity	✓	✓
3.4. CT# Accuracy		✓
3.5. Spatial Resolution	✓	✓
3.6. Low-Contrast Performance	✓	✓
4. Dosimetry		
4.1. Displayed CTDI value accuracy	✓	✓
4.2. Average Examination Doses	×	✓
5. Display monitor performance	×	✓
5.1. Visual analysis (Acquisition and diagnostic workstation monitors)	×	✓
5.2. Luminance checks (Acquisition and diagnostic workstation monitors)	×	✓

✓: Acceptance and routine QC tests, ×: QC tests not performed ☑ QC tests performed in acceptance only

To apply these protocols, specialized equipment for CT and mammography QC tests (for image quality and dosimetry) was supplied, as can be seen in **Table 1**. Additional experienced personnel were hired (number of MPs have increase to 7) and training of the existing personnel on the new modalities was also performed.

Table 7 The mammography QC protocol established and applied during the 3rd period and differences with the latest protocol [31,34].

PERFORMED QC TESTS \ Period	2015-2019	2020-2021
1. Beam Geometry Evaluation		
1.1. X-ray beam and light field alignment	✓	✓
1.2. Alignment of X-ray field with image receptor	✓	✓
1.3. Alignment of compression paddle at chest wall edge with image receptor	✓	✓
1.4. Accuracy of displayed compression force value	✓	✓
2. Generator and tube QC tests		
2.1. kVp accuracy and reproducibility	✓	✓
2.2. Tube output (O/P) reproducibility*	✓	✓
2.3. Tube output (O/P) linearity	✓	☑
2.4. Half Value Layer*	✓	✓
3. AEC tests		
3.1. AEC repeatability	✓	☑
3.2. AEC "black level" compensation	✓	☑
3.3. AEC thickness compensation	✓	✓
3.4. SNR variation with thickness	×	✓
4. Image quality		
4.1 ACR DM phantom score (fibers, microcalcifications, masses, SNR etc)	✓	✓
4.2 Limiting Spatial Resolution	✓	✓
5. Dosimetry		
5.1. IAK measurement and AGD calculation for the ACR phantom	✓	×
5.2. Displayed AGD accuracy for ACR**	✓	✓
5.3. Average Examination Doses	×	✓
6. Display monitor performance	×	✓
6.1. Visual analysis (Acquisition and diagnostic workstation monitors)	×	✓
6.2. Luminance checks (Acquisition and diagnostic workstation monitors)	×	✓
7. Manufacturer proposed tests (e.g. Image receptor uniformity, MTF, etc.)	×	✓

☑: QC tests performed in acceptance only, ✓: Acceptance and routine QC tests, ×: QC tests not performed

* In the software accompanying that latest QC protocol, the normalized O/P variation (in μGy/mAs at a reference distance) and HVL versus kVp selection dependence is fitted by a second order polynomial for all anode/filter combinations used, so that the IAK and AGD for any exposure can be automatically calculated from exposure factors and phantom thickness.

** In the software accompanying that latest QC protocol, the displayed AGD accuracy is extended not only to the ACR phantom but all other thicknesses, and furthermore to tomosynthesis acquisitions.

Further increase was observed in the number of the X-ray equipment as described in **Figure 3** as 5 new hospitals were added during this period: the Communicable Disease Center (CDC) in 2016, the Ambulatory Care Center (ACC) in 2017, the Women's Wellness and Research Center (WWRC) in 2017, the Qatar Rehabilitation Institute (QRI) in 2017 and the Hazm Mebaireek General Hospital in 2018 (HMGH). By the end of this period QC tests were performed for 242 out of 251 machines, covering all modalities except panoramic, dental cone beam CT (CBCT, 3D-Dental) and DEXA units.

These changes in the number and the complexity of the equipment and the required QC tests, triggered a change in the routine QC test frequency, which was reduced from twice to once a year. Apart from QC phantoms, 3 new sets of multifunction meters (Fluke RaySafe X2 X-ray Measurement System) were added in the QC equipment. These new systems have all the favorable characteristics of the older model and additionally have more beam calibrations and automatic HVL calculations for mammography. Also, these sets have pencil type ionization chambers for CTDI measurements required for CT (currently the available sets in the MPS are 11 such sets).

