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Dose Optimization for the Quality Control Tests of X-Ray Equipment

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1. Introduction

Radiation is a major risk in diagnostic and therapeutic medical imaging. The problem is caused from incorrect use of radiography equipment and from the radiation exposure to patients much more than required. Exposure of different dose values for the same clinical examination, is an enough reason to draw attention to this issue.

International Commission on Radiation Protection (ICRP), the International Atomic Energy Agency (IAEA) and other various independent institutions have been making publications in relation to ionizing radiation protection for more than fifty years. Report 60 of the ICRP and the Basic Safety Standards that was published in the IAEA report have three basic principles related to the radiation protection (ICRP, 1991; IAEA, 1996).

The most important issue in these principles is the optimization of radiation. In the mentioned policy, the lowest dose is aimed by considering the country's economic and social factors for acceptable applications. Personnel already receive low dose with protection systems in the working areas. However, the patient doses must be taken under control based on the principle of optimization as much as possible.

There are two important points when performing a radiological procedure:

- To obtain the best possible image for a clear diagnosis of the disease,
- To apply the lowest dose for protecting the patient while getting the best image.

The second point indicates that the patient's radiation dose level must be kept at the lowest possible dose. In other words, it indicates dose optimization. The dose optimization meaning "the minimum radiation dose of the optimum image quality", is achieved by applying quality control procedures, calibration and dosimetric measurements.

In the Radiology Quality Control systems, the biggest problem is dose control and dose optimization. Neither patient nor users knows how much dose is exposed because there is no any system in the x-ray device for measuring or showing dose during exposure.

Since there is no dose adjustment on the equipment, the systems are operated by using the usual parameters; kVp and mAs. Because dose can not be adjusted, the patient may receive more dose than the aimed dose.

For dose optimization, all exposures should be kept at the minimum dose level in according to the ALARA principle (ALARA-as low as reasonably achievable). The aim of the optimization is not to download the risks of irradiation to zero. It is to reduce them to an acceptable level. This can be possible only by examining all parameters that affect the X-ray, by investigating the relationship between dose and these parameters, on the basis of this relationship, by performing the necessary regulations.

In all x-ray equipment, the operator can control the quantity and the quality of the radiation with kVp and mAs controls. If the equipment is not properly controlled, it will not be possible to control the radiation output. For this reason, optimization consists of not only improving of image quality and low dose but also establishing quality assurance and quality control programmes to ensure a proper performance of the x-ray equipment.

As frequently documented in the scientific literature, patient dose and image quality are basic aspects of any quality control (QC) tests in diagnostic radiology. Image quality must be adequate for diagnosis and it must be obtained with low doses.

The following QC tests are performed for both patient dose and image quality evaluation;

- kVp Accuracy and Repeatability
- Dose-kVp Linearity Test
- Dose-mAs Linearity Test
- X-ray Tube Output-kVp Relation
- HVL (Half Value Layer)
- Image Quality (Beam alignment, collimation alignment, contrast and resolution)

The quality control tests' methods, as well as the criteria for scoring the results, are in full agreement with those specified in the American Association of Physicists in Medicine (AAPM) Report No.4 and IEC 61223-3-1 (AAPM, 1981; IEC 61223-3-1, 1999).

There are a number of recent studies about dose optimization. Some of them are the surveys about image quality and patient dose in radiographic examinations in the authors' countries (Bouzarjomehri, 2004; Ciraj et al., 2005; Ramanandraibe, 2009; Papadimitriou, 2001; Shahbazi-Gahrouei, 2006). Some investigators focused only patient dose optimization (Brix et al., 2005; Vano & Fernandez, 2007; Seibert, 2004; Williams & Catling, 1998), whereas the others examined both the patient dose and image quality in radiographic devices (Aldrich et al., 2006; Schaefer-Prokop et al., 2008; Geijer, 2002). There are also studies that give reference values for clinical x-ray examinations by measuring phantom dose (Gray et al., 2005). But there is no any study focused to the dose optimization during quality control tests of x-ray devices. Dose optimization is very important because of the quality and quantity of quality control tests of x-ray equipments.

The aim of this study is to provide optimal x-ray parameters that may be used for quality control tests in order to make quality control activities more efficient and can be controlled. The staff know how the quality control tests are performed, but they don't know which parameters' values give which qualified image. They have problems during evaluation of test results, although there are some recommendations in the standards (AAPM, 1981; IEC 61223-3-1, 1999). They need proven parameter values for comparison. In this study, it was examined during quality control tests which parameters give a high quality image and how much dose is measured when these parameters were applied.

This study was performed by investigating the effects of X-ray parameters' changes on dose and by modeling of dose related to these parameters. After the modeling, in according to the related parameters, the dose level can be controlled, and in different x-ray units the dose levels that are obtained by applying the same parameter setting, can be compared.

Thus, in addition to obtain optimal parameters, controlling of the accuracy of the measured dose values may be possible by calculating the dose value during quality control tests.

2. Parameters of x-ray

In radiography, dose and image quality are dependent on radiographic parameters. This study is concerned with the quantification of these parameters and an assessment of their effect on patient dose and image quality. The focus of this study is on the relationship between dose, image quality and other radiographic parameters.

2.1 Absorbed dose

Absorbed dose is the quantity that expresses the radiation concentration delivered to a point, such as the entrance surface of patient's body. Absorbed dose in air is recognized as air kerma and it is a measure of the amount of radiation energy, in the unit of joules (J), actually deposited in or absorbed in a unit mass (kg) of air. Therefore, the quantity, kerma, is expressed in the units of J/kg which is also the radiation unit, the gray (G) (Sprawls, 1987; Hendee et al., 1984).

In this study, the word of "dose" will be used instead of air kerma (absorbed dose in air).

2.2 kVp

The high energy of the x-ray spectrum is determined by the kilovoltage applied to the x-ray tube. The maximum photon energy is numerically equal to the maximum applied potential in kilovolts. The maximum photon energy is determined by the voltage during the exposure time. This value is generally referred as the kilovolt peak (kVp) and is one of the adjustable factors of x-ray equipment (Sprawls, 1987).

2.3 mAs

The x-ray cathode is heated electrically by a current from a separate low voltage power supply. The output of this supply is controlled by the mA selector on the x-ray unit. Additionally, the duration of the x-ray exposure is controlled by the time selector. mAs is described by multiplying of these two values (mA x second) (Hendee et al., 1984).

2.4 Half Value Layer (HVL)

Half value layer describes both the penetrating ability of specific radiations and the penetration through specific objects. HVL is the thickness of material that reduces the intensity of an x-ray beam by half, and is expressed in unit of distance (mm) (Sprawls, 1987).

2.5 Image quality

The purpose of the radiographic image is to provide information about the medical condition of the patient. A quality image is one that provides all the information required for diagnosis of the patient's condition (Hendee et al., 1984).

Image quality is not a single factor but is described with beam alignment, collimation alignment, contrast and resolution. Contrast means differences in the form of gray scales or light intensities, whereas the resolution is a measure of its ability to differentiate between two objects a small distance apart; such that they appear distinct from one another.

An image is acceptable as qualified only if it has high resolution and high contrast.

3. Material and method

The radiographic measurements were performed in ten stationary X-ray units in five hospitals. The X-ray units including: Siemens, Philips, Toshiba, General Electric and Shimadzu were participated in this study. The reason for chosing these x-ray units is that their age is between 5 and 7 years old and the machines have 3 phase generators, thus their HVL value is kept in a narrow range, such as between 3 and 3,2mmAl.

Dosimax Plus A (Wellhöfer, Scanditronix, IBA, Germany) dosimeter was used to measure radiation dose. Dosimax Plus A dosimeter is a universal basic device and is designed according to IEC 61674 for acceptance tests and for quality checks at radiographic X-ray units. In Dosimax Plus A, dose measurements are performed by using solid state detectors (RQA). The dose range is from 200nGy to 9999mGy (Iba Dosimetry, 2008). It was calibrated by the Iba Laboratory of Germany and found to be capable of performing within recommended level of precision and accuracy.
Dose measurement applications has been included in recent recommendations (AAPM, 1981; IEC 61223-3-1, 1999). The measurement procedures that were realized in this study, are explained below step by step.
Before starting dose measurements, kVp accuracy tests were performed for 10 units and it was seen that they have acceptable accuracy in according to the standards (AAPM, 2002).

