Evaluation of the doses delivered to premature babies in the Belgian Neonatal Intensive Care Units

PreDos Project

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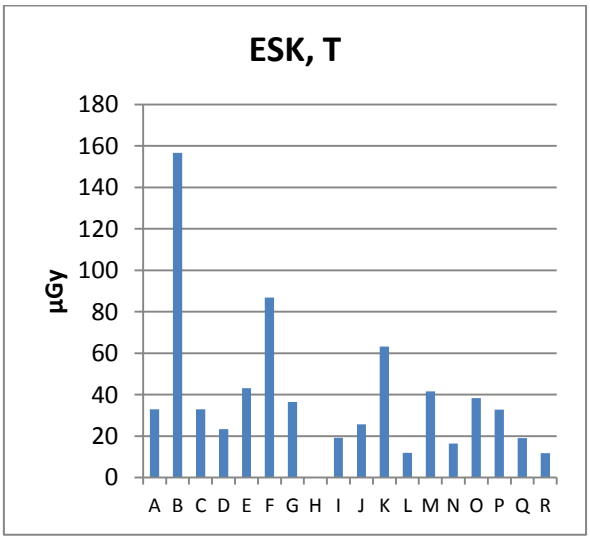
Executive summary

In the Neonatal Intensive Care Units (NICU's), diagnostic radiology plays a significant role in the diagnosis and follow-up of the patients. The most common radiographs performed in the NICU's are chest, abdomen and combined chest-abdomen examinations. Despite their frequent use, the contribution of these examinations to the patients' exposure is still widely unknown. This project aims at improving our knowledge in this field by investigating the doses delivered to new-borns during their stay in the Belgian NICU's. Entrance Surface Kerma (ESK), Kerma-Area Product (KAP), as well as doses to different organs of interest were evaluated. As most of the NICU's in Belgium participated in the 3 different regions (Flanders, Wallonia and the Brussels region), we managed to give an overview of the radiation exposure for the whole country. The project was financed by the federal Agency for Nuclear Control. The main executor of the project was the Belgian Nuclear Research Centre (SCK•CEN), who was responsible for the contacts within the hospitals, the organisation of the data collection and the data analysis. However, the contribution of the local staff in the participating centres, which collected all necessary data, is not to be underestimated and the authors wish to thank them for their collaboration.

