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Design and Development of an Indigenous In-house Tissue-Equivalent Female Pelvic Phantom for Radiological Dosimetric Applications

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ABSTRACT

Introduction: The present study is aimed to design and develop a tissue-equivalent pelvic phantom, mimicking the Indian female pelvic dimensions by means of locally available and cost-effective tissue substitutes having equivalent radiological properties.
Materials and Methods: For the purpose of the study, the real female pelvic bones were embedded for preparation. Paraffin wax, Aloe-vera powder, purified borax, and sodium benzoate, were used to obtain the proper density and effective atomic number. A hollow three-dimensional outer surface and the internal organs moulds were fabricated using gypsona bandage. The internal organs moulds were filled with semi-solid paraffin wax mixture, stabilized, and then embedded with pelvic bones and internal organs at the right anatomical positions. The surface mould, along with the bones and internal organs, were stabilized in their position in the final form, and verified with computed tomography (CT).
Results: The physical dimensions of the given female pelvic phantom were comparable with the mean dimensions of the Indian female pelvis. Furthermore this tissue-equivalent phantom was radiologically equivalent to the Indian human female pelvis in all respects. The CT numbers of the uterus, bladder, rectum, muscles, fats, bone, and cavities were 39.9, 30.5, 24.7, 34.6, -86.8, 578.6, and -220.9 HU, respectively. Furthermore, the relative electron densities of the muscle, fat and bones were 1.035, 0.913, and 0.779 in the phantom.
Conclusion: The dimensions and physico-radiological properties of the tissue substitutes provided a good inhomogeneous female pelvic phantom differing in dimensions with imported pelvic phantoms. Therefore, this phantom can be used for radiological dosimetric applications.

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Introduction

The carcinoma of the uterine cervix is the most prevalent malignancy affecting the Indian females. According to the latest report of the Indian Council of Medical Research of the National Cancer Registry Program [1], cervical cancer is very common among the females living in the Bangalore, Barshi, Bhopal and Chennai. Radiation therapy plays a vital role in the management of cervical cancer. A carefully planned radiation therapy yields excellent disease control and survival rate. The success of radiation therapy depends on the delivery of accurate radiation dose to the tumors site that is within the tolerance of the adjacent critical organs.

The female pelvis has various heterogeneous tissues (e.g., pelvic bones, soft tissues, fats, and air cavities).These pelvic heterogeneities have high potential to alter radiation doses on the tumor site and the adjacent critical organs [2, 3].

Therefore, the consideration of the effect of pelvic tissue heterogeneities on radiation doses is an issue of fundamental importance for the achievement of the radiotherapy goal. The verification of the final treatment plan on female pelvic phantom is an important step in the execution of radiotherapy plans on the patients with cervical cancer. Therefore, the specialized heterogeneous tissue-equivalent pelvic phantoms are necessary for direct radiation dose measurements and authentication of dose computational algorithms in treatment planning systems. Accordingly, these phantoms can facilitate the achievement of confidence on the finally approved plan or to improve the plans, if required.

The imported female pelvic phantoms for radiation dosimetry purposes are made up of bone

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tissue substitute and soft tissue substitutes [4-9]. In general, the radiation dosimetry is performed in water phantom of regular dimensions due to its easy availability and tissue equivalency [10]. When the measured dosimetric parameters are applied to patients for therapeutic purposes, the absorbed dose estimates are approximated in the bones, cartilages, fats, and air cavities. The transmission varies due to the presence of biological matters, such as urine, fecal matter, and cavities. This involves radiation dosimetry with corrections for heterogeneities.

The tissue heterogeneity correction algorithms available in the treatment planning systems need verification by direct measurements in phantoms. Followill et al. designed two heterogeneous anthropomorphic quality assurance phantoms to verify radiation dose delivery [11]. One of these phantoms was utilized for intensity-modulated radiotherapy in the pelvis, and the other one was intended for stereotactic body radiotherapy in the thorax.

