Development of a low-cost imaging performance evaluation phantom for a generic multi-detector CT scanner

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Abstract. For quality assurance, an evaluation phantom is an important tool used to assess the imaging performance of a multi-detector CT (MDCT) scanner. In doing so, this would help to prevent the production of low-quality images that may lead to misdiagnosis and repeats of x-ray exposure. However, imaging performance test phantoms available commercially are too costly for resource-limited CT facilities to procure. This study aims to design an imaging performance evaluation phantom, fabricate a low-cost prototype of the design, and assess the suitability of use of the fabricated phantom under existing performance testing protocols. The phantom was designed according to recommended specifications from IAEA and AAPM and the prototype of the design was manufactured using engineering plastics and industrial metals through computer numerical controlled (CNC) machining and stereolithography (SLA) 3D printing. The fabricated phantom prototype was then tested with United Imaging 80-slice MDCT scanner and its usability was compared to Gammex ACR 464 phantom following the ACR QC assessment methods. This research was able to produce a three-module solid plastic phantom with a performance at par with the commercial phantom. Furthermore, the overall manufacturing cost for the fabrication of the phantom was 87% cheaper than the cost of acquiring a commercial phantom. Thus, local development of a quality assurance phantom for CT is a cost-effective solution for resource-limited facilities.

1. Introduction

Multi-detector computed tomography (MDCT) scanning is an important imaging modality in healthcare as it provides physicians clinical images with a clear view of the anatomical feature of interest without the obstruction from the overlying structures [1]. The acquired CT images are useful in diagnosing a patient’s condition, for monitoring the patient’s treatment and for simulation of radiotherapy planning. As such, it is essential to test the imaging performance of a MDCT scanner before it will be utilized in the facility, and at a regular basis during the machine lifetime. This will prevent the production of a poor-quality CT image that may lead to misdiagnosis and repeats of x-ray exposure. To conduct an imaging performance assessment, a test phantom made of water or tissue equivalent materials that simulates the human head or body is used [2]. It contains modules with different embedded materials of various shapes and sizes for light field accuracy, low contrast resolution, CT number accuracy, image distance accuracy, noise, uniformity, artefacts, high contrast resolution and slice thickness accuracy tests. The imaging performance evaluation phantom are of two types, manufacturer-supplied and commercial. Manufacturers of MDCT scanners provide a proprietary phantom as an accessory to a
purchased CT scanner for used in the routine daily quality control (QC) tests of the CT scanner. On the other hand, commercial suppliers of medical imaging test tools offer internationally recognized standard phantoms that can cover all the required image quality tests and can be used in any MDCT scanner brand for acceptance, commissioning and annual quality assurance.

However, standard commercial phantoms are too costly for resource-limited CT facilities to procure. As a result, the comprehensive imaging performance testing of CT scanners in resource-limited facilities are conducted in a limited extent. In some of these facilities, the complete evaluation of the imaging performance of a CT scanner is only done during the installation of the equipment by medical physics testing laboratories hired to do the initial testing. For routine QC tests, only limited tests can be performed using the manufacturer’s phantom provided with the CT scanner during installation. While the facilities can still re hire a medical physics testing laboratory to conduct the annual comprehensive performance testing during the useful life of the machine, such a strategy will be very expensive in the long run.

As such, attempts to address the cost and availability of a comprehensive CT imaging performance test phantom for resource-limited facilities were carried out. [3-5]. These studies showed that local fabrication of a CT imaging performance test phantom is a cost-effective solution and their fabricated phantoms are of comparable quality to that of commercial phantoms. Nevertheless, the design of their phantoms still needs improvement as the phantoms either lack some essential image quality tests or consist of separate modules that need to be set up and scanned individually, making them inconvenient and inefficient to use. Hence, these previous attempts were still subject to modification and improvement.

The objectives of this research were to design a convenient and efficient to use imaging performance evaluation phantom that contain all the required image quality tests, fabricate locally a prototype of the designed phantom using inexpensive and readily-available manufacturing methods and materials, and assess the usability of the fabricated phantom. By providing a low-cost comprehensive imaging performance evaluation phantom, resource limited CT facilities will be able to acquire the phantom and the conduct of a comprehensive imaging performance testing at a regular basis would become more accessible for these facilities.

2. Methodology

2.1. Phantom Design and Fabrication

In this study, a design of a solid and modular phantom was developed. The imaging performance tests included, the dimensions of the test elements, and the materials to be used were based on the published reports from AAPM and IAEA [6-9]. The tests incorporated in the phantom design were light field accuracy, qualitative low contrast resolution, qualitative high contrast resolution, CT number accuracy, uniformity, and slice thickness accuracy. After the specifications of the phantom were formulated, the two-dimensional drawings of the phantom design following the specifications were generated using AutoCAD® and the three-dimensional (3D) model was rendered in SketchUp.