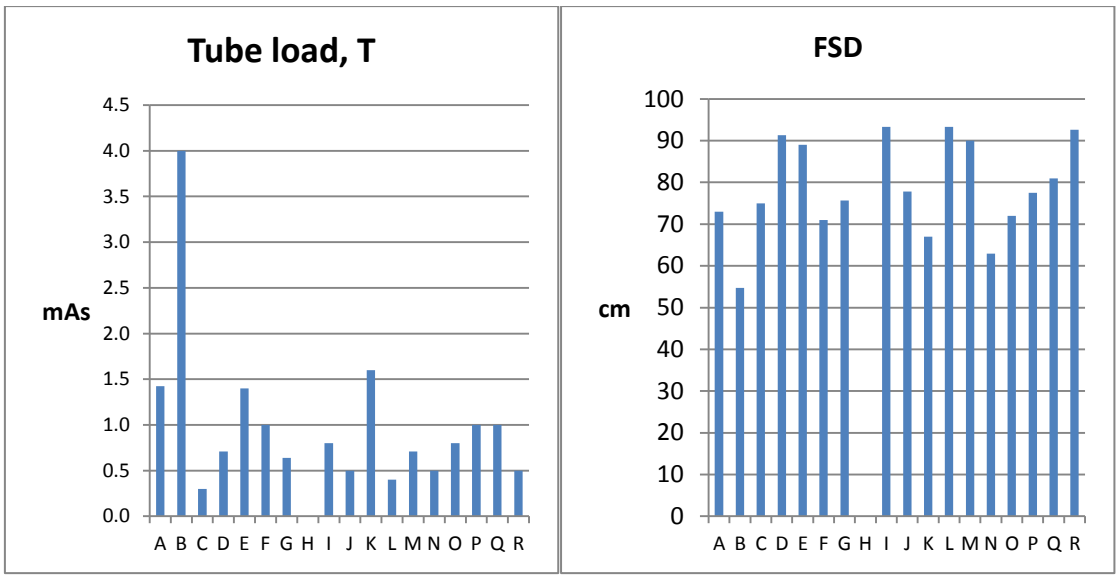
The eligible study subjects were patients born before 37 weeks of gestation and admitted in the NICU department of the participating centres. Patients were subdivided according to their weight. The 3 following weight categories were used: 1) < 1000 g; 2) [1000 - 2000 g]; 3) > 2000 g. The 3 most common examination types are considered: anterior-posterior radiographs of the chest (T), the abdomen (A) and combined radiographs of the chest-abdomen (TA). Specific tables were set up for the data collection and the following data were recorded: technical parameters (kVp, mAs and distances) and patient data (weight, height, gestational age and underlying pathology). Centres that had a KAP-meter also recorded the KAP value. While collecting the data, the tube output was measured for every contributing X-ray system. The collected data are used to determine the Entrance Surface Kerma (ESK) for each patient included in the study. Moreover, for each of the patients the total number of examinations was recorded from the hospital PACS system. This information, together with the average ESK per weight category in a specific hospital was used to determine the cumulative ESK of the patients during their entire stay in the NICU. Finally, organ doses were calculated by the mean of PCXMC, a program developed for the calculation of organ doses in medical radiographs. First, organ doses were calculated for each examination type and each patient, considering a standard field size. Secondly, in a subset of hospitals, the size of the X-ray field was also measured in the PACS, and the differences in organ doses for the measured field sizes compared to the 'standard' field size were investigated.

In total, data were collected for 830 examinations performed on 285 patients. It can be observed that the most frequent performed procedure is the chest examination (60% of all examinations). The combined chest-abdomen examination amounts to 30% of all collected data and the least frequent examination is the abdomen examination (10% of all examinations). A wide variation of estimated doses is observed among the centres. This is caused by a wide variation in examination settings, as well in the protocols as in daily practice. The distance between focus and detector varied

significantly. Moreover, a large variation was obtained in tube output for the different X-ray systems. In figure 1, an overview is given of the calculated median ESK values (a) in all hospitals for the chest examinations. The variation of selected tube load (b) and focus-skin distance (c) is also added as illustration.



(a)



(b) (c)

Figure 1: Comparison of the median ESK (a) and tube load (b) in each hospital for the chest examinations. The variation in focus-skin distance is also given (c).

The data collected for the chest and combined chest-abdomen examinations were sufficient to calculate national diagnostic reference levels (DRLs) for each weight category and for the total sample, as well for ESK as for KAP. For the abdomen examinations only a preliminary DRL of the total data sample was determined. In table 1, an overview of the calculated DRLs is given; the 25th percentile is also reported as representative of lowest doses observed in the study. The fact that

some centres exceed the DRLs (for ESK, KAP or both) can be explained by high mAs values, small focus-skin distances, high tube-output characteristics or large field sizes. Having a DRL both in terms of ESK and KAP gives us extra information. A lack of collimation of the radiation field can also be observed. A lack of collimation is common practice and is unacceptable in paediatrics.