3.1 Measurement procedure of X-ray dose variation with kVp

The dosimeter was positioned in central beam axis such that the X-ray tube focal spot-dedector distance (FDD) was 100cm for the measurements. The radiation field size was set to cover the dosimeter in order to avoid the possible scatter radiation to the dosimeter.
In order to investigate the effect of kVp to the dose, the unit was set at 20mAs and 50kVp value. An X-ray exposure was made and the dosimeter reading was recorded. This step was repeated at same constant mAs and different kVp settings (50, 70, 80 and 100kVp) and dosimeter reading was determined. Similar X-ray dose measurements were also determined for 40 and 50mAs settings for each kVp value (50, 70, 80 and 100kVp). All measurements were repeated for 60cm (FDD). The measured dose values were plotted against the corresponding kVp for each X-ray unit separately.

3.2 Measurement procedure of X-ray dose variation with mAs

The dosimeter was positioned at 100cm (FDD) from the focal spot of the X-ray tube.
In order to determine the effect of mAs to the dose, the exposures were performed with constant kVp (50kVp), but with gradually increasing mAs (10, 20, 40 and 50mAs). Similar X-ray dose measurements were also determined for 70 and 100kVp settings for each mAs value (10, 20, 40 and 50mAs). All measurements were repeated for distance of 60cm. The measurement results for each X-ray unit were plotted against the corresponding mAs.

3.3 Measurement procedure of X-ray tube output variation with kVp

The X-ray tube output was determined as the ratio of dose reading to the mAs setting. The values of X-ray tube output were plotted against kVp by using dose values obtained from two measurement procedures (Section 3.1 and 3.2).

3.4 Measurement procedure for Half Value Layer (HVL)

For dose measurements, filtration was realized by using aluminum (Al) filters with 1mm and 0,5mm.
During the measurements, mAs and kVp were stable (20mAs, 50kVp) and the distance was determined as 100cm. Initially, the dose measurement without the filter was generalized. After this, the dose measurement was repeated by using filter with different thickness. Each filter thickness was obtained by adding 1mmAl and 0,5mmAl. The dose measurements were taken in the conditions; without filter, 1mmAl, 2mmAl, 3mmAl and 3,5mmAl.

3.5 Observing of image quality

Test tool ETR1 (Iba Dosimetry, 2008) was used for image quality tests. The ETR1 is a multi-purpose test tool. With a single exposure on X-ray film made by using this tool, all criterias (alignments, contrast and resolution) can be checked for quality control of image.
Before exposure, a cassette with x-ray film was placed on the patient table. The distance between the film and the focal spot was set to 100cm. The test tool was placed over the cassette and the collimator was adjusted to ensure that the light beam covers exactly the inner pattern of the test tool. An exposure was performed with 50kVp and 20mAs. The exposure was repeated for each setting value adjusted for dose measurements mentioned in Section 3.1 and 3.2 (50kVp-40mAs, 50mAs; 70kVp-20mAs, 40mAs, 50mAs; etc…).
After developing the film, the image on the film was compared with the real test tool image. Beam alignment, collimation alignment, contrast and resolution factors were determined and recorded.

4. Results

During the quality control of x-ray equipment, it is essential to know the effects of x-ray parameters to the image quality. The x-ray parameters' effects were measured by using quality control test procedures and they were analysed graphically.
In result, the optimized dose in which parameters' value gave the high quality image was determined.

4.1 Assessment of X-ray dose variation with kVp

The measured doses by changing kVp are given in Table 1. During measurements, mAs was firstly kept stable (20mAs) and kVp was changed as 50, 70, 80 and 100kVp to investigate the effects of kVp to the dose at stable mAs.
After this, the same measurement procedure was applied to other mAs values (40 and 50mAs). All measurements were performed at distance of 100 and 60cm.
Graphical representations of the relationship between dose and kVp value for constant mAs (20, 40 and 50mAs) at 100cm and 60cm are given in Fig. 1, 2, 3 and Fig. 4, 5, 6, respectively.

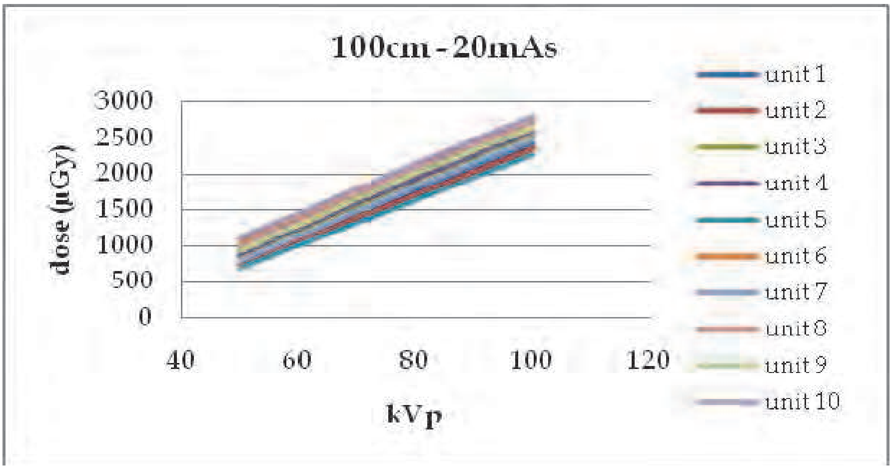

Fig. 1. Measured dose values of 10 x-ray units versus kVp for 20mAs at distance of 100cm.

	Dose (μGy)									
	Unit	**50 kVp**	**70 kVp**	**80 kVp**	**100 kVp**	**50 kVp**	**70 kVp**	**80 kVp**	**100 kVp**	
100cm - 20mAs	**1**	736,0	1439	1766	2420	1950	4230	5450	8050	**60cm - 20mAs**
	2	710,7	1388	1707	2357	1883	3955	5243	7588	
	3	824,3	1538	1866	2538	2327	4640	5905	8608	
	4	894,4	1605	1935	2601	2478	4915	6181	8909	
	5	690,4	1324	1642	2282	1554	3717	4981	7268	
	6	1048	1734	2101	2757	3310	5758	7006	9498	
	7	792,1	1481	1826	2483	2077	4353	5627	8277	
	8	988,4	1704	2070	2726	2999	5477	6722	9300	
	9	934,7	1657	2017	2652	2796	5157	6445	9062	
	10	1101	1784	2136	2792	3484	5872	7195	9741	
100cm - 40mAs	**1**	1482	2938	3622	5056	4190	8260	10800	15600	**60cm - 40mAs**
	2	1493	2863	3580	4912	3774	7983	10511	15123	
	3	1587	3129	3797	5276	4511	8588	11383	15515	
	4	1600	3136	3872	5335	4684	8981	11515	16089	
	5	1400	2738	3460	4861	3464	7613	10099	14656	
	6	1923	3461	4207	5716	5468	10097	12415	17247	
	7	1528	3082	3702	5185	4271	8716	10984	15797	
	8	1858	3335	4104	5561	5249	9773	12037	16986	
	9	1692	3290	3946	5405	4870	9408	11788	16487	
	10	2053	3581	4320	5855	5805	10618	12869	17610	
100cm - 50mAs	**1**	1790	3612	4590	6380	5350	12548	15800	22700	**60cm - 50mAs**
	2	1722	3443	4384	6194	4991	12168	15553	22313	
	3	1933	3678	4609	6608	6144	13528	15973	23548	
	4	1985	3697	4481	6652	6588	13249	16348	23704	
	5	1604	3345	4185	6008	4585	11712	15033	21972	
	6	2245	4020	4965	6995	8101	14631	17750	24808	
	7	1853	3665	4575	6518	5574	12999	15799	23255	
	8	2198	3813	4759	6823	7623	14240	17234	24484	
	9	2091	3799	4691	6712	7064	13751	16857	23892	
	10	2391	4213	5167	7194	8724	15027	18203	25283	

Table 1. Measured doses (μGy) for constant mAs but increasing kVp at different distances.

