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ESTIMATING THYROID DOSES IN MODIFIED BARIUM SWALLOW STUDIES

Heather Shaw Bonilha^{*,†}, Janina Wilmskoetter^{*}, Sameer V Tipnis[‡], Bonnie Martin-Harris[§], and Walter Huda^{**}

^{*} Health Sciences and Research, Medical University of South Carolina, 77 President St, MSC 700, Charleston, SC 29425-2503, USA

[†] Department of Otolaryngology – Head and Neck Surgery, Medical University of South Carolina, 135 Rutledge Ave, MSC 550, Charleston, SC 29425, USA

[‡] Department of Radiology and Radiological Science, Medical University of South Carolina, 96 Jonathan Lucas St, MSC 323, Charleston, SC 29425-3230, USA

[§] Communication Sciences and Disorders, Northwestern University, 70 Arts Circle Dr, Evanston, IL 60208, USA

^{**} Department of Radiology, Dartmouth-Hitchcock Medical Center, 1 Medical Center Dr, Lebanon, NH 03766, USA

Abstract

This study sought to obtain factors to convert entrance air kerma into thyroid doses for patients undergoing Modified Barium Swallow Studies (MBSSs). A commercial software package (PCXMC 2.0.1) was used to calculate patient thyroid doses in MBSSs, which were divided by the entrance air kerma to yield f_{thyroid} ratios. Exposure in the lateral and posterior-anterior (PA) projections were considered where the thyroid was directly irradiated. Calculations were obtained for adult patients as well as children ranging from birth to 10-years-old. The average value of f_{thyroid} in a normal sized adult was 0.63 ± 0.11 in the lateral projection, and 0.18 ± 0.06 for an upper GI PA projection. Increasing the beam quality from the lowest (60 kV + 3 mm Al) to the highest (110 kV + 3 mm Al + 0.2 mm Cu) values investigated nearly doubled the value of f_{thyroid} from 0.42 to 0.79 in the lateral projection and quadrupled the value from 0.07 to 0.29 in the upper GI PA projection. Values of f_{thyroid} decreased with increasing BMI. Average values of f_{thyroid} in 10 year olds were similar to those of adults, but always increased at the age of the exposed child was reduced. The average f_{thyroid} for newborns was 0.84, nearly one third higher than the corresponding ratio for normal sized adults.

Keywords

organ dose; thyroid; fluoroscopy; deglutition disorder

INTRODUCTION

Dysphagia, trouble swallowing, occurs in approximately one in every 25 adults per year in the United States (Bhattacharyya, 2014). An estimated 33% of patients with dysphagia develop pneumonia resulting in 60,000 deaths per year (Agency for Health Care Policy and Research (AHCPR), 1999). The primary examination used to diagnose dysphagia is a Modified Barium Swallow Study (MBSS). A MBSS is a fluoroscopic examination of swallowing anatomy and physiology. During a MBSS, the clinician examines a patient swallowing barium boluses of different viscosities and amounts to detect a swallowing impairment, determine the physiological cause of the impairment, and trial therapeutic approaches to resolve the impairment (Martin-Harris & Jones, 2008). While this examination is critical to understanding a patient's swallowing impairment, it must be used with caution as any fluoroscopic examination exposes patients to ionizing radiation. Clinicians must be aware of both the diagnostic importance and the radiation risks of MBSSs to make informed decisions about the use of these examinations.

A typical MBSS will include the majority of swallows viewed in a lateral projection, with a few swallows directed from the rear to assess symmetry and dynamically track the barium contrast agent as it moves down the upper part of the GI track (Martin-Harris et al., 2008). The field of view that is used in MBSSs is relatively small, with 22 cm x 16 cm being a representative image size for adult patients. For the majority of the MBSS, when a lateral x-ray beam is used, the thyroid gland will receive one of the highest organ radiation doses because the thyroid is in the direct beam and is fully exposed. Because relatively small fields of view are used in MBSSs, which are restricted to the upper regions of the GI track and mouth, all remaining radiosensitive organs and tissues receive very little radiation exposure. Radiation doses to organs such as the breast, stomach, and colon are negligible because they are far removed from the primary x-ray beam. Doses to organs such as the lung and red bone marrow will be very low because only a very small fraction of these organs will be directly irradiated.