Furthermore, Nan et al. developed voxel female pelvic phantom [12]. Additionally, a Taiwanese adult reference phantom was fabricated for dosimetry evaluation and planning simulation by Chang et al. [13]. All these phantoms were made for special applications, and data generated in these phantoms cannot be applied for the treatment of Indian female pelvic cancer patients. With this background in mind, this study is aimed to develop a cost-effective female pelvic phantom having the physical dimensions (i.e., shapes and sizes) of an average Indian female pelvis. Tissue-equivalence should be obtained using locally available tissue substitutes to fulfill the requirements of online radiation dosimetry in clinical radiotherapy.

Materials and Methods

Phantom design requirements

Axial CT-slices of 2 mm thickness were taken of the pelvic region of about 140 Indian female patients on a CT-Simulator. These axial slices were imported on a three-dimensional (3D)-Oncentra treatment planning system for the contouring of the surface and internal organs (i.e., uterus, bladder, and rectum). These contoured axial CT-slices were used for the 3D-geometrical reconstruction of the pelvic region (i.e., surface and internal organs) for each individual female patient.

The 3D-reconstructed female pelvic regions with internal organs images were utilized for measuring the surface length (i.e., from umbilicus to upper thigh), width (at umbilicus), and thickness at three points (i.e., umbilicus, symphysis, and upper thigh). Similarly, the bladder maximum (length, width, and thickness), uterus maximum (length, width), thickness at three points (upper, middle, and lower), and rectum length (from colon end to anus), where taken for all 140 female patients with the help of the available measuring tool in the Oncentra treatment planning system.

Subsequently, the female pelvic surface region, bladder, uterus, and rectum measurements (i.e., length, width, and thickness) were recorded in prepared excel sheets for all 140 female patients. Furthermore, the mean and standard deviation were computed for the surface region and internal organs (i.e. bladder, uterus, and rectum).

The mean values of the female pelvic surface region were used for making the outer surface mould, and the mean values of the bladder, uterus, and rectum were utilized for making the internal organ moulds.

Composition of structures

The bones of female cadavers (i.e., pelvic girdle, femur, and vertebrae) (Figure 1) were embedded for preparation.

Figure1. Pelvic and femur bone embedment

Paraffin wax amalgamated in suitable composition with Aloe-vera powder, purified borax, and sodium benzoate, were used to obtain the proper density and effective atomic numbers. Paraffin wax mixed with NaCl was utilized for fats and skin. The composition of materials used in the formation of internal organs was as follows:

1. Uterus (Paraffin wax [100 g] + Aloe-vera Powder [50 g] + Purified Borax [20 g] + Sodium benzoate [10 g])
2. Bladder (Paraffin wax [100 g] + Aloe-vera Powder [30 g] + Purified Borax [20 g] + Sodium benzoate [10])
3. Rectum (Paraffin wax [100 g] + Aloe-vera Powder [20 g] + Purified Borax [20 g] + Sodium benzoate [10 g])
4. Muscles (Paraffin wax [100 g] + Aloe-vera Powder [40 g] + Purified Borax [20 g] + Sodium benzoate [10 g])

5. Fats (Paraffin wax [100 g] + NaCl [20 g])

6. Bones: Indian Female Pelvic girdle bones

Fabrication of phantom

The inhomogeneous female pelvic phantom was made in four sequential steps: (i) a hollow outer surface and the internal organ shells were prepared with the aid of gypsona bandages and water: (ii) paraffin wax, mixed with aloe-vera powder, purified borax and sodium benzoate, was poured into the internal organ shells and left for stabilization: (iii) internal organs and pelvic girdle bones were placed in the outer pelvic surface shell at the right anatomical positions: finally,(iv) the semi-solid paraffin wax mixture was poured in the surface mould; subsequently, the whole assembly was left for cooling and stabilization. Figure 2 illustrates the pelvic phantom in its final form.