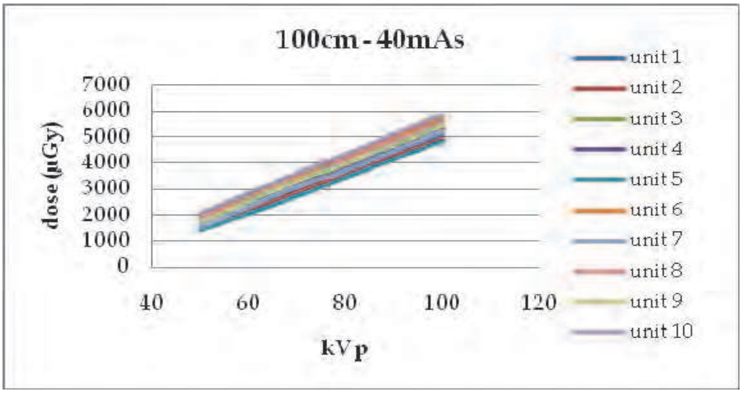

Fig. 2. Measured dose values of 10 x-ray units versus kVp for 40mAs at distance of 100cm.

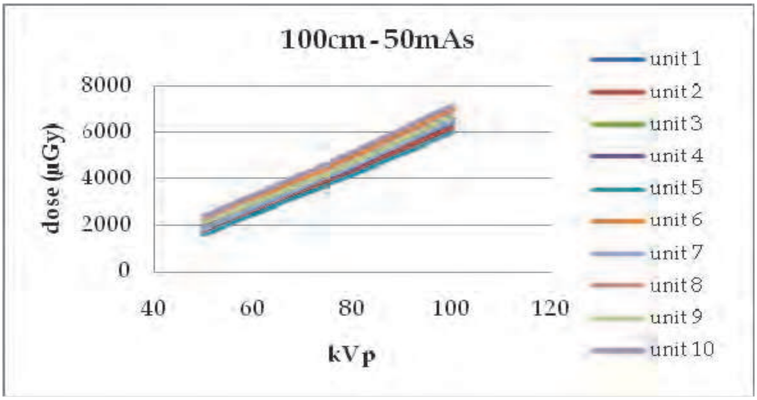

Fig. 3. Measured dose values of 10 x-ray units versus kVp for 50mAs at distance of 100cm.

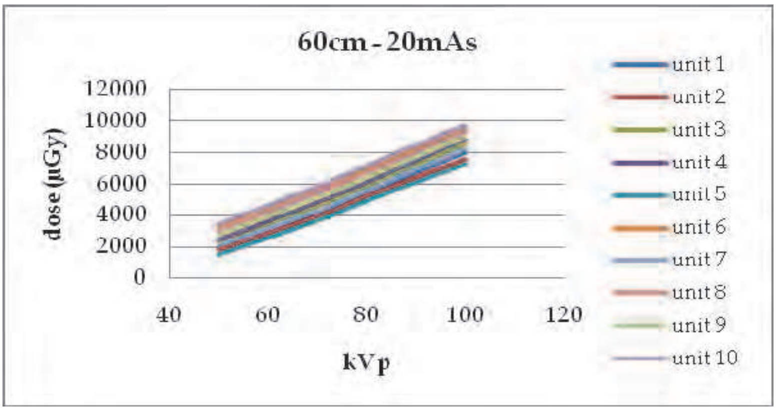

Fig. 4. Measured dose values of 10 x-ray units versus kVp for 20mAs at distance of 60cm.

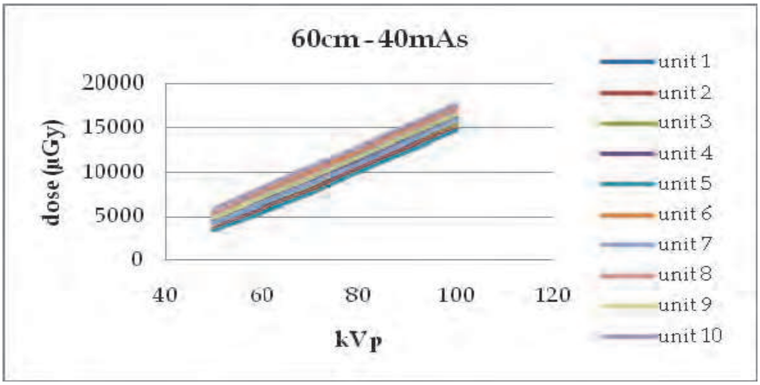

Fig. 5. Measured dose values of 10 x-ray units versus kVp for 40mAs at distance of 60cm.

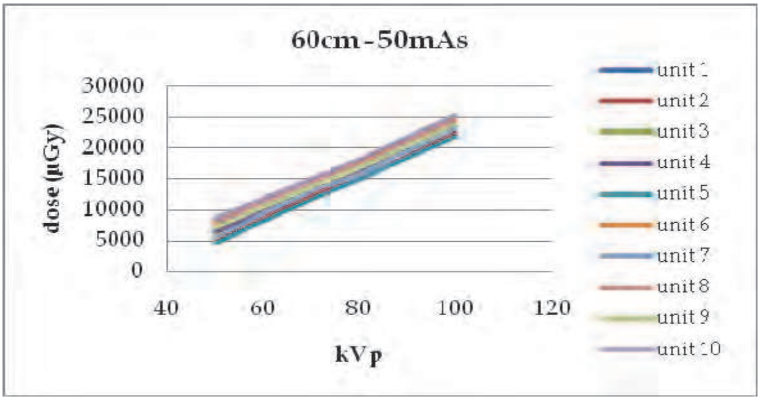

Fig. 6. Measured dose values of 10 x-ray units versus kVp for 50mAs at distance of 60cm.

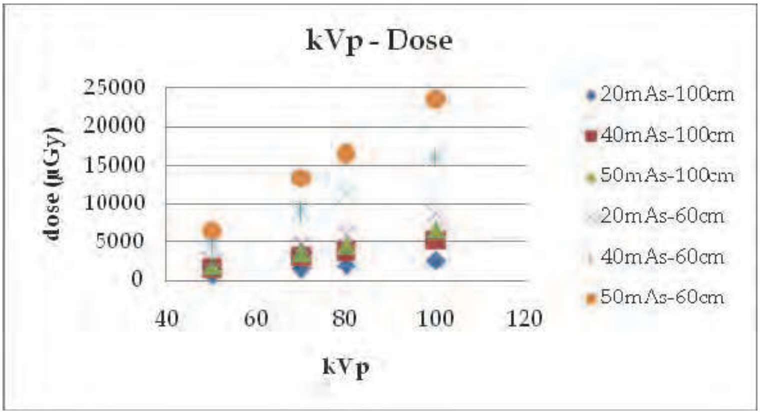

Fig. 7. Mean dose values of 10 x-ray units versus kVp for different mAs and distance setting.

The dose values obtained from 10 x-ray units were analysed statistically and the mean dose values for each setting parameter were defined with standard deviation in Table 2.
For different distance and mAs settings, the mean dose values were plotted against kVp (Fig. 7). Hence, the small differences that are caused from unit changes were eliminated, and the effect of kVp to dose variation was focused.

Dose	100cm - 20mAs				60cm - 20mAs			
(µGy)	50kVp	70kVp	80kVp	100kVp	50kVp	70kVp	80kVp	100kVp
Mean	872,0	1565,4	1906,5	2560,7	2485,8	4807,5	6075,5	8630,2
std	144,3	155,9	172,4	174,8	645,3	753,0	760,0	823,6
Dose	100cm - 40mAs				60cm - 40mAs			
(µGy)	50kVp	70kVp	80kVp	100kVp	50kVp	70kVp	80kVp	100kVp
Mean	1661,6	3155,3	3861,1	5316,0	4628,7	9003,7	11440,1	16110,9
std	215,4	266,5	283,4	329,3	742,1	962,9	866,6	957,6
Dose	100cm - 50mAs				60cm - 50mAs			
(µGy)	50kVp	70kVp	80kVp	100kVp	50kVp	70kVp	80kVp	100kVp
Mean	1981,3	3728,4	4640,7	6608,4	6474,2	13385,3	16455,0	23595,8
std	249,7	254,1	280,0	356,4	1387,9	1069,0	1024,1	1075,5

Table 2. The statistic analysis of dose from 10 units for different kVp at constant mAs.