The International Commission on Radiological Protection (ICRP) considers the thyroid gland to be of moderate sensitivity and has allocated this organ a tissue weighting factor (w_T) of 0.04 (ICRP, 2007). The thyroid gland tissue weighting factor is thus much lower than the value of 0.12 allocated to radiosensitive organs such as the lung and red bone marrow. This low tissue weighting factor is largely a result of the low mortality rate of thyroid cancer, given that the ICRP considers non-fatal cancers of less importance than fatal cancers in computing the total radiation detriment. Furthermore, ICRP weighting factors are averaged over sex and age. Thyroid cancer risks are strongly influenced by age and sex, with risks in infant females much higher than in older males (NCRP, 2008). For these reasons, it is of interest to study thyroid doses in patients undergoing MBSSs. In this paper, we develop practical conversion factors from entrance air kerma into thyroid doses. Speech-Language Pathologists and Radiologists will then be able to use these factors to calculate thyroid doses in their patients who undergo MBSSs.

METHOD

A: PCXMC

We made use of a commercial software program (PCXMC 2.0.1) which calculates organ doses to patients undergoing any type of medical radiographic x-ray examination (Tapiovaara & Siiskonen, 2008) using patient anatomical data, in the form of mathematical hermaphrodite phantom models, in conjunction with Monte Carlo techniques. This version incorporates corrections to the head and neck region (Eckerman & Ryman, 1993; Möller & Reif, 1994). PCXMC allows the operator to vary the x-ray beam quality (i.e., penetrating power) adjusting the x-ray tube voltages as well as the amount of x-ray beam filtration. The operator can also select the filter material commonly used in MBSSs, Aluminum (Al) and/or Copper (Cu), and adjusted the filter thickness. Most adult fluoroscopy systems will likely make use of 3 mm of Al filtration, whereas those that are dedicated for use in pediatric patients will most likely used added Cu filtration (0.1 or 0.2 mm) (Huda, 2016). The added Cu filtration in pediatric systems will harden the x-ray beam to make it more penetrating, and thereby reduce pediatric radiation doses when fluoroscopy is performed using Automatic Exposure Control systems.

The intensity of the x-ray beam incident on a patient is expressed as air kerma (K_{air}) which is measured in mGy. Patient entrance air kerma is directly related to the peak skin dose (PSD) that the patient will receive, which is approximately independent of the x-ray beam area. When air kerma is multiplied by the corresponding x-ray beam area, we obtain the Kerma-Area Product (KAP), which is often referred to as the Dose Area Product (DAP), and is measured in Gy-cm². KAP is a measure of the total amount of radiation incident on the patient, and is directly related to the patient effective dose, and the corresponding total patient stochastic (carcinogenic) radiation risk. PCXMC allows the operator to compute organ doses for either an incident entrance air kerma (mGy) or KAP (Gy-cm²).

B: Patient irradiation geometry

PCXMC permits the operator to define the x-ray irradiation geometry, which includes image receptor dimensions, as well as the source to image receptor distance (SID) and the corresponding air gap. We used a projection angle of 0° to correspond to a lateral (LAT) orientation or 90° to correspond to a PA orientation, and kept the cranio-caudal orientation constant at 0°. For a standard adult patient with a Body Mass Index of 24 kg/m² (i.e., weight of 78 kg and a height of 1.8 m), and a rectangular x-ray field with a vertical height of 22 cm and lateral width of 16 cm at the image receptor. Figures 1E and 2C show the irradiation geometry obtained from PCXMC, and illustrates that the thyroid gland is entirely within the irradiated field of view. Due to the focus on the thyroid gland, we included both lateral and upper GI PA projections in our investigation. MBSS studies can also include middle and lower GI PA projections, which were excluded from this study as the thyroid gland is not directly irradiated in these projections.

PCXMC also offers pediatric patient ages ranging from newborn to 10 years old. These pediatric models which are based on the anatomical hermaphrodite phantoms of Cristy and Eckerman (Cristy & Eckerman, 1987). Figures 1A to 1D show the lateral projection for each

of these models. Figures 2A and 2B show the upper GI PA projection for 5 and 10 year olds. The location of the thyroid gland is visible and is totally within the observed x-ray beam area. Since upper GI PA projections are rarely undertaken in infants and one-year-olds, this projection was only investigated in adults, 10 year olds and 5 year olds. Table 1 provides a summary of the irradiation geometry for all simulations, including the image receptor size, the focus to skin distance, and location of the center of each image in the PCXMC software. Note that image size is greater for 5-year old than 10-year old children, image sizes have been based on clinical MBSSs. Five-year old children are typically less able to remain still with all relevant anatomy in the image than 10-year old children, thus a larger image size is used during their MBSSs.