ESK (µGy)

	<1000g		*1000g<…<2000g*		*>2000g*		***total***	
	25th	*75th*	*25th*	*75th*	*25th*	*75th*	***25th***	***75th***
Chest	21	40	19	47	25	51	**19**	**42**
Chest-abdomen	24	47	27	51	27	58	**26**	**43**
Abdomen	/	/	/	/	/	/	**20***	**59***

(a)

KAP (mGy.cm²)

	<1000g		*1000g<…<2000g*		*>2000g*		***total***	
	25th	*75th*	*25th*	*75th*	*25th*	*75th*	***25th***	***75th***
Chest	1.1	5.1	3.7	7.1	5.4	9.6	**4.0**	**7.4**
Chest-abdomen	5.8	9.8	7.7	11.5	7.6	14.5	**6.5**	**11.0**
Abdomen	/	/	/	/	/	/	**5.4***	**8.3***

(b)

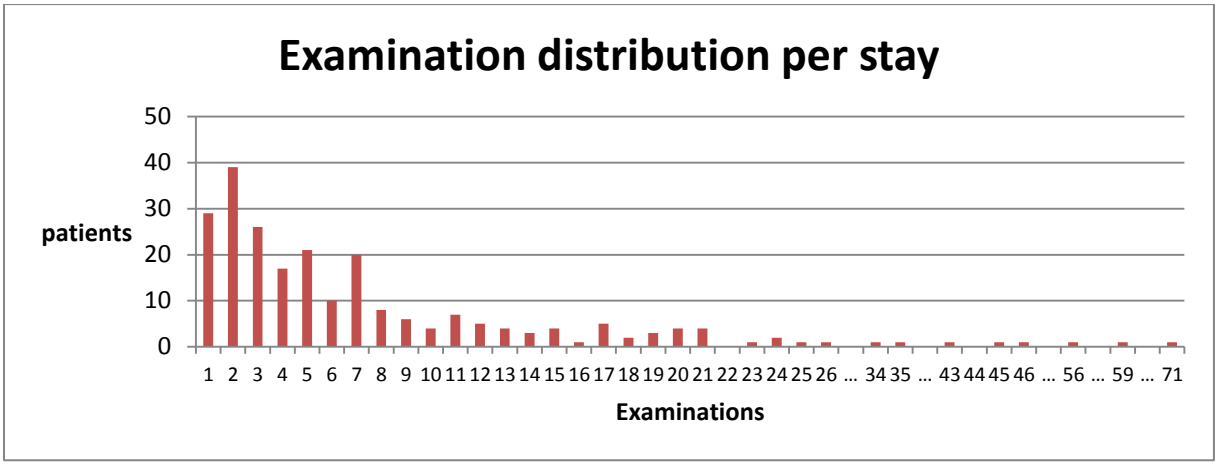
Table 1: DRLs and 25th percentile of the dose distribution in terms of ESK (a) and KAP (b)

The dose to the thyroid is of the order of a few micro grays for the chest and combined chest-abdomen examinations. The red bone marrow also receives a few micro grays for the chest and abdomen examinations. For the combined chest-abdomen examination, the red bone marrow dose could amount to 12 µGy. The highest organ doses are delivered to the breast (up to 95 µGy) for the chest and combined chest-abdomen examinations and to the stomach (up to 57 µGy) for the abdomen examinations. The comparison of organ doses computed with the standard field size and with actual field sizes observed in the hospitals can lead to differences up to 80% for organs located close to the X-ray field edges. For the chest and combined chest-abdomen examination the thyroid dose would become 5 to 10 times larger for the actual fields compared to the standard field. The dose to the red bone marrow increased by 5 to 10% for the chest examinations.