It must be noted that in **Table 4, 5, 6 and 7** are not included QC tests regarding personnel safety assessment (shielding assessment which is carried out for all X-ray installations during acceptance and periodically ever after). These tests for the case of CT are more demanding in view of the high workload involved, something which is also valid for fluoroscopic installations. The presence of protective equipment for personnel and patients (like lead aprons and collars) is also recorded and periodically checked for wear and tear, while personnel dosimetry services are also offered by a subsection of the MPS.

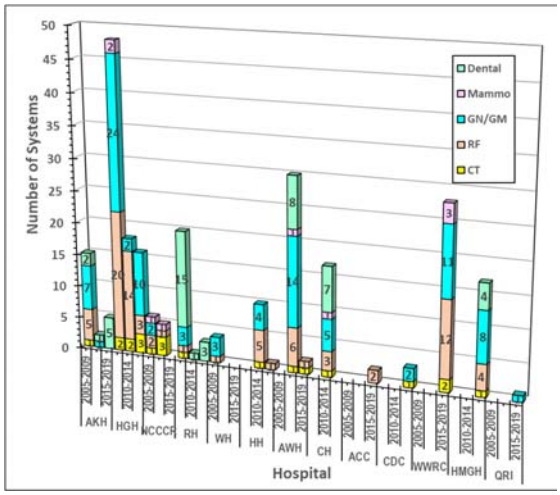

Figure 3 The types and numbers of new X-ray modalities distributed in the Clinical Imaging Departments of the 13 HMC hospitals during the period 2015-2019.

4th period: 2020 – 2021

By the end of the 3rd period QC protocols for all modality types have been established and applied for five years. Medical physicists have gained significant experience in QC procedures and in the use of all new electronic equipment and phantoms required for performing QC tests. Furthermore, the proper procedures for communicating the problems found in any of the X-ray modalities to the respective servicing companies, in order to resolve the problems and restore the operation of the X-ray modalities back to normal, had also being established. As a highlight of the end of this period came the accreditation of our QC services by the MEFOMP (Middle East Federation of Organizations of Medical Physics) in January 2020. In other words, MEFOMP certified that the MPS has implemented and maintained the Quality Control Service Provider (QCSP) requirements according to MEFOMP accreditation program for quality control service provider of X-ray medical equipment for the following X-ray units: CT, fluoroscopy units, general radiography and mobile X-Ray, mammography (2D and DBT), dental units (intra oral, panoramic, cephalometric and CBCT), bone densitometer (DEXA or DXA) and EOS-biplanar Bone Scan. This accreditation was granted after comprehensive audit by external auditors of the QCSP procedures that verified compliance with the MEFOMP requirements. The accreditation is valid until 26-01-2023 (https://www.mefomp.com/CERTIFICATE-OF-ACCREDITATION-001_a6988.html).

During the accreditation process that was finalized just at the beginning of the 4th period, a task group was created within the MPS to prepare the transition to a new era. The first step was to review all the latest international QC protocols from United States and Europe, to search for any changes and additions in the QC procedures, operational limits and QC equipment used. Using as a base the QC procedures already applied in the Department and incorporating all new information found in the reviewed literature, a book entitled "Quality Control Procedures for diagnostic X-ray equipment" was finalized and will be published soon by HMC (henceforth referred to as QC Procedures Handbook). The idea that came into play was that all QC tests should be homogenized, that is to be performed in exactly the same way by all MPS personnel, so as to mitigate any differences in the QC results that may arise from slight variations in the geometrical set-up or equipment used. The QC Procedures Handbook was reviewed by all experienced medical physicists of the MPS until it was finalized. These QC tests are described in **Tables 5-7** for fluoroscopy, mammography and CT modalities respectively. The QC tests for X-ray systems and mobile units are basically those described in **Table 4** for the period 2015-2019. Modified and added QC tests are described in the respective footnotes. The literature used for describing the QC procedures and setting the pass/fail limits are given in the *References* section [35].