To investigate the influence of adult patient size, we calculated the radiation dose for patients with a range of heights and weights. For height, we investigated three values (short, average, and tall). For weight, we investigated six values (light, underweight, normal, overweight, moderately obese, and severely obese). For each examination, adjustments were made to ensure the appropriate patient anatomy was included, with no unnecessary radiation. Table 2 shows the 18 adult patient sizes investigated in this study, and shows the range of BMI investigated, which ranged from 15 to 42 kg/m² (WHO, 1995). The thyroid was completely within the x-ray beam of all patients during the MBSSs.

C: Dose conversion factors

For a given x-ray beam quality, radiation dose in any organ is affected by both the intensity of the x-ray beam, as well as the corresponding x-ray beam area. If the x-ray beam area increases from covering just one lung to both lungs, the lung dose will likely double even though the air kerma does not change. However, when an organ is completely included within an x-ray beam, then increasing the x-ray beam area will have only very modest effect on the organ dose due to a slight increase in the scatter contribution. Our interest is in the dose to the thyroid, which is generally total included within the x-ray beam, and it is the entrance air kerma that is incident on the patient that primarily affects the thyroid dose. Accordingly, in this study we computed the thyroid dose fraction, f_{thyroid} , defined as the thyroid dose (mGy) divided by the corresponding incident entrance air kerma (mGy). PCXMC defines the entrance air kerma “free in air” and which excludes patient backscatter. The entrance air kerma is automatically computed by the PCXMC software taking into account the x-ray tube output, x-ray beam filtration, and the irradiation geometry together with the known patient size.

Increased beam qualities are generally associated with more penetrating radiation beams. As a result, organ doses that are normalized to the entrance air kerma generally increase with increasing x-ray beam quality. We used a range of beam qualities covering the span that might be encountered in clinical practice. Adult fluoroscopy units would likely use 3 mm total filtration, with a Half Value Layer at 80 kV of about 3 mm Al. Pediatric units would likely use additional 0.1 to 0.2 mm Cu filters, and the additional loss of photons is tolerable because smaller patients require less radiation (Huda, 2016). Accordingly, the lowest beam quality investigated was an x-ray tube voltage of 60 kV with a total of 3 mm Al filtration,

and the highest was an x-ray tube voltage of 110 kV with a total filtration of 3 mm Al as well as 0.2 mm Cu.

RESULTS

A. Adults

Figure 3 shows how f_{thyroid} varies with six levels of x-ray tube voltage (kV) at three filtrations for lateral projections in a normal sized adult (i.e., BMI 24 kg/m²). The average value of f_{thyroid} for each projection investigated are shown in Table 3, showing how values of f_{thyroid} always increase with both increasing x-ray tube voltage, and with increasing x-ray beam filtration. At the lowest x-ray beam quality investigated (60 kV + 3 mm Al), the value of f_{thyroid} in the lateral projection was only 0.42. Increasing the beam quality to the highest value investigated (i.e., 110 kV + 3 mm Al + 0.2 mm Cu) nearly doubled this value of f_{thyroid} to 0.79.

Table 4 shows how f_{thyroid} varies with patient size for the beam quality that is most likely to be used to image adult patients (i.e., 80 kV & 3 mm Al filtration). Values of f_{thyroid} decrease with increasing BMI, with an average of 0.65 ± 0.04 for a BMI of 15 kg/m² which was reduced to 0.41 ± 0.03 for a BMI of 42 kg/m². Increasing the height of the exposed adult generally reduced the values of f_{thyroid} , but these reductions were modest, the average reduction was < 10% when the patient height increased from the short (150 cm) to the tall (200 cm) categories.

B. Children

Table 3 and Figures 4 and 5 show how f_{thyroid} varies with x-ray tube voltage and x-ray beam filtration for pediatric patients ranging from 5 to 10 year olds in the lateral and upper GI PA projections. For both the lateral projection and upper GI projections, average values of f_{thyroid} for 10 year olds were similar to those used in adults. The overall average of f_{thyroid} for the 5 year olds, however, were markedly higher than in adults. For the lateral projection, f_{thyroid} values were nearly 40% higher than in adults, and for the upper GI projections, f_{thyroid} values were about 70% higher than in adults.