Figure 2. Pelvic phantom containing structures

Evaluation of radiological properties (Hounsfield Unit and Relative Electron Density)

The physico-radiological characteristics of this inhomogeneous female pelvic phantom were compared with those of the RANDO- female pelvic phantom (Atom Dosimetric Phantoms Inc., USA) and RANDO whole body female phantom (Phantom Laboratory, USA) in a 16-slice CT-simulator (Somatom-Emotion Siemens, Germany). Provisions were made for keeping various dosimeters at clinically relevant points using the plastic tubes of different dimensions. The physico-radiological properties of the phantom were validated by comparing them with real patient's pelvic data and RANDO female pelvic phantom data.

Results

Dimensions and internal contours

The dimensions of the surface and internal organs in the female pelvic phantom were within an accuracy of ±2 mm against the mean values measured in a group of about 140 patients (Table 1). The locations of internal organs with reference to Umbilicus landmark in the fabricated prototype phantom were comparable to the real female pelvic, as shown in Table 2. Furthermore, the distances of the structures against the bony land marks were also found comparable against the values obtained in the CT images of the cervical cancer patients.

Table 1. Dimensions of Human female pelvis and internal organs compared with three phantoms

Location and Structures				Real Indian Female Pelvis Dimensions	Present prototype pelvic phantom	Pelvic Phantom (Atom Dosimetry USA)	Pelvic Phantom (Phantom Lab, USA)
S.N.	Organs			Dimension (mean ± SD) in cm	Average values	Average values	Average values
1	Surface	Length (from umbilicus to upper thigh)		29.16±1.91	29	39	37
		Width (at Umbilicus)		31.12±2.36	31	32	26
		Thickness	Umbilicus	19.25±4.57	19	16	12
			Symphysis	17.56±3.81	18	18	19
			Upper Thigh	14.71±3.21	15	12	13
2	Bladder (empty)	Length (max)		5.75±1.21	6	-	-
		Width (max)		3.66±0.41	4	-	-
		Thickness (max)		3.05±0.47	3	-	-
3	Uterus (non-pregnant female)	Length (max)		6.33±0.54	6	-	-
		Width	Upper	4.16±1.01	4	-	-
			Middle	5.32±0.69	5	-	-
			Lower	2.89±0.34	3	-	-
		Thickness	Upper	2.72±0.69	3	-	-
			Middle	3.84±0.62	4	-	-
			Lower	2.44±0.58	3	-	-
4	Rectum (empty)	Length (from colon end to anus)		12.26±1.84	12	-	-
		Width (mid)		4.25±0.66	4	-	-
		Thickness (mid)		3.41±0.74	3	-	-

Table 2. Location of internal organs from pubic symphysis

Distance of Internal Organs from Pubic Symphysis			
S.N.	Organ	Distance in human female pelvis (cm)	Present prototype pelvic phantom
1	Bladder (empty)	4.09±0.69	4
2	Uterus (non-pregnant female)	8.12±1.41	8
3	Rectum (empty)	11.88±1.23	12

Table 3. A comparison of Hounsfield Units and Relative electron densities of organs

		CT Number and RED of hospital patients		CT Nos. & RED of the present prototype inhomogeneous pelvic phantom		CT Nos. & RED of commercial pelvic phantom (Phantom Lab, USA)		CT Nos. & RED of commercial pelvic phantom (Atom Dosimetry, USA)	
S. N.	Pelvic organs	HU	Relative electron density	HU	Relative electron density	HU	Relative electron density	HU	Relative electron density
1	Uterus	31.7±8	1.037±0.008	39.9	1.0399	-	-	-	-
2	Bladder	24.5±8	1.0245±0.008	30.5	1.305	-	-	-	-
3	Rectum	28.8±14	1.0288±0.014	24.7	1.0247	-	-	-	-
4	Muscles	36.4±12	1.0364±0.012	34.6	1.0346	26	1.026	20	1.02
5	Fats	-86.5±15	0.9135±0.015	-86.8	0.9132	-	-	-	-
6	Bones	557.8±200	1.5578±0.200	578.6	1.5786	362	1.362	752	1.752
7	Cavities	-197.8±70	0.8022±0.070	-220.9	0.7791	-	-	-	-