4.2 Assessment of X-ray dose variation with mAs

The obtained dose values at constant kVp by increasing mAs can be seen in Table 3. The dose measurements were performed at 50, 70 and 100kVp with changing mAs (10, 20, 40 and 50mAs) in distance of 100 and 60cm.
Graphical representations of the relationship between dose and mAs for constant kVp (50, 70 and 100kVp) at 100 and 60cm are shown in Fig. 8, 9, 10 and Fig. 11, 12, 13, respectively.

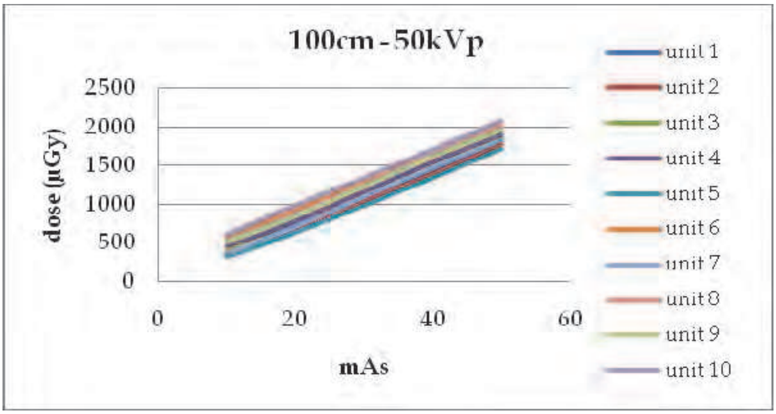

Fig. 8. Measured dose values of 10 x-ray units versus mAs for 50kVp at distance of 100cm.

Dose (μGy)										
	Unit	**10 mAs**	**20 mAs**	**40 mAs**	**50 mAs**	**10 mAs**	**20 mAs**	**40 mAs**	**50 mAs**	
100cm - 50kVp	**1**	378,0	736,0	1432	1810	1050	2089	4188	5120	**60cm - 50kVp**
	2	339,8	695,4	1397	1773	932	1940	4056	5075	
	3	402,2	796,4	1527	1886	1202	2231	4276	5245	
	4	464,0	786,5	1554	1911	1247	2333	4329	5394	
	5	321,1	632,5	1344	1717	826	1846	3975	5026	
	6	565,8	934,5	1688	2068	1494	2532	4680	5715	
	7	370,2	712,0	1483	1834	1123	2152	4245	5206	
	8	530,9	879,0	1641	2006	1342	2402	4516	5657	
	9	510,4	844,6	1610	1952	1272	2342	4447	5551	
	10	606,9	987,6	1711	2091	1597	2614	4801	5862	
100cm - 70kVp	**1**	714,4	1469	2871	3652	2310	4180	8140	10077	**60cm - 70kVp**
	2	641,8	1372	2787	3528	2187	4040	7966	9846	
	3	801,0	1618	3055	3874	2604	4401	8428	10480	
	4	874,9	1687	3180	3902	2799	4675	8672	10585	
	5	574,9	1292	2683	3414	1993	3828	7692	9613	
	6	1001	1881	3401	4157	3317	5186	9123	10959	
	7	754,2	1558	2955	3773	2580	4309	8359	10228	
	8	987,4	1764	3387	4084	3221	4956	8972	10745	
	9	956,6	1718	3292	3952	2989	4936	8832	10645	
	10	1075	1926	3515	4219	3503	5387	9280	11210	
100cm - 100kVp	**1**	1404	2808	5616	7020	3250	7288	15435	19426	**60cm - 100kVp**
	2	1198	2623	5387	6819	3006	6870	14811	18926	
	3	1641	2927	5751	7255	3870	8097	15872	20058	
	4	1690	2922	5964	7285	4278	8296	16080	20415	
	5	1045	2444	5308	6622	2421	6342	14354	18465	
	6	1854	3182	6215	7558	4940	8955	17157	21594	
	7	1582	2885	5703	7131	3537	7601	15343	19500	
	8	1797	3060	6070	7429	4509	8735	17102	21306	
	9	1717	3055	6070	7407	4448	8584	16399	20958	
	10	1889	3343	6266	7638	5290	9310	17697	21944	

Table 3. Measured doses (μGy) for constant kVp but increasing mAs at different distances.

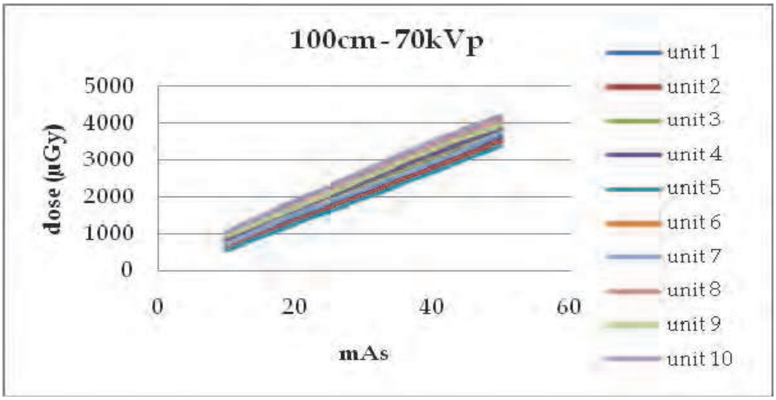

Fig. 9. Measured dose values of 10 x-ray units versus mAs for 70kVp at distance of 100cm.

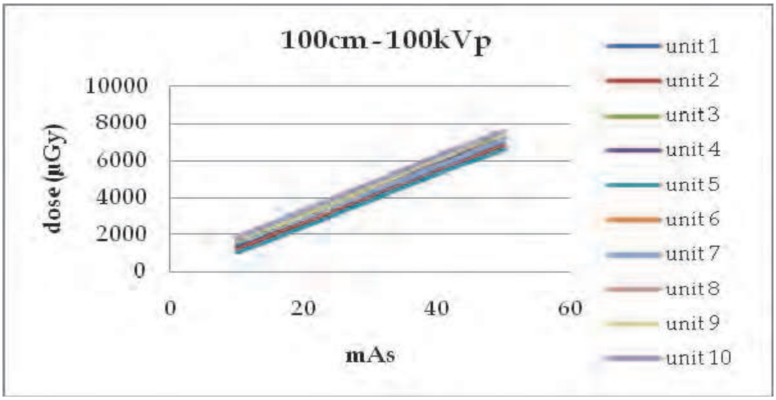

Fig. 10. Measured dose values of 10 x-ray units versus mAs for 100kVp at distance of 100cm.

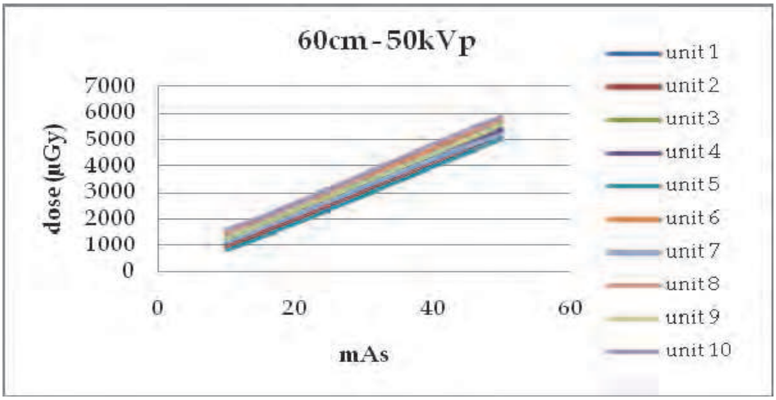

Fig. 11. Measured dose values of 10 x-ray units versus mAs for 50kVp at distance of 60cm.

