RESEARCH

Evaluation of effective dose from a RANDO phantom in videofluorography diagnostic procedures for diagnosing dysphagia

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Objectives: Videofluorography (VF) is useful for diagnosing dysphagia; however, few reports have investigated appropriate effective doses for VF. The present study aimed to estimate the effective radiation dose in VF for diagnosis of dysphagia.

Methods: Radiation doses to tissues and organs were measured using the anthropomorphic RANDO woman phantom as an equivalent to the human body. Effective doses were estimated according to the recommendations of the International Commission on Radiological Protection (ICRP) 60 in 1990 and ICRP 103 in 2007. The tissues measured were those recommended by ICRP 60 and ICRP 103 including gonads (ovaries and testes), red bone marrow and tissues in which excessive radiation commonly causes malignant tumours including lung, thyroid gland, stomach, large intestine, liver, oesophagus, bladder, breast, bone marrow, skin, brain and salivary gland. Skin dose was also measured using thermoluminescent dosimeters.

Results: Using ICRP 103, the effective dose was estimated as 118.1 μ Sv at a tube voltage of 50 kV and 82.4 μ Sv at 45 kV. However, using ICRP 60 the effective dose for 1 min of VF was estimated at 62.4 μ Sv and 47.2 μ Sv under the same exposure conditions.

Conclusions: Using ICRP 103, the effective dose for VF per examination at a total estimation time of 1 min was estimated as approximately 2.5–8.3 times that observed for digital panoramic radiography and 1/12 to 3 times depending on the measurement device for cone beam CT (CBCT). This value can be decreased in the future using a smaller irradiation field and decreased time for examination in VF in the future.

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Introduction

Dysphagia is characterized by an abnormality in the transfer of a bolus from the mouth to the stomach.^{1–3} To investigate the causes of such swallowing dysfunction and allow treatment of this condition, techniques for observing movements associated with swallowing have been developed using cineradiography,¹ videofluorography (VF),^{4,5} ultrasonography,⁶ and electromyography.⁷ Cineradiography has a long history of use,¹ but requires numerous exposures and therefore places a considerable radiation burden on the patient.⁸ VF is less

costly⁹ and requires approximately one-sixth the radiation dose of cineradiography when performed at the lowest exposure possible,⁸ and has therefore become mainstream and is now performed for observation of dysphagia at many medical and dental hospitals.⁹

However, few researchers have investigated appropriate absorbed radiation doses for VF. These studies have measured scattered radiation,¹⁰ total dose absorbed by the patient^{11–13} and doses to specific tissues such as the skin, salivary glands and thyroid during VF.³ In addition, few reports have described effective radiation doses for VF.^{12–15}

In this study we have, therefore, attempted to determine the effective radiation dose in VF for diagnosing and evaluating dysphagia.

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Materials and methods

The fluoroscope used for VF was a Clearscope SXT 9000A (Toshiba, Tokyo, Japan). This device has a 23 cm image intensifier and a charge-coupled device (CCD) camera. The image intensifier and X-ray generator were connected with a C-shaped arm. As a variable tube voltage of 45–50 kV can be used during VF, irradiation conditions of 45 kV and 50 kV were used with a tube current of 1 mA.

The phantom used for the present study was an anthropomorphic RANDO woman phantom (Alderson Research Laboratories, Stanford, CT), which is considered equivalent to the human body in terms of X-ray absorption and scattering (Figure 1). Tissues for measurement were determined by reference to texts on human anatomy¹⁶ and on CT cross-sections,¹⁷ and by the method described by Golikov.¹⁸ The position and size of each tissue and organ were determined using radiographs of the phantom.

The tissues and organs measured were those listed in the International Commission on Radiological Protection (ICRP) publication 60 in 1990¹⁹ and ICRP 103 in 2007²⁰: the gonads (ovaries and testes) and tissues and organs in which excessive radiation commonly causes malignant tumours, *i.e.* red bone marrow; lung; thyroid gland; stomach; large intestine; liver; oesophagus; bladder; breast; skin; thymus; adrenal gland; kidney; spleen; pancreas; small intestine; upper large intestine; uterus; brain; and major salivary glands (parotid, submandibular and sublingual), as well as the lens. Selected tissues, organs and tissue-weighting factors have been changed between the publication of ICRP 60¹⁹ and ICRP 103,²⁰ and for tissue-weighting factors we used the ICRP in which the tissue or organ was mentioned. Equivalent doses for each tissue were measured. Bone

marrow dose was calculated by distribution of the red bone marrow weight as described by Miyagawa.²¹