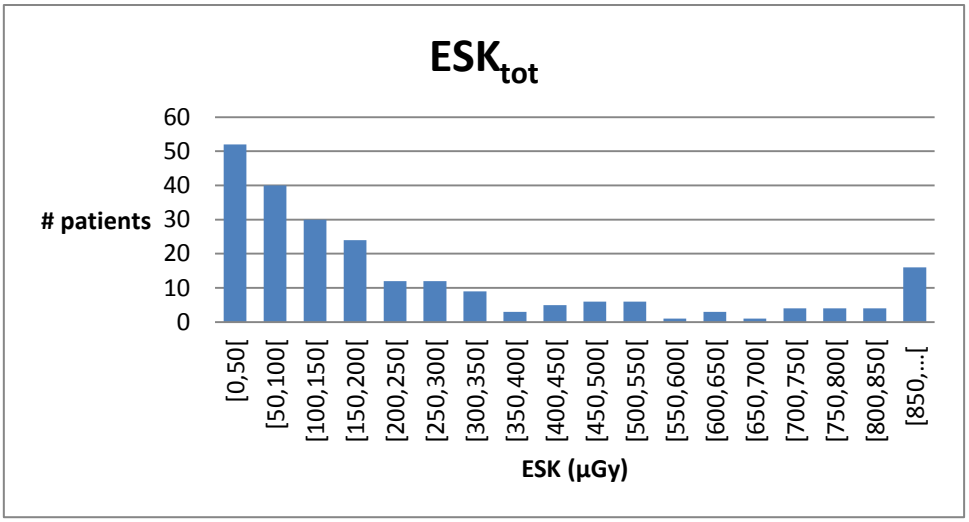
Important to note is also the large variation in the number of examinations performed on patients during their stay in the NICU, thus resulting in a large variation in cumulative ESK and cumulative organ doses. In figure 2, the distribution of the total number of examinations (a) and of the resulting

cumulative ESK (b) received by the patients included in the study are illustrated. On average, 8 examinations were performed per patient, but a maximum of 71 was registered. To explain the considerable variation in the number of examinations performed between the different centres, an analysis according to the underlying pathology of the patients would be of particular interest. This should be further investigated.

The percentage of patients receiving a cumulative ESK inferior to 50 µGy, amounts to 22%; for a cumulative ESK inferior to 150 µGy, this percentage increases to 52%. Less than 6% (13 out of the 232 patients), received a cumulative ESK superior or equal to 1 mGy. Median cumulative entrance surface kerma amounts up to 540 µGy. Risk estimates for various radio-induced cancers were calculated based on the cumulative organ doses. Important variations of the risk estimates were observed. The principal radio-induced cancers are colon and lungs cancers for male patients and, breast and lungs cancers for female patients. On average, female patients are about 5 times more likely to develop one of the cancers specifically considered in the study (leukaemia, breast, colon, lungs and thyroid cancers) than male patients.



(a)



(b)

Figure 2: Total number of examinations (a) and cumulative ESK distribution (b) for the entire stay in the NICU at the Belgian level

The results of this study indicate that there is ample opportunity to optimize the practices and reduce the doses. Within this scope, specific recommendations, adapted to the situation observed in the participating hospitals, are available in a separate document. One of the limitations of the study is the lack of image quality evaluation. If any kind of optimisation would be performed, image quality is an important factor to take into account, aside from the patient dose.

Introduction

Over the course of the recent decades, the vital prognosis of premature new-borns has dramatically increased. One of the reasons for this spectacular progress is the development of a hospital section specifically dedicated to premature new-borns, the Neonatal Intensive Care Unit (NICU's). In these units, diagnostic radiology plays a significant role in the diagnosis and follow-up of the patients. The most common radiographs performed in the NICUs are the chest, abdomen and combined chest-abdomen examinations. Since the late nineties, the awareness of the potential risks of diagnostic radiology in neonates has considerably increased, as indicated by the growing number of papers published in the scientific literature (see amongst others, ((1; 2; 3; 4; 5; 6; 7; 8)(1-8)). However, in Belgium, the contribution of these examinations to the patient's exposure is still largely unknown: only one study has been realised in a university hospital (9).

In directive 97/43/Euratom of the European Commission (10), the importance of the ALARA principle, which stipulates that the doses should be kept as low as reasonably achievable, is highlighted. The same directive also calls for specific attention which should be given to paediatric patients is also emphasized. To meet these objectives, the first step should be to get better knowledge of the doses delivered to the patients, which is the main objective of the present study.

This project aims at fulfilling this objective, by investigating the doses delivered to new-borns during their stay in the Belgian NICU's. Entrance Surface Kerma (ESK) as well as doses to different organs of interest were evaluated, for the most common anterior-posterior radiographs. The influence of the examination protocols on those doses was also considered.