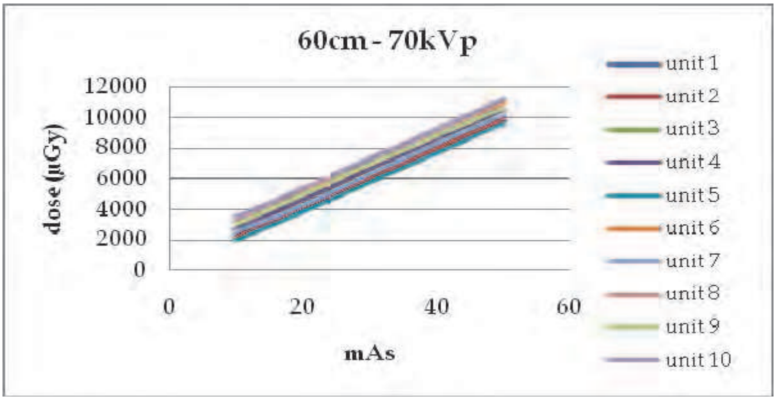

Fig. 12. Measured dose values of 10 x-ray units versus mAs for 70kVp at distance of 60cm.

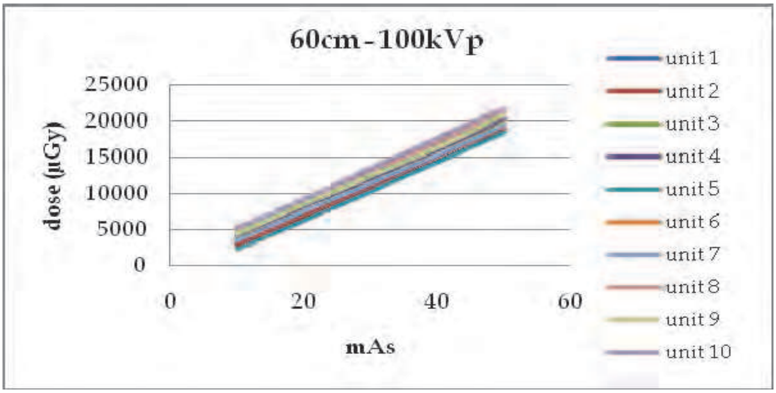

Fig. 13. Measured dose values of 10 x-ray units versus mAs for 100kVp at distance of 60cm.

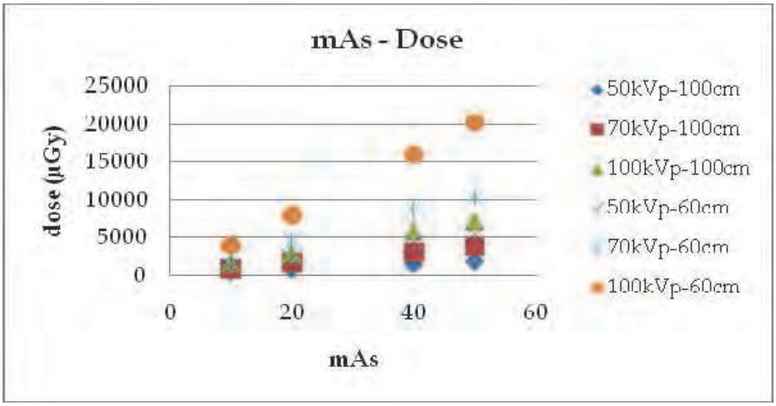

Fig. 14. Mean dose values of 10 x-ray units versus mAs for different kVp and distances.

The dose values obtained from 10 x-ray units were analysed statistically and the mean dose values for each setting parameter were defined with standard deviation in Table 4.
For different distance and kVp settings, the mean dose values were plotted against mAs (Fig. 14). Hence, the small differences that are caused from unit changes were eliminated, and the effect of mAs to dose variation was focused.

Dose (µGy)	100cm - 50kVp				60cm - 50kVp			
	10mAs	20mAs	40mAs	50mAs	10mAs	20mAs	40mAs	50mAs
Mean	448,9	800,5	1538,6	1904,9	1208,4	2248,1	4351,4	5385,1
std	100,5	111,8	125,0	125,0	238,3	246,1	262,3	295,3
Dose (µGy)	100cm - 70kVp				60cm - 70kVp			
	10mAs	20mAs	40mAs	50mAs	10mAs	20mAs	40mAs	50mAs
Mean	838,2	1628,5	3112,6	3855,6	2750,4	4589,7	8546,2	10438,6
std	167,4	208,6	285,7	266,1	526,1	518,1	519,6	498,2
Dose (µGy)	100cm - 100kVp				60cm - 100kVp			
	10mAs	20mAs	40mAs	50mAs	10mAs	20mAs	40mAs	50mAs
Mean	1581,7	2924,9	5835,1	7216,4	3954,8	8008,0	16025,0	20259,2
std	281,9	261,2	334,7	322,8	903,1	960,3	1079,2	1180,2

Table 4. The statistic analysis of dose from 10 units for different mAs at constant kVp.

4.3 Assessment of X-ray tube output variation with kVp

In order to investigate the relationship between the x-ray tube output and kVp, firstly the x-ray tube outputs for 10 x-ray units, were calculated by dividing the measured dose values to the mAs values. It was seen that there is a dose distribution because of the measured different doses of each x-ray unit. Therefore, the mean of the x-ray tube output values for each mAs values were used for plotting of the x-ray tube output against the kVp.
Additionally, the graphics show that there is a different distribution that are caused from different distances although all distributions were similar for each mAs value.
For each different distance, the mean of the calculated tube output for different mAs were plotted with equations.

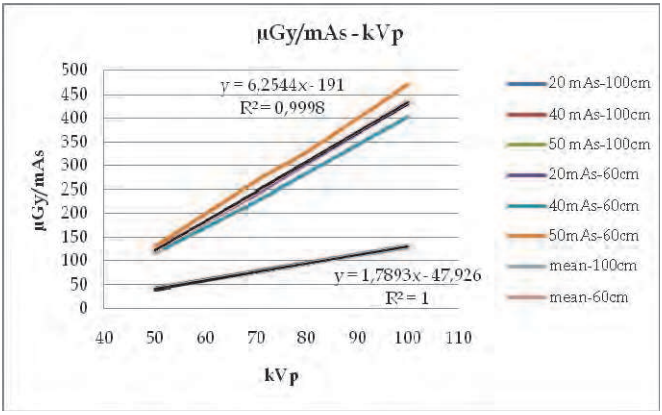

Fig. 15. X-ray tube output changes with kVp (dose values from procedure in Section 3.1).

In Figure 15, the dose values that were obtained by applying the procedure mentioned in Section 3.1 and the procedure settings (mAs, kVp), were plotted, whereas in Figure 16 the values obtained from procedure in section 3.2, were used.

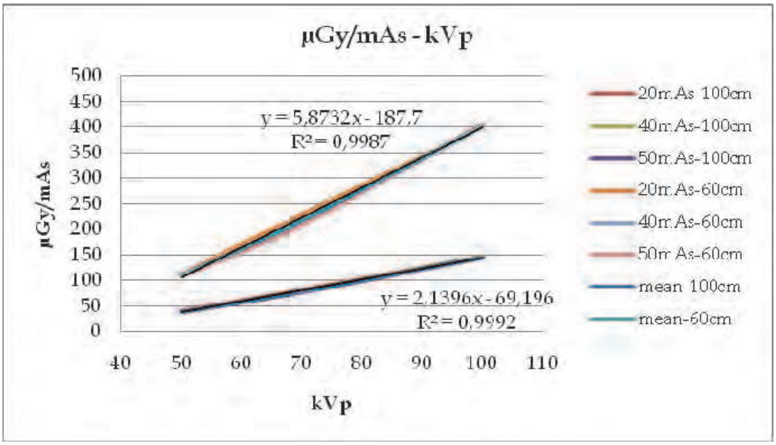

Fig. 16. X-ray tube output changes with kVp (dose values from procedure in Section 3.2).