Two different types of thermoluminescence dosimeter (TLD) were used for measurements, the UD-170A (BeO) (Panasonic, Osaka, Japan) and the UD-110S (CaSO₄:Tm) (Panasonic). The UD-170A TLD has an effective atomic number of 7.6 compared with the tissue value of 7.4, and is therefore unsuitable for low-level dose measurements. The UD-110S TLD consists of a high atomic number phosphor (effective atomic number, 14.4) dosimeter with a much higher energy dependence than BeO and is suitable for low-level measurements. The UD-170A and UD-110S TLDs were used as rods (diameter, 2 mm; length, 12 mm). The variation between these TLDs was $\pm 7\%$ using standard irradiation with ⁶⁰Co. We used a UD-512-P TLD Reader (Panasonic). High equivalent doses were anticipated for the head and neck region and so the UD-170A dosimeter was used for this region based on its low sensitivity but good energy response. Skin doses in directly irradiated areas were also measured using the UD-170A dosimeter. Low equivalent doses were expected for non-skin tissues and organs and so the UD-110S dosimeter with high sensitivity was used. Effective energy of the X-ray fluoroscope was measured using a Kyokko X-ray analyser (Model 100; Kasei Optonix, Odawara, Japan).

Measurements were performed under two conditions: 50 kV, 1 mA (effective energy, 27.7 keV) and 45 kV, 1 mA (effective energy, 26.9 keV). This is because VF uses a tube voltage with an automatic setting, but actual tube voltage varied from 45 kV to 50 kV. Fluoroscopic time was fixed at 5 s. Adjustment of the TLD was performed using a KXO-15 X-ray generator (Toshiba) emitting an effective energy similar to the effective energy measured at the same tube voltage as the fluoroscope used. A total of 164 TLDs were used for the measurement (*e.g.* 52 TLDs for bone marrow). A TLD was calibrated by an ionization chamber, which in turn had been calibrated to the Japan National Standard defined by the National Institute of Advanced Industrial Science and Technology in Tsukuba (Japan). This TLD was irradiated at the same time as the UD-170A on the surface of a Mix-Dp phantom. In addition, UD-170A and UD-110S dosimeters were irradiated at the same time in association with the standard dosimeter and direct radiation in the phantom and area of scattered radiation, and calibration was performed.

Tissue dose was measured under the following conditions. Exposure was performed with a distance of 57.5 cm from the focus of the X-ray tube to the mid-sagittal plane of the phantom and a distance of 35 cm from the mid-sagittal plane of the phantom to the image intensifier. Skin dose was measured using 10 TLDs firmly attached to the skin surface of the phantom on the tube side of the central X-ray.

The ratio of the mass absorption coefficients was calculated as 0.876 with effective energies of 26.9 keV and 27.7 keV in soft tissue and 4.3 at the bone

Figure 1 Overview of the fluoroscopic unit with RANDO woman phantom (while measuring radiation dose). Distance from the focus of the X-ray tube to the mid-sagittal plane of the phantom was 57.5 cm. Distance from the mid-sagittal plane of the phantom to the image intensifier (II) was 35 cm

surface.²² Equivalent dose was calculated using tissue doses obtained from the experiment, and the effective dose for fluorography was determined according to tissue-weighting factors as recommended by the ICRP 60 and ICRP 103. The effective dose for the skin was considered proportional to the whole-body surface area of the patient in terms of the directly irradiated area. As the whole-body surface area was 1.5 m², effective dose was estimated at 2.5% for a directly irradiated area of 0.032 m². The remaining tissues were assigned a tissue-weighting factor of 0.05 according to ICRP 60. Of these, the brain was assigned a weighting factor of 0.025, and mean equivalent doses for the thymus gland, adrenal gland, kidney, spleen, pancreas, small intestines, upper large intestine and uterus were calculated from the remaining weighting of 0.025.

Measurement of equivalent doses of the oral mucosa and extrathoracic region was not performed, but we estimated these doses using our own assumptions, similar to Ludlow *et al*²³ and Roberts *et al*²⁴ who hypothesized estimations for effective doses of ICRP 103 and 60. That is, the calculation of the mean dose to remaining tissue made the following assumptions:

1. Dose to the tongue was assumed to be the same as dose to the oral mucosa. Dose to the extrathoracic region was assumed to be the same as mean dose to the salivary glands.
2. Mean dose to the remaining tissues was considered to be the sum of values for doses to the thymus, adrenal gland, kidney, spleen, pancreas and small intestine, added to the above-mentioned doses to the tongue and extrathoracic region.