For the fabrication of the prototype of phantom design, engineering plastics and metals were sourced from local industrial suppliers and were used as phantom materials. The engineering plastics were cut into the designed sizes by the machinist/s of the supplier using a computer numerical control (CNC) router to form the phantom body and the test objects for CT number accuracy and low contrast resolution. Holes were drilled in the phantom body using the same equipment where the test objects were inserted. Four lines along the length of the phantom body of equal circumferential distances from each other, and a line around the circumference at the center of each phantom modules were engraved using the CNC router for phantom positioning and alignment. For the qualitative high contrast resolution test object, it was manufactured by a local fabrication laboratory through stereolithography apparatus (SLA) 3D printer using a standard photopolymer resin. For the slice thickness accuracy test, a metal was used and manually cut into the designed size. For the light field accuracy test, metals were fixed on the
surface of the phantom body at the designed locations. After the phantom body and the test objects were constructed, the test objects were then inserted and fixed on the phantom body.

2.2. Usability Testing
For testing the usability of the phantom, imaging performance testing using the prototype phantom was conducted on a newly installed United Imaging uCT 550 80-slice CT scanner in a local hospital facility. The ACR QC testing protocol for each imaging performance parameter was followed [10]. The output phantom images were then opened in a DICOM viewer and tools for image analysis in the software were used to evaluate the quantitative tests (CT number accuracy, uniformity and slice thickness accuracy) and the qualitative tests (low contrast resolution, high contrast resolution, light field accuracy) were assessed visually. The assessment method from ACR, IAEA and Catphan® were followed [8,10,11]. Afterwards, the results of the image analysis were validated with established acceptance criteria and compared with the results of the acceptance testing using the Gammex ACR 464 phantom conducted prior to the scanning of the phantom prototype. The established acceptance criteria used to evaluate the results of imaging performance test using the prototype phantom were based from [8-10].

3. Results and Discussion

3.1. Designed Phantom and Fabricated Prototype
The finished design of the phantom was a solid cylinder with a body made of high-density polyethylene (HDPE) plastic and consisted of three modules. The diameter of the phantom body was 20 cm and the thickness of each module was 4 cm. HDPE was chosen as the ICRU committee had already studied the use of HDPE as a phantom material for CT and the committee specified that this material is a more physiologically relevant than the typically used PMMA [12]. The density of the HDPE (0.97 g/cm³) is also closer to the density of water (1.00 g/cm³) than the PMMA (1.19 g/cm³). Moreover, HDPE is cheaper, not vulnerable to moisture absorption and has an excellent impact resistance and high tensile strength than PMMA, making it more durable and not prone to accidental cracks or breakage. The phantom was designed specifically to have three modules such that less material would be used but still with a homogenous section for uniformity test, and without overcrowding a single module with different test objects. Table 1 below presents the specifications of the designed phantom and figure 1 and 2 shows the 3D model and the actual prototype of the designed phantom, respectively. The module 1 of the phantom contains the tests for CT number accuracy and low contrast resolution, module 2 is the plain middle section for uniformity test and module 3 contains the tests for high contrast resolution and slice thickness accuracy. On the surface of the phantom body, the test objects for light field accuracy test were fixed on the center of the module 1 and 3 at four locations of equal distances from each other for each module. The machinability, manufacturing costs, and availability of the materials used were considered when the specifications of the phantom was designed. Presented in figure 3 and 4 respectively are the CNC-machined phantom body and test plastics, and the SLA-printed high-resolution test pattern. For CNC-machined test plastics, the deviation of its actual dimensions from the designed specifications were all within 1%. This fabrication method was able to achieve the designed specifications with high accuracy. Moreover, the SLA 3D printer was able to create the designed high contrast resolution test pattern up to 0.6 mm holes. For the cost of fabrication of the prototype, the expenses for the materials and the manufacturing services in total were only 13% of the cost of acquiring a commercial phantom.

| Imaging Performance Test | Dimensions/Material |
|--------------------------|---------------------|
| CT Number Accuracy       | PE, PA, PMMA, PC, PET, PTFE rods |
|                          | PE container with distilled water |
|                          | Air hole |

Table 1. Designed phantom specifications for each imaging performance test.
Low Contrast Resolution
Uniformity
High Contrast Resolution
Slice Thickness
Light Field Accuracy