The tube output which is derived from direct measurement can be expressed in equations obtained from Figure 15 and Figure 16, because kVp is related to tube output directly.
For distance of 100cm, tube output can be written separately in different two equations that were obtained from graphics in Fig. 15 and Fig. 16.

$$\text{Tube output } (\mu Gy/mAs) = 1{,}7893kVp - 47{,}926 \qquad R^2 = 1 \tag{1}$$

$$\text{Tube output } (\mu Gy/mAs) = 2{,}1396kVp - 69{,}196 \qquad R^2 = 0{,}9992 \tag{2}$$

Dose can be determined from tube output, and mAs can be placed in Equations 1 and 2.

$$\text{Dose } (\mu Gy) = (1{,}7893kVp - 47{,}926) \times mAs \tag{3}$$

$$\text{Dose } (\mu Gy) = (2{,}1396kVp - 69{,}196) \times mAs \tag{4}$$

For distance of 60 cm, again tube output can be written separately in different two equations obtained from Figure 15 and Figure 16, respectively.

$$\text{Tube output } (\mu Gy/mAs) = 6{,}2544kVp - 191{,}0 \qquad R^2 = 0{,}9998 \tag{5}$$

$$\text{Tube output } (\mu Gy/mAs) = 5{,}8732kVp - 187{,}7 \qquad R^2 = 0{,}9987 \tag{6}$$

When mAs is placed in Equations 5 and 6, the following Equations 7 and 8 are derived.

$$\text{Dose } (\mu Gy) = (6{,}2544kVp - 191{,}0) \times mAs \tag{7}$$

$$\text{Dose } (\mu Gy) = (5{,}8732kVp - 187{,}7) \times mAs \tag{8}$$

To test the validity of these equations, an external set of dose values obtained from measurements (10mAs-50kVp, 10mAs-70kVp and 10mAs-100kVp for 100cm and 60cm) was selected. kVp and mAs values were plugged into the Equations 3, 4, and Equations 7, 8 to predict the dose values for applied kVp and mAs values of measurement procedures (Section 3.1 and 3.2). The results were then compared with the measured dose values, as shown in Table 5.

It is seen from Table 5, the predicted dose values are within the measured dose value with standard deviations for each measurement procedure (in different distance, firstly constant mAs with increasing kVp, afterly constant kVp with increasing mAs). The predicted dose values obtained from equations that shows the relationship between x-ray tube output and kVp during measurement procedure (mAs is increased with constant kVp), are approximately similar with the predicted dose values that were derived from measurement procedure of constant mAs and increasing kVp. Relatively it can be said that dose measurements are not affected from the application style of parameters (kVp and mAs). Not only keeping mAs as constant and increasing kVp, but also keeping kVp as constant and increasing mAs doesn't affect the measured dose values for the same kVp and mAs. For example, the dose value obtained from measurement of 50kVp-40mAs are approximately similar during application of both constant 50kVp with increasing mAs and constant 40mAs with increasing kVp. This result showed that taking into account the results that were obtained from only one measurement procedure is sufficient. Especially, Equation 3 and Equation 7 can be preferred for dose estimation because of their best R^2.

Distance 100cm	**Mean dose from direct measurement (µGy)**	**Dose calculated from Equation 3 (µGy)**	**Dose calculated from Equation 4 (µGy)**
10mAs-50kVp	448,9 ± 100,5	415,39	377,84
10mAs-70kVp	838,2 ± 167,4	773,25	805,76
10mAs-100kVp	1581,7 ± 281,9	1310,04	1447,64
Distance 60cm	**Mean dose from direct measurement (µGy)**	**Dose calculated from Equation 7 (µGy)**	**Dose calculated from Equation 8 (µGy)**
10mAs-50kVp	1208,4 ± 238,3	1217,2	1059,60
10mAs-70kVp	2750,4 ± 526,1	2468,08	2234,24
10mAs-100kVp	3954,8 ± 903,1	4344,4	3996,20

Table 5. Measured and calculated dose values.

4.4 Assessment of Half Value Layer (HVL)

Testing of half value layer is performed by measuring dose values with different Al thickness and it verifies that half value layer is sufficient to reduce patient exposure to low energy radiation. The obtained dose measurement results of each x-ray unit in this study for stable mAs and kVp are given in Table 6.

The dose measurement results were plotted against the aluminum (Al) thickness (Fig. 17). Dose (µGy) equations were obtained as a function of Al thickness and from these equations, the Al thickness in which the dose decreased to its half value was calculated (Table 7).

kVp = 50, mAs = 20, Distance = 100cm					
Unit	**Dose (µGy)**				
	0mmAl	**1mmAl**	**2mmAl**	**3mmAl**	**4mmAl**
1	736,0	520,9	451,8	374,0	342,8
2	710,7	519,9	446,8	370,1	337,7
3	824,3	647,5	522,0	431,6	388,9
4	894,4	643,1	554,2	462,3	415,7
5	690,4	502,1	431,8	359,5	322,0
6	1047,8	767,3	654,0	524,1	493,8
7	792,1	598,8	485,7	401,8	360,0
8	988,0	702,1	588,9	499,6	454,9
9	934,7	704,2	577,1	474,8	425,2
10	1101,0	782,2	656,0	556,6	506,8

Table 6. Dose measurements for different aluminum thickness (mm).

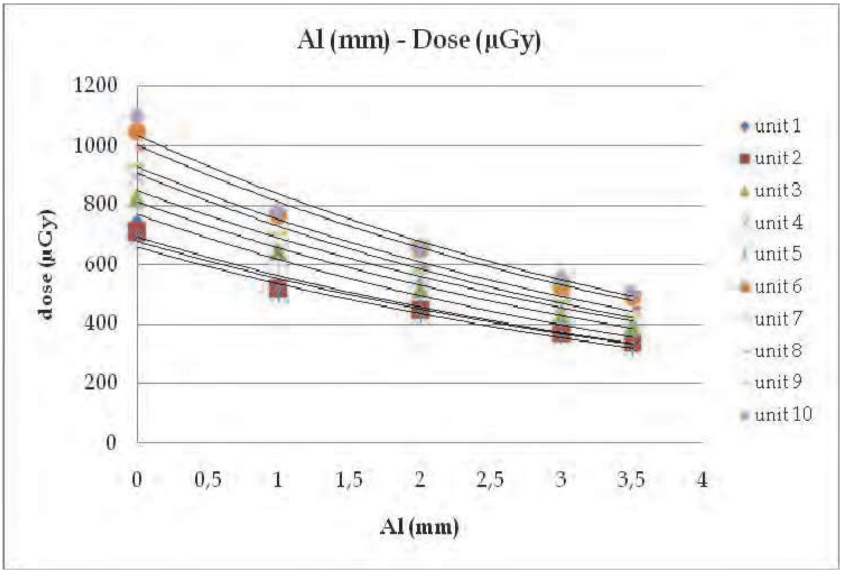

Fig. 17. Al(mm)-Dose(µGy) graphic for each X-ray unit.

Unit	Dose (μGy) = f(Al (mm))	Calculated HVL (mm)
1	$y = 693{,}18\ e^{-0{,}208x}$ $R^2 = 0{,}9714$	3,0
2	$y = 678{,}13\ e^{-0{,}204x}$ $R^2 = 0{,}9819$	3,1
3	$y = 811{,}49\ e^{-0{,}212x}$ $R^2 = 0{,}9979$	3,2
4	$y = 848{,}79\ e^{-0{,}208x}$ $R^2 = 0{,}9775$	3,1
5	$y = 658{,}65\ e^{-0{,}207x}$ $R^2 = 0{,}9812$	3,1
6	$y = 1002{,}5\ e^{-0{,}211x}$ $R^2 = 0{,}9830$	3,1
7	$y = 769{,}50\ e^{-0{,}220x}$ $R^2 = 0{,}9940$	3,0
8	$y = 929{,}33\ e^{-0{,}212x}$ $R^2 = 0{,}9723$	3,0
9	$y = 907{,}66\ e^{-0{,}219x}$ $R^2 = 0{,}9939$	3,0
10	$y = 1035{,}5\ e^{-0{,}212x}$ $R^2 = 0{,}9722$	3,0

Table 7. Dose=*f*(Al) equations and calculated HVL values.

As it is seen from the table, the observed x-ray units' HVL values change from 3,0 to 3,2 mmAl. Because it is required that the HVL of an acceptable x-ray unit with 3 phase generator must exceed 2,9mm, the observed 10 x-ray units were appropriate to the international standards (AAPM, 1981).

4.5 Image quality

Image quality tests were performed by controlling of beam alignment, collimation alignment, contrast and resolution of image.

As a result of the beam aligment and collimation alignment tests, it was seen that beam alignment and collimation alignment are only related to the quality of x-ray tube, are not dependent to the x-ray parameters, such as kVp, mAs and dose. For this reason, the test results that were obtained from only one measurement setting (50kVp, 20mAs, 100cm), are sufficient to obtain information about alignments of each x-ray units (Table 8).