Results

For a 1 min VF examination at 1 mA the equivalent dose to bone marrow was estimated at 39.0 µSv for a 50 kV tube voltage and 26.6 µSv for a 45 kV tube voltage (Table 1). Equivalent doses for other tissues and

Table 1 Integrated bone marrow dose and bone marrow dose for videofluorography (VF) examination

Region	VF-50 kV	VF-45 kV
Skull	15485.8	10221.4
Mandible	1844.6	1183.6
Cervical vertebrae	10209.6	7310.0
Sternum	322.4	184.2
Scapulae	101.4	67.0
Clavicle	165.6	116.8
Ribs	333.0	201.2
Thoracic vertebrae	1224.8	957.6
Lumbar vertebrae	12.6	11.0
Sacral vertebrae	6.0	5.4
Iliac bone	25.8	23.0
Femur	13.6	11.6
Arm	92.8	48.8
Total	20341.8	20341.8
		(g·µSv/l min)
Bone marrow dose	39.0	26.6
		(µSv/l min)

organs are shown in Table 2. The skin dose, which is included in the irradiation field, was 7460 µSv using a 50 kV tube voltage compared with 5660 µSv for 45 kV.

Of the other organs and tissues, the salivary gland received the highest dose because of the position within the irradiation field. The thyroid gland showed the second highest equivalent dose.

The effective dose per 1 min VF examination, as determined by tissue-weighting factors recommended by ICRP 103, was 118.1 µSv at a tube voltage of 50 kV and 82.4 µSv at 45 kV (Table 3). Effective dose estimated according to ICRP 103 was 75–90% higher than that for ICRP 60.

Discussion

The present study estimated effective dose from various tissue doses measured during VF examinations. In our oral and maxillofacial radiology clinic, VF examination is performed a mean of 4.5 times for each patient, with each examination lasting approximately 5.1 s. Another facility has reported a mean of 5.4 examinations per patient with 12.4 s for each examination.⁸ In such cases,

Table 2 Equivalent dose of videofluorography (VF) examinations (µSv/l min)

Organ and tissue	VF-50 kV	VF-45 kV
Thyroid gland	968	756
Lungs	2.48	1.15
Stomach	0.523	0.374
Colon	0.174	0.148
Liver	0.242	0.171
Oesophagus	3.37	2.07
Bladder	0.135	0.125
Breasts	10.5	7.58
Bone marrow	39.0	26.6
Bone surface	406	266
Ovaries	0.145	0.121
Testes	0.142	0.139
Skin	7460	5660
Brain ^a	86.9	55.3
Parotid gland	2897	2155
Submandibular gland	1352	823
Sublingual gland	639	361
Thymus ^b	17.5	10.8
Adrenal gland ^b	0.219	0.173
Kidney ^b	0.201	0.171
Spleen ^b	0.336	0.240
Pancreas ^b	0.243	0.207
Small intestine ^b	0.135	0.135
Upper large intestine ^a	0.186	0.167
Uterus ^b	0.134	0.118
Lingua ^b	2088	1273
(Remainder tissues) ^c	415	266
Eyes (ocular lens)	88.4	58.0

^a Remainder tissues of ICRP 60

^b Remainder tissues of ICRP 103

^c Remainder tissues: Equivalent dose was averaged for the remaining organs in the ICRP 103 recommendation. We assumed that lingual equivalent dose was the same as the equivalent dose for the oral mucosa, and equivalent dose for the extrathoracic region was the same as that for the salivary glands