C. Infants

Table 3 and Figures 6 and 7 show how f_{thyroid} varies with x-ray tube voltage and x-ray beam filtration for young pediatric patients ranging from newborn to 1 year olds. Average values of f_{thyroid} for infants was 0.83, which is ~ 30% higher than for older children and normal sized adults. Qualitatively, the trends for pediatric f_{thyroid} values with increasing beam quality are very similar to those observed in adults although absolute values were of higher magnitude. Increasing the beam quality from the lowest to the highest values investigated increased the value of f_{thyroid} by approximately 60%.

DISCUSSION

The thyroid gland is of particular interest in radiation protection practice because cancer risks are highly dependent on the age and sex of exposed individuals. Data presented in the

BEIR VII report show that thyroid cancer risks in a newborn are two orders of magnitude higher than in 50-year old males and females. Even more striking is the fact that in uniformly exposed newborns, the estimated thyroid cancer induction risk accounts for 4.5% of the total cancer risk in males, and 13.3% of the total cancer risk in females. For these reasons, understanding of thyroid doses to patients undergoing diagnostic MBSS radiological examinations is essential. Knowledge of thyroid doses will be helpful in justifying patient exposures to ensure that there is a net patient benefit. In addition, knowledge of thyroid doses will be important in optimizing these types of studies to ensure that patient doses are kept As Low As Reasonably Achievable. The purpose of this study was to provide a practical tool to MBSS practitioners that will enable thyroid organ doses to be estimated in routine clinical practice.

The doses to the salivary glands in MBSS examinations are generally comparable to those of the thyroid glands. At 80 kV and with an x-ray beam filtration of 3 mm, the ratio of the dose to the salivary glands to the entrance air kerma (i.e., f_{salivary}) was determined to be 0.45 for lateral projections, and 0.23 for the Upper GI projection. Organ doses in MBSS examinations are well below the threshold doses for the induction of deterministic effects that have been described in the literature (Grundmann 2009, Konings 2005). The carcinogenic sensitivity of the salivary glands is generally considered to be relatively low, with this organ not receiving a tissue weighting factor in ICRP Publication 26 (1977) or ICRP Publication 60 (1990). It was only in ICRP Publication 103 (2007) that this organ was given a weighting factor of 0.01. In addition, the salivary glands are not explicitly mentioned in the risk factors provided in BEIR VII, whereas the thyroid doses are believed to be responsible for an average of 9% of all cancers induced in newborns from uniform whole body irradiation. In young patients, the thyroid cancer risk will therefore be much higher than any carcinogenic risk from irradiation of the salivary glands, whereas in older patients the carcinogenic risks from these two organs will both be relatively low.

The dosimetry performed in this study did not consider the presence of barium in the patient, which may affect the resultant patient doses. A recent study (He et al, 2014) investigated the effect of adding iodine to patient doses, which is likely to be applicable to barium given the close similarity between Iodine ($Z = 53$; k-edge 33 keV) and barium ($Z = 56$; k-edge 37 keV). In this study, the addition of iodine was found to have negligible effects on absorbed tissue doses at locations that are in front of the added iodine, but that substantial dose reductions can occur at x-ray beam locations that are behind the added contrast material. For PA and lateral projections used in MBSS examinations, the x-ray beam will be incident on the thyroid before it reaches the barium, and there will be no shielding of the radiation to this organ to the incident x-ray beam. Overall, it is therefore likely that the thyroid dose conversion factors computed in this study will be valid even in the presence of added barium contrast material to patients undergoing MBSS examinations.

We performed a PCXMC simulation to assess the how inclusion of additional views (middle and lower GI) would affect thyroid doses. The calculation was performed for an average adult patient, using a beam quality of 80 kV and 3 mm Al total filtration, with 30% of the Kerma Area Product (KAP) allocated in the lateral projection. The remaining KAP was distributed between three PA projections that cover the upper GI tract (upper, middle, and

lower esophagus) with allocations of 15%, 15% and 40%, respectively. Adding the middle and lower GI PA projections would have increased the thyroid dose by approximately 2%. This finding is expected given that the thyroid gland is not directly irradiated in these additional views (i.e., middle and lower GI), so that this organ would only be exposed to scatter radiation.