CT: computed tomography, RED: relative electron density, HU: Hounsfield Unit

Radiological Properties

Figure 3 displays the CT images of an Indian female pelvis and prototype pelvic phantom at the level of symphysis pubis bone. As could be observed, the comparable structures are well depicted in our pelvic phantom. Recording the CT numbers (Hounsfield units) and relative electron densities (with respect to water) of the uterus, bladder, rectum, muscles, fats, bones, and cavities computed from the CT-Simulator for patients' female pelvis. The two commercial phantoms were in good agreement with the values obtained for prototype pelvic phantom fabricated in this study (Table 3) [14].

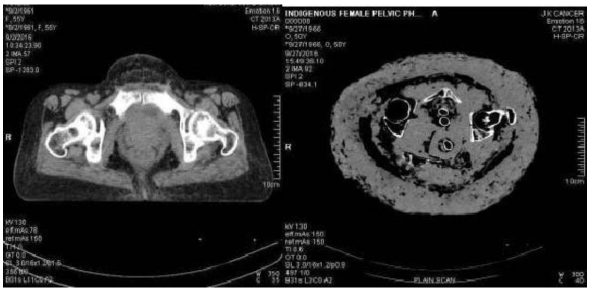

Figure 3. Images of pelvis and pelvic phantom

Discussion

In the present study, an attempt was made to develop an inhomogeneous pelvic phantom, compatible with the approximate dimensions of the Indian female subjects. We used original pelvic bones (pelvic girdles, vertebrae, and femoral bone) obtained from several cadavers. Paraffin wax, purified borax, sodium benzoate, Aloe-vera powder, and NaCl were included as tissue-equivalent materials, making the incorporated structures mimicking the realistic situation in the real female pelvis. The materials were easily available, and the fabricated phantom was really cost-effective, as compared to the materials used in the imported ones.

As seen in Figure 3, the various small micro and macro air cavities of locally developed female pelvic phantom simulate the constituents of real female pelvic tissues (i.e., air cavities, liquid, and bones) due to their similar radiological properties. Based on tables 1, 2, and 3, it can be concluded that the prototype pelvic phantom could be useful for obtaining test scans with Computed Tomography and planning new radiotherapy techniques for the evaluation and repetition of these techniques.

The commercially available female pelvic phantoms have only bone tissue substitutes and soft tissue substitutes. However, the indigenously made female pelvic phantom had female pelvic bones, soft tissue substitute, and internal organs (i.e., bladder, rectum, and uterus). Therefore, the contouring of the internal organs for radiotherapy planning and planning evaluation was simple in the indigenously made female pelvic phantom (Figures 4a, 4b).

Figure 4. Images of tissue-equivalent rubber phantoms

According to table 2, the physical dimensions of empty bladder, uterus (non-pregnant), and empty rectum from the pubic symphysis in both real female pelvis and locally made inhomogeneous female pelvic phantoms were in good agreement. This implied that radiotherapy plans could be compared if they are tested with our indigenous phantom.

We aimed to make local inhomogeneous female pelvic phantom to investigate the effects of pelvic tissue heterogeneities in radiotherapy dosimetry and authenticate the computational ability of tissue heterogeneity correction algorithms for cervical cancer.

The computed radiological properties, such as Hounsfield unit and relative electron density of various internal organs (i.e., uterus, urinary bladder, and rectum), obtained from the CT-axial slices in the locally developed phantom confirmed the efficacy of our new phantom for its successful utilization in the departments. Based on table 3, it can be stated that the locally made inhomogeneous female pelvic phantom and real female pelvis were comparable. Nonetheless, our prototype phantom had some deviations in few parameters with the commercially available phantoms.