As most of the NICU centres in Belgium participated in the 3 different regions (Flanders, Wallonia and the Brussels region) we managed to give an overview of the radiation exposure for the whole country. The project was financed by the Federal Agency for Nuclear Control. The main executor of the project was the Belgian Nuclear Research Centre (SCK•CEN), which was responsible for the contacts within the hospitals, the organisation of the data collection and the analysis of the data. However, the contribution of the local staff in the participating centres, which collected all necessary data, is not to be underestimated and the authors wish to thank them for their collaboration.

Material and Methods

NICU centres

New-born babies who need intensive medical attention are often admitted into a special unit of the hospital called the neonatal intensive care unit (NICU). The NICU combines advanced technology and specifically trained healthcare professionals to provide specialized care for the tiniest patients. Most babies admitted to the NICU are premature (less than 37 weeks of gestation), have low birth weight (less than 2.5 kg), or have a medical condition that requires special care. In the NICU, premature babies are kept in incubators. Modern neonatal intensive care involves sophisticated measurement of temperature, respiration, cardiac function, oxygenation and brain activity. Treatments include fluids and nutrition through intravenous catheters, oxygen supplementation, mechanical ventilation, and medications. Several of the infants admitted into the NICU have underdeveloped lungs, which

may lead directly to respiratory distress syndrome (RDS). Diagnosis and follow-up of the respiratory distress syndrome is based on chest radiographs.
In general, radiological examinations are performed at the radiology department. However, due to their physical inability and their dependence on external life support, patients of the NICU are unable to be transported to the radiology department. Therefore, radiographs are taken with a mobile radiograph device at the NICU.

There are 19 formally recognised NICU centres in Belgium, evenly distributed among the three Regions of the country: 6 in Brussels, 7 in Flanders and 6 in Wallonia.
Both the radiology and neonatology departments in each hospital were contacted for collaboration. In total, 17 of the 19 centres joined the study. Approval of the ethical committees were sought and obtained. The participating centres are identified by a letter; they are distributed among the 3 regions as follows: 6 in Brussels, 6 in Flanders and 5 in Wallonia.

Study subjects

The eligible study subjects were all patients born before 37 weeks of gestation and admitted to the NICU department of the participating centres.

Patients were subdivided according to their weight. The 3 following **weight categories** were used:

- less than 1000 g
- between 1000 and 2000 g
- more than 2000 g

The choice to include a patient in the study was left to the local investigator's discretion, and dependent on the agreement of the legal representative of the child, as stated in the law of May 7th 2004 concerning experiments on the human person.

Data collection

Examinations

This study aimed to assess the doses delivered by the most common radiographic examinations performed on premature babies in the NICU; namely, anterior-posterior radiographs of the chest (T), the abdomen (A) and combined radiographs of the chest-abdomen (TA).

Data were collected in every participating centre for at least **40** radiographic examinations; the distribution of the three types of radiological study depends on the clinical practices of each centre.

All data collected for the 3 types of examination are exhaustively listed in the following paragraph.

Radiograph settings and patient's data

Specific tables were developed for the data collection and, where necessary, adapted to the particular situation of the centre.

In order to assess the examination from a technical point, of view the following data were recorded:

- Tube voltage (kVp)

- Tube load (mAs)
- Focus Skin Distance[1] (FSD)
- Focus Detector Distance (FDD)

When a KAP-meter was used, the KAP value per examination was also recorded. In that case, extra dose estimation was available, besides the calculated entrance surface kerma. Moreover, the KAP-value gives some additional information on field size, which is not considered for the entrance surface kerma.

Regarding the patient's characteristics, the following data were collected:

- Gestational age (in weeks)
- Height
- Weight
- Underlying pathology

If, with regard to the X-ray equipment, protocols dedicated to new-born infants were used in the daily practice, these particular settings were also registered.