Although the values of f_{thyroid} were higher in infants and very small children compared to adults, this is unlikely to result in higher thyroid doses in clinical MBSSs. Fluoroscopy is generally performed using Automatic Exposure Control (AEC) which maintains a constant radiation intensity (K_{air}) at the image receptor. Because children attenuate much less radiation than adults, the entrance air kerma will be lower in children than in adults. At typical beam qualities used in diagnostic radiological imaging, 3 cm of soft tissue will attenuate approximately half the incident radiation. If we assume that a child is 6 cm thinner than an adult, only 25% of a beam of radiation at the same quality would be required to achieve the same radiation intensity at the image receptor. Accordingly, it is very likely that the reductions in entrance air kerma in small children undergoing MBSSs would be much greater than the increases in f_{thyroid} obtained in this study. Assuming comparable imaging times and examinations performed at the same x-ray beam quality, infant and pediatric thyroid doses should be lower than those in adults.

The observed trends in adult f_{thyroid} depicted in Table 4 are expected given that the thyroid is totally visible in all the BMI categories studied. Larger patients will inevitably further attenuate the x-ray beam thereby reducing the values of f_{thyroid} . The highest value of f_{thyroid} was 0.65 in adults with the lowest BMI category (15 kg/m^2), and the lowest value of f_{thyroid} was 0.38 in severely obese adults ($\text{BMI } 42 \text{ kg/m}^2$). The ratio of these high to low values (i.e., 1.7) is relatively large in the lateral projection and even larger in the upper GI PA projection (i.e. 3.3), and suggest that BMI should be taken into account when estimating thyroid doses in adults.

MBSS examinations are invariably performed on fluoroscopy systems which employ Automatic Exposure Control systems, where the radiation intensities at the image receptor are kept constant. For this reason, using higher x-ray beam qualities will most likely reduce thyroid doses, even though f_{thyroid} values increase as depicted by the data in Table 3. Increasing beam quality results in a more penetrating x-ray beam, thereby needing less incident radiation to achieve a given x-ray air kerma at the image receptor (Schaetzing, 2004; Hamer et al., 2005). Reductions in radiation incident on the patient at higher beam qualities are greater than the corresponding increases in f_{thyroid} values.

For any given patient who undergoes a specified examination, the thyroid dose may be readily obtained by multiplication of f_{thyroid} values provided in this paper with the corresponding entrance air kerma incident on the patient in the lateral projection. One way of obtaining the entrance air kerma is by dividing the Kerma-Area Product ($\text{Gy}\cdot\text{cm}^2$) by the estimated area of the x-ray beam incident on the patient. KAP is generally provided explicitly on most modern imaging systems, and is also available in the DICOM header information that is now standard in radiological imaging. Tube voltage information is also readily available in any radiographic image DICOM header. X-ray tube filtration is generally

available in reports issued by medical physicists who are required by regulations to test each radiographic unit that is used clinically.

One important reason for computing thyroid doses in MBSS is to investigate whether increased beam qualities could be used to perform MBSS examinations without affecting diagnostic performance. Optimization of radiation protection (i.e., ALARA) would study how changes in x-ray beam quality, as well as x-ray beam quantity, impact on diagnostic performance. Currently, clinicians are reducing fluoroscopy beam pulse rate to decrease radiation exposure from MBSSs. However, this also reduces the temporal resolution of the MBSS and greatly diminishes diagnostic accuracy (Bonilha et al., 2013). Modifications to beam quality, which would preserve the temporal resolution, may be a better approach to optimizing radiation protection. Whenever radiographic techniques are adjusted, it is essential that diagnostic performance is maintained so that patient outcomes are not adversely affected. When diagnostic performance is kept constant, the set of radiographic techniques that provide the lowest patient doses would be deemed to be optimal. The thyroid dose conversion factors generated in this study may be taken to be the first step in any such optimization program.

CONCLUSIONS

The thyroid gland is the only radiosensitive organ to carcinogenesis that is fully exposed to radiation in the lateral projection and the upper GI PA projection of the MBSS. We found that patient size has an impact on f_{thyroid} , with the largest patients having a value of f_{thyroid} that is 40% less when compared to that of a normal sized patient. Infants and small children have a higher f_{thyroid} . Clinicians can use the conversion factors provided in this manuscript, along with readily available information from fluoroscopy units, to determine patient thyroid dose.