Something new in this QC Procedures Handbook was the classification of QC tests in two different priority categories. Those that it is imperative to be performed in every routine QC test and those that can be postponed for a later time or even until the next QC. Given the fact that time is an issue in busy Clinical Imaging Departments and that sometimes the available time is not enough to complete all QC tests, it was accepted that QC tests of parameters that are known to be fairly constant or are of secondary importance were assigned to the second category.

To obtain complete homogenization, it was understood that it was not enough for the QC tests to be performed in the same way. It was also necessary that all measurements would be processed in the same way and the results would be reported in the same way, leaving as possible no space for errors in calculations or deviations in the QC report format. For this purpose, electronic QC forms (eQC-forms) were prepared using Microsoft Excel for all modalities that had some unique characteristics. First, only those cells that were designated for data input were unlocked. All the rest cells that were used to perform calculations or report the QC results were locked to prevent accidental modifications that could alter the calculations and results. Secondly, in these eQC-forms, limits were stored in a specific worksheet (to be able to change them in case that a limit is revised in the future) and along with the baseline values were appearing in the 1st page of the QC report. In this way, all performed QC tests, the pass/fail limits and the QC results (pass/fail) were shown in a single page. Distinct colored symbols were used to denote Pass/Fail and QC tests that were not performed were clearly shown, since all the cells assigned to report the QC results, the pass/fail limits and the pass/fail QC result were automatically blanked out. To accept a QC report as adequate, only QC tests of secondary priority are allowed to be blank. Each QC report before being uploaded to the portal and being officially available, it must be reviewed and approved by the assigned qualified clinical medical physicist.

Another interesting characteristic was that every data input in these forms were compared with the baseline QC results or/and the QC limits where applicable. Using conditional formatting, every time that a data input deviated by 5% or 10% (depending on the case) from the baseline, taking into account possible differences that could exist between these QC tests (e.g. a different mAs value or source-to-detector distance), the input value was turned into red color or was assigned with a pass, fail (depending on the case) to alert the medical physicist that special care should be taken to check if the measurement has been done in the proper way or a typing error was made. It must be noted that while these forms are designed in such a way that eventually all measurements from the multifunction meter can be automatically fed into the appropriate cells, there are always cells were values had to be manually typed or selected from a drop-down list of selections. Similarly, cells containing calculations may become red or be assigned with a pass, fail or in some cases a warning symbol when they deviate from

limits, baseline values, previous measurement or desired values. Special techniques to avoid error signals or collapse of graphical representations in case that one or two values are omitted (e.g. if 5 instead of 6 measurements for reproducibility are performed) were used, though the completeness of QC tests is always pursued. Finally, it should be mentioned that these forms are made in a way so that the QC report page and all measurement and calculation pages to be printed easily and seamlessly in a PDF formatted file, for electronical archiving or/and hard copy printing.

Regarding QC equipment, during 2020 new QC equipment that has been ordered since 2019 was received (Leeds PIX 13, CBCT-161, Coarto Force Gauge, Gammex Modular DBT™ Phantom, RaySafe DXR+, iba Primus A Phantom, Leeds TOR DEN digital, Gammex Mercury 4.0 phantom) while tenders for the supply of software for image analysis of ACR CT phantom, and Leeds Phantoms Gafchromic XR-M2/CT2) are ongoing. Regarding the X-ray equipment, during 2020 two new hospitals were established: Mesaieed Hospital (MH) and Ras Laffan Hospital (RLH) with additional 17 X-ray systems (3 CT, 3 fluoroscopic systems & C-arm units and 11 fixed radiographic and mobile X-ray units). Also, the Trauma Department of HGH (Hamad General Hospital) got extended like a new hospital with a total of 15 X-ray systems, bringing the total number of X-ray units which are supervised by MPS to over 300. The increase in hospitals (including the number of X-ray units and Medical Physicists) with respect to the increase of population in the state of Qatar is summarized in **Figure 4**.