Table 3 Effective dose of videofluorography (VF) examination

<i>Tissue and organs</i>	<i>Tissue weighting factor (ICRP 103)</i>	<i>Tube voltage 50 kV</i>	<i>Tube voltage 45 kV</i>	<i>Tissue weighting factor (ICRP 60)</i>	<i>Tube voltage 50 kV</i>	<i>Tube voltage 45 kV</i>
Thyroid glands	0.04	38.7	30.2	0.05	48.4	37.8
Lungs	0.12	0.298	0.138	0.12	0.298	0.138
Stomach	0.12	0.0626	0.0448	0.12	0.0624	0.0444
Colon	0.12	0.0208	0.0178	0.12	0.0204	0.0180
Liver	0.04	0.0096	0.0068	0.05	0.0120	0.0084
Oesophagus	0.04	0.135	0.0828	0.05	0.169	0.1032
Bladder	0.04	0.0054	0.0050	0.05	0.0072	0.0060
Breast	0.12	1.26	0.910	0.05	0.526	0.379
Bone marrow	0.12	4.68	3.19	0.12	4.68	3.19
Bone surface	0.01	4.06	2.66	0.01	4.06	2.66
Ovaries	0.08	0.0116	0.0096	0.2	0.0288	0.0240
Testes	0.08	0.0114	0.0110	0.2	0.0288	0.0276
Skin ^a	0.01	1.87	1.42	0.01	1.87	1.416
Remainder tissues ^b	0.12	49.8	32.0	0.025	0.0588	0.0276
Brain	0.01	0.869	0.553	0.025	2.17	1.38
Salivary glands	0.01	16.3	11.1			
Effective dose	1.0	118.1	82.4(μ Sv/1 min)	1.0	62.4	47.2(μ Sv/1 min)

^a Total area of skin for a human is generally assumed to be 1.5 m². We assumed the area of skin in the irradiation field to be 0.025% of total skin area

^b The calculation of the effective dose for ICRP 103 was performed using mean doses to thymus, adrenal gland, kidney, spleen, pancreas, small intestine and uterus (female only), along with oral mucosa and extrathoracic region

Calculation of the effective dose for ICRP 60 was performed using mean doses to the thymus, adrenal gland, kidney, spleen, pancreas, small intestine, upper large intestine and uterus (female only)

fluoroscopic time for all VF procedures would be 67 s in total.⁸ We therefore examined radiation doses for a 1 min fluoroscopy period.

In the present study, VF used a tube voltage with an automatic setting. However, actual delivered voltage varied from 45 kV to 50 kV. Tube current was fixed at 1 mA, as used clinically in our institution, but these are both lower than those reported by other facilities and require about one-third the fluoroscopic time.⁸

If the diameter of the image intensifier is too small (<10 cm), the mouth and pharynx cannot be observed simultaneously. Many facilities therefore use an irradiation field of 12–15 cm or 10–15 cm.^{8,11,12} The present study did not collimate irradiation fields and allowed observation of a wide area with an 11.5 cm diameter irradiation field at the skin surface.

As mentioned above, exposure conditions differed from those used in other facilities, but equivalent doses in the present study were higher. At the submandibular gland and sublingual gland, doses were 1.5 to 2 times those measured under exposure conditions using identical VF times.¹³ Equivalent dose for the parotid gland in the present study was four or five times that measured by Hasegawa *et al.*¹³ Moreover, equivalent doses were 968–756 μ Sv for the lens and 88.4–58.0 μ Sv for the thyroid gland, about 3 times the values described by Hasegawa.¹³ This discrepancy was largely attributed to differences in size of the irradiation field. We also considered that the thyroid and parotid glands would be within the cut-off zone in the irradiation field, and changes in patient position could thus potentially decrease equivalent doses to these tissues. Equivalent dose to the lens could potentially be decreased by narrowing the irradiation field. Equivalent dose has been reported to vary widely between hospitals, with up

to a ten-fold difference for similar examinations.²⁵ These variations are considered to result from differences in the equipment used by each facility, exposure conditions (tube voltage, tube current and fluoroscopic time) and size of the irradiation field.

Bone marrow dose is affected by the skull and cervical spine, which are within the irradiation field. These bony tissues thus receive about 92% of the whole bone marrow dose, and the specific gravity of bone marrow in the chest effectively increased this to >99%.

Hasegawa *et al.*¹³ stated a skin dose of 3.19 mGy for exposure conditions of 70 kV and 0.6 mA, and 1 min at the phantom surface. In the present study, the equivalent dose for skin was 5.66–7.64 mSv for 1 min, 1.7–2.3 times higher than that observed by Hasegawa *et al.*