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Figure 1:
Lateral Projection – Different Patient Ages

Figure 2:
PA upper GI Projection – Different Patient Ages

Figure 3:
thyroid for an Average Adult Across Tube Voltages for Different Levels of Filtration

Figure 4:
fthyroid for 10-Year-Olds Across Tube Voltages for Different Levels of Filtration

Figure 5:
fthyroid for 5-Year-Olds Across Tube Voltages for Different Levels of Filtration

Figure 6:
 $f_{thyroid}$ for 1-Year-Olds Across Tube Voltages for Different Levels of Filtration

Figure 7:
 $f_{thyroid}$ for Newborns Across Tube Voltages for Different Levels of Filtration

Table 1.

Image sizes, Focus to Skin Distances, and the location of the image center in the PCXMC geometry for simulated examinations. In all simulations, the Source to Image Receptor distances were 110 cm, and the air gap between the patient and image receptor was 5 cm.

Projection	Patient	Image		Focus-to-Skin distance (cm)	Co-ordinate (cm)		
		Vertical x	Horizontal		X	Y	Z
Lateral	Adult	22 × 16		90	7.6	−4	80
	10 yo	16 × 15		90	7.4	−4.5	59
	5 yo	20 × 22		91	7.0	−2.9	46.5
	1 yo	15 × 15		93	6.1	−2.8	37
	nb	11 × 11		95	4.9	−2.6	26.5
Upper GI PA	Adult	22 × 16		89	0	5.6	80
	10 yo	16 × 15		89	0	5.4	59
	5 yo	20 × 22		91	0	4.2	46.5

Table 2:

Phantom sizes.

Patient BMI	Patient Height (cm)		
	Short (150cm)	Normal (180cm)	Tall (200cm)
Light (BMI 15)	34kg	49kg	60kg
Underweight (BMI 18)	40kg	58kg	72kg
Normal (BMI 24)	54kg	78kg	96kg
Overweight (BMI 30)	68kg	97kg	120kg
Moderately Obese (BMI 37)	83kg	120kg	148kg
Severely Obese (BMI 42)	95kg	136kg	168kg

Table 3:

Selected f_{thyroid} values that are depicted in Figures 3, 5, 7, 9 and 10 for different sized patients undergoing MBSS examinations in the lateral and upper GI PA projections. The mean values are for the each patient/projection which were obtained at 18 different beam qualities.

Body Region	Projection	Mean f_{thyroid} ($\pm \sigma$)	X-ray beam quality		
			60 kV (3 mm Al)	80 kV (2 mm Al + 0.1 mm Cu)	110 kV (3 mm Al + 0.2 mm Cu)
Lateral	Adult *	0.63 ± 0.10	0.42	0.63	0.79
	10 year old	0.68 ± 0.10	0.47	0.67	0.83
	5 year old	0.87 ± 0.13	0.61	0.87	1.07
	1 year old	0.88 ± 0.11	0.64	0.88	1.02
	Newborn	0.77 ± 0.11	0.56	0.77	0.94
Upper GI PA	Adult *	0.18 ± 0.06	0.07	0.17	0.29
	10 year old	0.21 ± 0.07	0.10	0.20	0.34
	5 year old	0.31 ± 0.10	0.13	0.29	0.48

* BMI 24 kg/m²

Table 4:

Values of f_{thyroid} for varying weight and height computed for lateral projection and upper GI PA projections using an x-ray beam generated at 80kV and a total filtration of 3mm Al.

Projection	Patient BMI	Patient Height (cm)		
		Short (150cm)	Normal (180cm)	Tall (200cm)
Lateral	Light (BMI 15)	0.61	0.65	0.61
	Underweight (BMI 18)	0.62	0.58	0.55
	Normal (BMI 24)	0.55	0.51	0.51
	Overweight (BMI 30)	0.50	0.47	0.47
	Moderately Obese (BMI 37)	0.48	0.41	0.41
	Severely Obese (BMI 42)	0.44	0.41	0.38
Upper GI PA	Light (BMI 15)	0.18	0.17	0.15
	Underweight (BMI 18)	0.20	0.16	0.15
	Normal (BMI 24)	0.14	0.12	0.13
	Overweight (BMI 30)	0.11	0.10	0.09
	Moderately Obese (BMI 37)	0.09	0.09	0.08
	Severely Obese (BMI 42)	0.07	0.08	0.06