IV. Discussion

In the results section the evolution of the QC services of MPS has be presented for the last 17 years along with the revised QC procedures, described in the QC Procedures Handbook and the respective eQC-forms created. It is a fact that the rapid growth of HMC in terms of diagnostic X-ray equipment, has forced the MPS to grow accordingly, nevertheless with a relative time delay as the increase in personnel and QC equipment was slower and not synchronized with the needs in terms of QC services required. Despite difficulties, MPS has grown in terms of personnel and QC equipment but most importantly has evolved in terms of the quality of QC services offered.

The current QC protocols have adopted most of the 3rd period's QC protocols, but with certain revisions and additions, to give more gravity in three main fields: a) the homogenization in terms of QC test procedures, data processing and QC results reporting, b) the evaluation of the image quality of imaged phantoms and the image quality of display monitor used for acquisition or diagnosis of any type of X-ray images, c) the incorporation in QC test of review of patient dose data regarding examinations performed in each X-ray system under QC. This is possible since a Dose Monitoring System was installed in 2018 which collects patient dose related data from almost all radiology systems. In this way the QC includes the results of patient dose data and their comparison with relevant Diagnostic Reference Levels (DRL) set for specific examinations.

Regarding homogenization, the methods used to achieve this, were described in the previous sections and the outcome will be evident in the years to come. Using standardized QC report forms for all X-ray modalities of a certain type will allow the QC results to be easily mined, so that the long term performance monitor of all radiology systems would be easily presented in graphs in relation to time for the years to come.

Regarding image quality, it must be reminded that regardless deviations of any parameter from the limits set, what is the concern is the final product of the imaging chain which is the image itself. An X-ray system that is perfect in terms of all QC parameters related to generator, tube and AEC systems could still produce non-diagnostic images, if for example the image receptor is not properly calibrated or it has artifacts. Furthermore, for digital systems, the digital images will be distributed within the clinic or even to associated hospitals via web and the diagnosis will be made in display monitors whose characteristics and adjustments should be such that the information contained within the digital image is properly displayed to the eyes of the radiologist or any other physician reviewing and interpreting this image.

CT scanners were the first X-ray modalities which were digital right from the start, though in the beginning CT images were printed in films, using wet processors (laser cameras) and later dry printers, and diagnosis was made using viewing boxes. However, it is well known that gradually films were abolished and CT diagnosis for many years now is made using monitors. The same situation now applies for mammography, fluoroscopy and X-ray systems (even for the mobile ones) and dental imaging of all types (intraoral, panoramic and 3D CBCT images). The requirements regarding the technical characteristics of CT monitors are far inferior to those used in mammography, which is the most demanding imaging modality regarding the diagnostic workstations' monitors. Whatever the modality is, QC of monitors was incorporated in our QC procedures, since is a key-element that is often overlooked. Digital images like the SMPTE or TG18 family images can be used to evaluate the diagnostic monitors. Ideally, the same monitors used for diagnosis should be used to score the images of QC phantoms, however, when this is not possible, phantom IQ scoring can be performed in the acquisition workstation monitor as well, which should be always tested, since it is the monitor used for the first image quality assessment made by the radiation technologist in order to decide if the IQ is satisfactory or a repeat examination is required.