Beam alignment test gives the deviation of the centre from the middle of the exposed film to the middle of the test tool (point "a" in Figure 18). The test's results that were given in Table 8 show that the beam misalignments were less than 10mm for 10 x-ray units.

In the collimation alignment test, the vertical misalignment was defined as the sum of the deviation of the top and bottom edges, horizontal as the sum of the deviation of the right and left edges (point "b" in Figure 18). In according to the international standards, the misalignment must each be less than 25mm (AAPM, 1981). As it is seen from Table 8, all misalignmenst for 10 units are appropriate to the standards.

For the measurement of the resolution, parallel lead strips separated by a distance equal to the width of the strips, that are placed on the test tool (point "c" in Figure 18) were used. The common practice is to describe the line width and separation distance in terms of line pairs (lp) per unit distance (millimeters) (Lp/mm). One line pair consists of one lead strip and adjacent separation space. The number of line pairs per millimeter is actually an expression of spatial frequency. As the lines get smaller and closer together, the spatial frequency increases (Sprawls, 1987). The test pattern contains areas with different spatial frequencies. To evaluate an imaging system, the visible line group is recorded as line pairs per mm. In according to the international standards, resolution below 0,8Lp/mm is not acceptable (AAPM, 1981). The obtained test results in this study, are shown in Table 9.

Evaluating the contrast was performed by looking at the copper step wedge from the test pattern that are placed on the test tool (point "d" in Figure 18). The visible copper step wedges were recorded in order to describe the resolution quality (Table 10). In according to the international standards, all copper steps have to be clearly visible (AAPM, 1981).

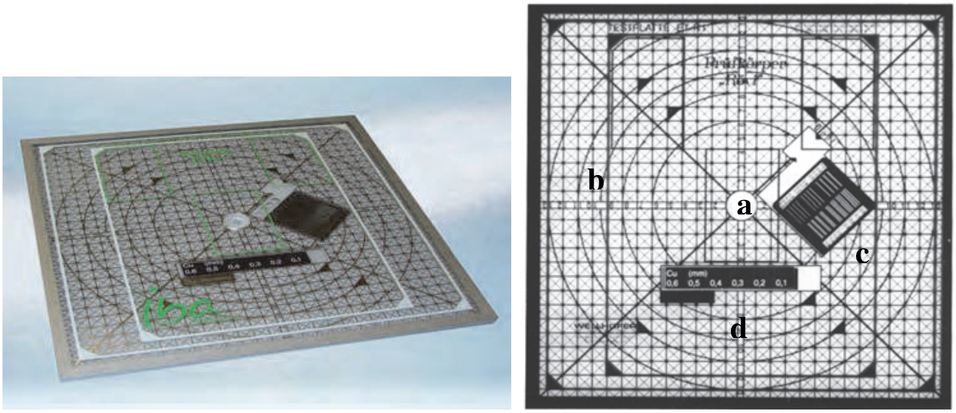

Fig. 18. ETR1 test tool used for image quality test.

Unit	Beam Alignment (mm)		Collimation Alignment (mm)			
1	< 10mm	OK	Top: 3mm Right: 1mm	Bottom: 2mm Left: 1mm	Total: 5mm Total: 2mm	OK
2	< 10mm	OK	Top: 5mm Right: 3mm	Bottom: 3mm Left: 1mm	Total: 8mm Total: 4mm	OK
3	< 10mm	OK	Top: 1mm Right: 2mm	Bottom: 1mm Left: 1mm	Total: 2mm Total: 3mm	OK
4	< 10mm	OK	Top: 3mm Right: 2mm	Bottom: 2mm Left: 3mm	Total: 5mm Total: 5mm	OK
5	< 10mm	OK	Top: 2mm Right: 2mm	Bottom: 1mm Left: 2mm	Total: 3mm Total: 4mm	OK
6	< 10mm	OK	Top: 6mm Right: 3mm	Bottom: 4mm Left: 3mm	Total: 10mm Total: 6mm	OK
7	< 10mm	OK	Top: 2mm Right: 3mm	Bottom: 2mm Left: 1mm	Total: 4mm Total: 4mm	OK
8	< 10mm	OK	Top: 4mm Right: 1mm	Bottom: 3mm Left: 1mm	Total: 7mm Total: 2mm	OK
9	< 10mm	OK	Top: 5mm Right: 2mm	Bottom: 4mm Left: 2mm	Total: 9mm Total: 4mm	OK
10	< 10mm	OK	Top: 7mm Right: 4mm	Bottom: 5mm Left: 3mm	Total: 12mm Total: 7mm	OK

Table 8. Beam alignment and collimation alignment test results.

As it is seen from Table 8, both beam alignments and collimation alignments of 10 x-ray units are appropriate to the international standards and there is no unwanted effect on the image quality.
Although beam alignment and collimation alignment are not dependent to the kVp and mAs value, resolution and contrast are directly related to these parameters. On Table 9, it is seen that resolution increases with increasing parameter setting values, especially with kVp.
From Table 10, it can be said that contrast is good on the values of 70kVp, especially on 70kVp-40mAs for 10 x-ray units. At this value of parameters, all copper steps on the test tool can be seen definitely. While the values on the Table 10 decreases from 0,6 to 0,1, the contrast also decreases and the seeable points on the film loss step by step.

5. Discussion

In this study, the x-ray units with ages between 5 and 7 years old were selected to prevent the wide distribution of measured dose because the x-ray tubes don't produce the same exposure and the output decreases with age of x-ray unit.
Again, in this study, three phase generators were preferred because they produces more radiation exposure per unit mAs. This characteristic is essential for modeling of dose.
A difference in tube output among tubes is often caused by variations in the filtration. For this reason, this study were performed on the x-ray units with HVL values that changes approximately from 3,0 to 3,1mmAl. It also prevented the wide distribution of measured dose. The obtained HVL values in this study are acceptable in according to the international standards (AAPM, 1981).
It is known that dose is more sensitive to the kVp changes than mAs changes. Exposure errors can occur if the actual kVp generated by the x-ray generator is different from the adjusting kVp value. Before dose measurements, kVp accuracy testing were performed correctly and it was seen that the kVp during exposure was the close within the acceptable deviation to the selected kVp value.
All dose measurements were performed at different distance of 100cm and 60cm. With this application, the distance effects on dose were investigated and it was used for dose modeling because of the inverse-square effect.
For dose measurements, two different measurement procedures were used. In the first procedure, mAs value was kept constant and kVp values were changed to investigate the dose variation with kVp. In the second procedure, kVp value was kept constant and mAs values were changed to investigate the dose variation with mAs. Thus, the effects of kVp and mAs were examined separately.
Because the x-ray units were selected in according to the criterias mentioned above, the measured dose values didn't show wide distribution for each measurement setup in all 10 x-ray units. In this condition, the mean of the dose values of 10 x-ray units for each measurement setup was used to show the tube output variations with kVp. Plotting of tube output to kVp (Figure 15 and 16) were performed by using dose values obtained from two different measurement procedures. By this way, it was seen that the tube output variations related to kVp were approximately similar at different mAs value. Hence, the mean variations were used for modeling of dose.
Modeling was realized twice for dose values at different distances of 100cm and 60cm, because the different variations were seen between measurement values obtained different distances. By using equations (Equation 3 and Equation 7) in the models related to the