Effective dose for 1 min in the present study was 118.1 μ Sv at a tube voltage of 50 kV, and 82.4 μ Sv at 45 kV, according to the ICRP 103. Effective dose for VF according to ICRP 60 was estimated as 62.4 μ Sv (50 kV) to 47.2 μ Sv (45 kV). The effective dose as calculated using ICRP 103 was therefore 75–90% higher than that calculated using ICRP 60. Our results suggest that an effective dose for VF is about five to eight times higher than that for conventional rotational panoramic radiography as described by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) report in 2000²⁶ and our 2005 study.²⁷ This value is also 2.5 to 3.3 times higher than the effective dose for intraoral radiography of the lower molars.²⁷ In those studies the effective dose was estimated based on an irradiation field about two to three times larger than that used in intraoral radiography. Wright *et al.*¹² investigated effective dose in VF and described a mean effective dose of 0.4 mSv per examination, which is about 14 times higher per examination than that

estimated in the present study. The fluoroscopic time used by Wright et al was 286 s in total, which is 13.3 times longer than the time used in the present study. Crawley et al reported that median screening time was 3.7 min per examination and effective dose was very high (0.85 mSv).¹⁴ Zammit-Maempel et al also reported that median time was 171 s per examination and typical VF effective dose was 0.2 mSv.¹⁵

Irradiation doses during VF to observe swallowing seem to differ depending on the facility at which the procedure is performed, and depend on fluoroscopic time, size of the irradiation field, patient condition and characteristics of the image intensifier. The present results suggest that equivalent doses may be decreased in the future with changes in exposure time and irradiation field.

Tissue weighting factors were changed in ICRP as a result of re-evaluation of cancers occurring in the maxillofacial region, including oral mucosa and salivary glands. Ludlow et al estimated the effective dose as 14.2 μ Sv from a panoramic Orthophos XG (Sirona Group, Bensheim, Germany) with a CCD and as 24.3 μ Sv from a panoramic ProMax (Planmeca, Helsinki, Finland) with a CCD using ICRP 103 compared with 4.3 μ Sv and 7.1 μ Sv, respectively, using ICRP 60.²³ Effective dose with ICRP 103 was therefore approximately 3.4 and 8.3 times the value with ICRP 60. In the present study, effective dose of VF was 118.1 μ Sv using ICRP 103, 1.8 times the 62.4 μ Sv using ICRP 60.

The reason for this was that equivalent dose to the salivary glands was considered high with both conventional and digital panoramic radiography, and these structures are close to the rotation centre for rotational panoramic radiography, explaining the smaller increase compared with panoramic radiography. Gavala et al²⁸ estimated effective dose using ICRP 60 as 17 μ Sv without salivary glands and 26 μ Sv including salivary glands during conventional panoramic radiography, while estimated effective dose using ICRP 60 was 23 μ Sv without salivary glands and 38 μ Sv including salivary glands during digital panoramic radiography under ordinary irradiation conditions.²⁸ The effective dose for our VF examination was estimated as 2.5 to 2.7 times their result for digital panoramic radiography.

A comparison of CBCTs has shown many different effective doses depending on the specific unit, with an effective dose of VF approximately two to three times higher than that with NewTom 3G (QR, Verona, Italy),²⁹ approximately three times with 3DX Accutomo (J. Morita MFG, Corp, Kyoto, Japan),³⁰ but close to half that with i-CAT (Imaging Sciences Int, Hatfield, PA)²⁹ and 1/12 to 1/3 that with CB Mercuray (Hitachi Medical Corp, Tokyo, Japan).²⁹ We also estimated effective dose for ICRP 103 with an Alphard unit (Asahi Roentgen, Kyoto, Japan), without salivary glands or extrathoracic region. Effective dose with this device was 24.4–72.5 μ Sv in D mode, 114 μ Sv in P mode and 219 μ Sv in I mode with a wider field of irradiation.³¹ An effective dose for VF using ICRP 103 is the value that is almost an effective dose for I mode, but these effective doses are thought to be larger than that of VF when including salivary glands and the extrathoracic region.

In conclusion, effective dose per 1-min VF examination was 118.1 μ Sv at 50 kV and 82.4 μ Sv at 45 kV. This effective dose was estimated about 2.5 to 8.3 times higher than that observed for digital panoramic radiography, about 1/12 to 3 times that for CBCT and about 5 to 8 times higher than that observed for conventional panoramic radiography estimated by ICRP 60 in previous reports.^{26,27} Effective dose of VF seems moderately higher than these, but appear to represent a low dose when we consider looking at successive video images for observing movement in a wide area using a wide field of irradiation. This value can be expected to decrease in the future with the use of smaller irradiation fields and reduced time requirements for observing VF.

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