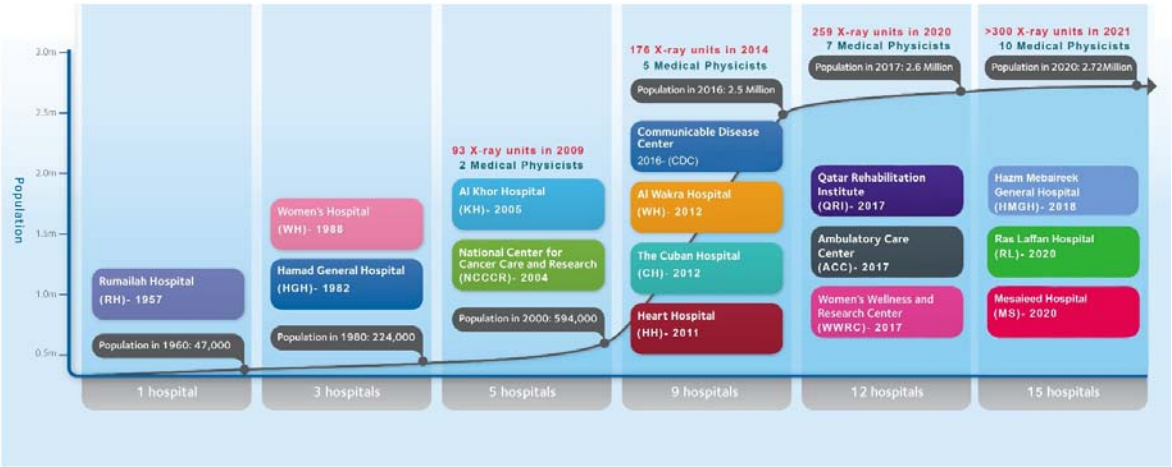

Figure 4 The timeline of the increase of number of hospitals under HMC (including the number of X-ray units and Medical Physicists) with the increase of population in Qatar from between 1957 and 2020.

Finally, the review of patient average doses is meaningful addition in the QC procedures, since in this way it is reviewed not only the X-ray modality performance but also the radiation technologist practices, regarding the radiation protection of patients. This is feasible given the fact that a dose monitoring system (RDM, Medsquare, France) is available and connected to most of the X-ray systems currently operating in our hospital.

What should be also mentioned as a closing argument, is that the extra focus given in image quality and patient dose related QC tests aims to make medical physicists more visible to all medical specialties involved in the use medical imaging. Medical physicists in radiology should assume their new role which is not only what is very graphically described as "the vampire physicist who only appears at night and only leaves reports …" [17, 36]. The results are quite encouraging since the last 2-3 years the MPS are always participating in meetings and projects that aim to improve the existing institutional policies and procedures for the safe and effective use of radiation, but also to research activities related to patient radiation safety and diagnostic image quality.

Therefore, it is important for all medical physicists which work in the field of diagnostic radiology worldwide, to comprehend that hard work and continuous effort is needed to achieve the goals that promote both the essence and the appearances of the qualified clinical medical physicist profession. Medical physicists should be knowledgeable and have the appropriate QC tools to be able to evaluate the performance of the X-ray systems, interpret the QC test results and identify the possible cause of a failed QC test. They should be able to keep up with the pace of the evolution of radiology equipment which generates the needs of new QC tests and this means that they should follow the international literature related to this field. Most important medical physicists should comprehend that being useful to radiologists, technologists, service engineers, is a major goal and helps the medical physicists to be visible and indispensable for the operation of a radiology facility, not only for reasons related to radiation safety of personnel. However, it should be always remembered that the ultimate goal of our profession is to be useful to the patients who should be able to have their medical images being acquired with the least possible radiation dose and the best possible image quality.

V. Conclusions

The MPS of HMC started its operation in 2000 and during the last 17 years has grown in terms of personnel and equipment number, but most importantly has evolved in terms of QC services offered for the HMC hospitals' radiology equipment. Starting form 93 X-ray systems that could not be all supervised, now the section is at a point where over 300 X-ray systems are all supervised using state-of-the-art QC equipment and procedures.

Despite the recent accreditation from the MEFOMP organization which gave the MPS staff added confidence to carry out their duties with sheer perseverance, it is always good to remember that there is always room for improvement and that QC is an ongoing process that should be continuously evolve to keep up with the evolution of the X-ray equipment. For this reason, the international developments regarding QC procedures in new techniques (like for example breast tomosynthesis and dental CBCT) were implemented, and as experience is gained, the QC test procedures, performance limits and eQC-forms may be further enriched and revised. This article will hopefully serve

as guidance for medical physics groups that want to update their QC services, obtain accreditation, keep up with the pace of the rapidly evolving technology of radiology equipment and make themselves visible to the rest medical professionals.

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