Resolution (Lp/mm)										
	Unit	**50kVp**	**70kVp**	**80kVp**	**100kVp**	**50kVp**	**70kVp**	**80kVp**	**100kVp**	
100cm - 20mAs	**1**	2,2	3,1	3,4	4,0	2,2	3,4	3,4	4,0	**60cm - 20mAs**
	2	2,2	3,4	3,7	4,3	2,2	3,1	3,4	4,0	
	3	2,5	3,1	3,7	4,0	2,0	2,8	3,0	3,7	
	4	2,5	3,4	3,4	4,0	2,2	3,1	3,4	4,3	
	5	2,5	3,4	3,4	4,3	2,5	3,4	3,4	4,3	
	6	2,0	2,8	3,7	4,3	2,2	3,1	3,4	4,0	
	7	2,5	3,1	3,7	4,3	2,2	3,1	3,4	4,3	
	8	2,0	2,8	3,4	4,0	2,0	2,8	3,1	4,0	
	9	2,0	2,8	3,4	4,0	2,2	3,1	3,4	4,3	
	10	2,2	3,1	3,7	4,3	2,2	3,1	3,7	4,3	
100cm - 40mAs	**1**	2,2	3,4	3,7	4,3	2,5	3,4	3,7	4,3	**60cm - 40mAs**
	2	2,2	3,4	3,7	4,3	2,0	3,1	3,4	4,0	
	3	2,5	3,4	4,0	4,3	2,5	3,4	3,7	4,3	
	4	2,5	3,1	3,4	4,0	2,2	3,1	3,4	4,0	
	5	2,2	3,4	3,7	4,3	2,5	3,4	3,7	4,0	
	6	2,8	3,4	3,7	4,3	2,8	3,7	4,0	4,3	
	7	2,8	3,7	4,0	4,3	2,5	3,4	3,7	4,0	
	8	2,2	3,4	3,7	4,0	2,5	3,4	3,7	4,0	
	9	2,5	3,4	3,7	4,3	2,2	3,1	3,7	4,3	
	10	2,2	3,1	4,0	4,3	2,2	3,4	4,0	4,3	
100cm - 50mAs	**1**	2,5	3,1	4,0	4,3	2,2	3,1	3,7	4,3	**60cm - 50mAs**
	2	2,8	3,4	4,0	4,6	2,5	3,1	3,7	4,3	
	3	2,8	3,4	4,0	4,6	2,8	3,4	4,0	4,6	
	4	2,5	3,1	3,7	4,3	2,2	3,1	3,7	4,3	
	5	2,5	2,8	3,7	4,3	2,2	3,1	3,7	4,6	
	6	2,8	3,1	4,0	4,6	2,0	2,8	3,7	4,3	
	7	3,1	3,4	4,3	4,6	2,8	3,1	4,0	4,6	
	8	2,8	3,1	4,0	4,3	2,0	2,8	3,7	4,0	
	9	2,8	3,1	4,0	4,6	2,5	3,1	4,0	4,6	
	10	3,1	3,7	4,3	4,6	3,1	3,4	4,3	4,3	

Table 9. Resolution test results for 10 x-ray units

Contrast (mmCu)										
	Unit	**50kVp**	**70kVp**	**80kVp**	**100kVp**	**50kVp**	**70kVp**	**80kVp**	**100kVp**	
100cm - 20mAs	**1**	0,3	0,5	0,4	0,1	0,4	0,5	0,3	0,1	**60cm - 20mAs**
	2	0,4	0,4	0,3	0,2	0,3	0,5	0,3	0,1	
	3	0,3	0,5	0,4	0,1	0,4	0,4	0,4	0,2	
	4	0,4	0,5	0,3	0,1	0,4	0,4	0,4	0,1	
	5	0,4	0,4	0,3	0,3	0,5	0,5	0,3	0,2	
	6	0,3	0,5	0,3	0,2	0,4	0,5	0,4	0,1	
	7	0,4	0,5	0,4	0,3	0,3	0,6	0,4	0,3	
	8	0,5	0,6	0,4	0,1	0,4	0,5	0,3	0,1	
	9	0,4	0,5	0,3	0,2	0,5	0,6	0,3	0,1	
	10	0,3	0,4	0,4	0,2	0,4	0,4	0,4	0,2	
100cm - 40mAs	**1**	0,5	0,6	0,5	0,3	0,4	0,6	0,5	0,2	**60cm - 40mAs**
	2	0,5	0,6	0,4	0,2	0,5	0,6	0,4	0,2	
	3	0,4	0,6	0,4	0,2	0,3	0,6	0,5	0,3	
	4	0,4	0,6	0,5	0,3	0,5	0,6	0,5	0,2	
	5	0,5	0,6	0,5	0,3	0,4	0,6	0,4	0,2	
	6	0,4	0,6	0,5	0,2	0,4	0,6	0,5	0,3	
	7	0,5	0,6	0,4	0,1	0,5	0,6	0,4	0,1	
	8	0,5	0,6	0,4	0,2	0,5	0,6	0,5	0,2	
	9	0,4	0,6	0,5	0,3	0,3	0,6	0,5	0,3	
	10	0,4	0,6	0,4	0,2	0,5	0,6	0,4	0,2	
100cm - 50mAs	**1**	0,4	0,6	0,5	0,3	0,5	0,5	0,4	0,3	**60cm - 50mAs**
	2	0,5	0,6	0,5	0,2	0,5	0,6	0,5	0,2	
	3	0,5	0,5	0,4	0,3	0,4	0,5	0,4	0,3	
	4	0,4	0,6	0,5	0,3	0,4	0,6	0,5	0,3	
	5	0,4	0,6	0,5	0,4	0,4	0,6	0,5	0,4	
	6	0,5	0,6	0,5	0,3	0,5	0,6	0,4	0,3	
	7	0,4	0,6	0,5	0,2	0,5	0,6	0,5	0,2	
	8	0,5	0,5	0,4	0,2	0,4	0,6	0,4	0,2	
	9	0,5	0,6	0,5	0,3	0,4	0,6	0,5	0,3	
	10	0,5	0,6	0,5	0,3	0,5	0,6	0,5	0,3	

Table 10. Contrast test results for 10 x-ray units.

distances, the dose was calculated for the parameter settings that are different from the parameter settings used for dose modeling. After estimation, the measured and calculated dose values were compared. And, it was seen that the dose estimation was very successful.
For observing of image quality, a film was exposed during each dose measurement, after this, it was developed. Contrast and resolution tests were performed on these films. From Table 10, it can be said that contrast decreased with increasing kVp. It was seen that the best contrast is possible at the values of 70kVps, especially at 70kVp-40mAs. Although the other mAs values with constant 70kVp show good contrast, the best contrast with low dose is determined at 70kVp-40mAs.
In the resolution tests, from Table 9, it can be said that resolution increased related to increasing kVp. Because of this, the resolution is good in kVp values of 100kVp with different mAs.
But, in this study, because our aim is to obtain high image quality (both good contrast and good resolution), the optimum parameter values were selected as recommendation. The parameter setting values of 70kVp-40mAs can be accepted as the recommended technical parameters to obtain high quality image and low dose. If it is wanted to increase the number of recommended parameters, all mAs changes with constant 70kVp (20, 40, 50mAs) can be used as quality control test parameters.
If a radiographic staff adjusts these recommended parameters in an x-ray device, he/she will know which characteristics will appear on the image and how much dose will be measured. Hence, by this way, the staff can control and evaluate his/her tests' results during quality control tests of x-ray units.

6. Conclusion

The technical x-ray parameters are very important to reduce the dose and to obtain the image with good quality. The dose reduction can be obtained by adequate changes of physical parameters without lose of image quality. The optimal radiation dose for optimal image quality can be achieved by understanding of the parameters that affect radiation dose and image quality. The dose optimization process also consists of quality control programs to test radiographic devices periodically. In this study, it was studied in which parameters' values were appropriate to obtain high quality image and to reduce dose, in other words, dose optimization, during quality control tests of x-ray units.
This study shows that optimization of technical factors may lead to a substantial dose reduction. If the optimized parameters are applied to X-ray equipment during quality control tests, it is possible to determine how much good image quality will be obtained with this optimized parameters and how much dose will be measured when this qualified image is developed.
The results show the importance of radiographic staff training about the recommended parameters that are applied to the x-ray units for a qualified quality control system. It is essential to provide relevant education and training to staff in the radiology departments.
It can be sure that with such a study the questions on many professional staff's mind will be answered, and the dose and the image characteristics will be parameters that are controlled and managed.

7. Acknowledgment

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8. References

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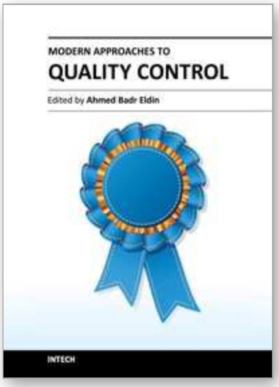

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