PMMA rods (ø: 3 – 16 mm)
Plain middle section of HDPE body (ø: 200 mm)
Square air holes (ø: 0.5 mm – 2.5 mm)
0.5 mm thick aluminum plate inclined at 45°
Steel ball bearings (ø: 1 mm)

| Figure 1. 3D model of the designed phantom specifications showing the surface of (a) module 1 and (b) module 3. |
| Figure 2. Actual fabricated prototype of the designed phantom showing the surface of (a) module 1 and (b) module 3. |
| Figure 3. (a) CNC-machined voids of phantom body and the (b) test plastics for CT number accuracy test. |
| Figure 4. Fabricated designed pattern for high resolution test using SLA 3D printer. |

3.2. Usability Testing Results

Figure 5 and 6 below shows the scanned CT image of the prototype and Gammex ACR 464 phantom, respectively using adult abdomen protocol (120 kVp, 80 mAs) at 5 mm slice thickness. Each imaging performance test on the Gammex ACR 464 phantom can also be found on the developed phantom. It can be observed from table 4 that for the prototype phantom, the mean values of each imaging performance test parameters were within the acceptance criteria as with the results using the Gammex ACR 464 phantom. Each designed imaging performance test element of the developed phantom was able to test the MDCT scanner at par with the test materials of Gammex ACR 464 phantom. Moreover, similar with solid modular commercial phantoms, the developed phantom was efficient to use as it can be set-up as is on the CT table throughout the testing after proper alignment and only a few scans were needed for imaging performance analysis. This is a good feature as it minimizes the time consumed during testing and the tube usage. In terms of portability, the prototype phantom weighed 37% lighter.
than Gammex ACR 464 phantom [13]. As such, it is convenient to use and would also be suitable for field service applications.

Table 2. Summary of imaging performance testing results using the developed phantom and the Gammex ACR 464 phantom.

| Imaging Performance Test          | Acceptance Criteria | Designed Phantom | Gammex ACR 464 Phantom |
|----------------------------------|---------------------|------------------|------------------------|
| CT Number Accuracy Test          |                     |                  |                        |
| Teflon                           | 850 to 970 HU       | 931.00 HU        | 907.70 HU              |
| Air                              | -1005 to -970 HU    | -997.64 HU       | -985.40 HU             |
| Acrylic                          | 110 to 135 HU       | 127.40 HU        | 127.10 HU              |
| Water                            | -7 to +7 HU         | -2.60 HU         | 4.90 HU                |
| LDPE                             | -107 to -84 HU      | -53.53 HU        | -88.175 HU             |
| HDPE                             | -35 to -75 HU       |                  |                        |
| Low Contrast Resolution          | At least 6 mm ø rod/s must be distinct | 3 mm          | PASS                   |
| Uniformity                       | < 5 HU difference from center ROI  | 3.87 HU       | PASS                   |
| High Contrast Resolution         | HRC: 8 lp/cm        | HRC: 8.33 lp/cm  | HRC: 10 lp/cm          |
| Adult Abdomen: 6 lp/cm           | PASS                | PASS             | PASS                   |
| Slice Thickness Accuracy         | ± 0.5 mm difference from nominal | 0.30 mm      | PASS                   |
| Light Field Accuracy             | All four BBs must be visible | All visible | PASS                   |

Figure 5. CT scanned images of the modules of the prototype phantom: (a) low contrast resolution and CT number module, (b) uniformity module and (c) high contrast resolution and slice thickness module.

Figure 6. CT scanned images of the modules of the Gammex ACR 464 phantom: (a) CT number and slice thickness module, (b) low contrast resolution module, (c) uniformity module and (d) high contrast resolution module.
4. Conclusions
This research was able to provide a design and a prototype of a solid and modular imaging performance evaluation phantom for MDCT scanner. It was feasible to locally fabricate the phantom from readily available materials using small-scale machining methods at low costs. The fabrication methods and materials utilized were found to be accurate and applicable for phantom development. From the results of the usability testing, it can be inferred that the prototype phantom performed comparably well with the Gammex ACR 464 phantom. Thus, the developed design of the phantom test elements, the chosen materials, and their method of assessment, were suitable and adequate for CT scanner imaging performance testing. Similar with the commercial phantoms, the evaluation of each imaging performance parameter in the prototype phantom was not complex and can be done quickly with any DICOM viewer software. Furthermore, the phantom developed was relatively light, transportable, efficient and convenient to use. In general, the developed phantom is appropriate for imaging performance testing of MDCT scanner and is a cost-effective alternative for resource-limited facilities.

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