The surface dimensions of the Indian female pelvis form the umbilicus to the upper thigh were (29.16±1.91 cm) in length, (31.12 ± 2.36 cm) in width, and (19.25± 4.57 cm) in thickness at the umbilicus. Regarding, indigenously made female pelvic phantom, were 29, 31and 19 cm respectively, showing the agreements of within 1 mm. Similarly, the length, width and thickness of the empty bladder were 5.75±1.21, 3.66±0.4, and 3.05± 0.47 cm, respectively. These values were 6.33±0.54, 4.16±1.01, and 2.72±0.69 cm in the uterus and 12.26±1.84, 4.25±0.66, and 3.41±0.74 cm in the empty rectum, respectively. Furthermore, in the indigenously made female pelvic phantom, the length, width, and thickness were 6, 4, and 3 cm in the empty bladder, 6, 4, 3 cm in the uterus and 12, 4, and 3 cm in the empty rectum respectively.

Additionally, the surface dimensions (i.e., length, width, thickness) of the commercially available RANDO female pelvic phantoms (The Phantom Laboratory, USA and Atom Phantoms Lab. Make) at umbilicus were found to be (39, 32, and 16 cm), (37, 26, 12 cm), respectively. Seems the critical internal structures of the commercially available phantoms were not visualized in the CT-axial slices, the dimensions of these organs could not be taken in a study conducted by Inderjeet Singh et al. [15], average hip breadths were reported as (33.44±3.19), (34.58±3.53), and (35.12±3.57) for north, south and west zones of Indian women, respectively. In the mentioned study, the uterus length, width, and thickness were 7.5, 5 and 2.5 cm, respectively [16-18], which is in good agreement with the observed values in this study.

During the course of this study, the sagittal distance of the internal organs, namely bladder (empty), uterus (non-pregnant), and rectum (empty), were measured in both real female pelvis and indigenously made Indian female pelvic phantom based on CT-axial slices. These values were 4.09± 0.69, 8.12± 1.41, and 11.88 ± 1.23 cm for the real female pelvis and 4, 8, and 12 cm for the phantom, respectively.

Winslow et al. [19] have also computed the Hounsfield unit of 10-40 for human muscles, -50 to -100 for soft tissue equivalent substitute, 622 for bone tissue equivalent substitute, which supports our study. The relative electron densities of adipose, muscles, and bone were also estimated by Trujillo et al. [20] and Kanematsu [21], which were reported as 0.96, 1.04, and 1.31, as well as 0.952, 1.04, and 1.116, respectively. These results are also in good agreement with our observed values (0.913, 1.035, and 1.578 respectively).

As the findings indicated, the values of Hounsfield unit and relative electron densities of our new pelvic phantom were in close agreement with those of the human female pelvis. However, in the commercially available phantoms, except the bone and muscle, other critical organs (i.e., uterus, bladder, rectum, and fatty tissue substitute) are missing in comparison with the indigenously made female pelvic phantom and real female pelvis. Therefore, the radiological parameters like Hounsfield unit and relative electron densities could not be computed and compared in the commercially available female pelvic phantoms.

Conclusion

In the recent study, an indigenous inhomogeneous female pelvic phantom was made locally for radiotherapy dosimetric applications. As far as the physico-radiological properties, size, and anatomy of the Indian female pelvic are concerned, the designed phantom simulated the Indian female more realistically. Our observations validated our efforts to develop an Indian female pelvic phantom as a substitute for the commercially available female pelvic phantoms for online radiation dosimetry.

Tissue substitutes chosen for making an inhomogeneous female pelvic phantom were non-toxic, non-degradable, locally available, cost-effective, tissue equivalent, and strong enough to maintain structural integrity. The internal structures of the indigenously made female pelvic phantom were distinguishable in the CT-images used for treatment planning. Moreover, this phantom can be useful for authenticating the computational ability of tissue heterogeneity correction algorithms in the treatment planning systems. This phantom also has some provisions to accommodate various dosimeters at the clinically relevant points.

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