Tube output

The tube output of an X-ray system is the dose generated at 1 m distance of the focus, per unit of mAs, and is mathematically expressed by the following formula:

$$OP_{kVp} = Dose * (\frac{D_1}{1m})^2 * \frac{1}{mAs}$$

Where *Dose* is the dose measured at a distance D_1 and *kVp* and *mAs* are the tube voltage and the tube load respectively. The dose was measured by means of a Diados E dosimeter connected to a solid state detector (PTW, Freiburg, Germany). The Diados E dosimeter is calibrated in the secondary calibration laboratory of the Belgian Nuclear Research Centre (SCK•CEN). The kVp and mAs values were recorded as displayed on the X-ray machines.

The tube output was measured for different kVp settings. As this relation appeared to be linear, it was sufficient to extrapolate the tube output for the complete kVp range of interest.

Total number of examinations

The total number of examinations performed on each patient involved in the study was obtained by consulting the PACS system of the participating hospitals. For each patient, the total number of examinations performed during his/her stay in the NICU was registered, including chest examinations, combined chest-abdomen and abdomen examinations.

These data were not obtained for hospitals B, F, L and P.

[1] The FSD is defined as the distance between the focus and the intersection of the incident XR-beam on the patient's skin.

Data analysis

Entrance Surface Kerma

For each examination documented in the study, the Entrance Surface Kerma (ESK) to the patient was calculated from the data collected in all hospitals. The ESK is defined as the kerma at the point of the intersection of the X-Ray beam with the entrance surface of the patient (*i.e.*, the patient's skin). In this study, no contribution of the backscatter factor is included. The relation between the ESK and the examination settings is:

$$ESK = OP_{kVp} \times mAs \times FSD^{-2}$$

Where OP_{kVp} is the tube output for a specific tube voltage and expresses the radiation dose produced by the X-Ray-machine per unit of tube load at 1 meter distance. The method used to determine the tube output is described above.

Cumulative Entrance Surface Kerma

Using the ESK per examination and the total number of examinations undergone per patient, the cumulative ESK can be determined. The following formula was used:

$$ESK_{tot} = \sum_{cat_i} \sum_{type_j} (D_{av,ij} \times N_i)$$

Where $D_{av,ij}$ is the average dose for a specific examination type *j*, within the weight category *i*; N_i is the number of examinations undergone in the weight category *i*. In order to categorize the different examinations into the correct weight class, the date of the examinations was also recorded. In certain cases, missing weight data were estimated using growth curves (11), based on the gestational age and known weight at a certain time.

Diagnostic Reference Levels

Diagnostic reference levels (DRL) are investigation values intended to be used as tools for identifying situations where the levels of patients' doses are unusually high. In general, the DRL is calculated as the 75th percentile of the dose distribution for a specific examination. If it is found that the relevant DRL is consistently exceeded, measures should be taken to reduce the doses. DRL should be considered as a tool to reduce doses, not as a dividing line between good and bad medical practice (12).

Similarly, the 25th percentile of the dose distribution for a specific examination may be considered as a level representative of the lowest doses observed in the study. In this report, the abbreviation DRL only refers to the 75th percentile of the dose distribution. The 25th percentile is given for informative purposes only.

The diagnostic reference levels were proposed in terms of ESK and, also, of KAP, owing to its increasing availability in the NICU centres. A reference level was calculated for each weight category separately and for the total patient sample.

Organ Doses

Organ doses were calculated using PCXMC (13). PCXMC is an easy to use software tool developed by the Finnish nuclear and safety authority (Stuk, Helsinki, Finland) for the calculation of organ doses in medical radiography. The software tool calculates the dose to the organs by means of Monte-Carlo simulations. The patients are modelled by mathematical hermaphrodite phantoms (different age's available, new-born infant amongst others). The phantoms can be scaled down/up to the actual patient's size, based on the patient's weight and height.

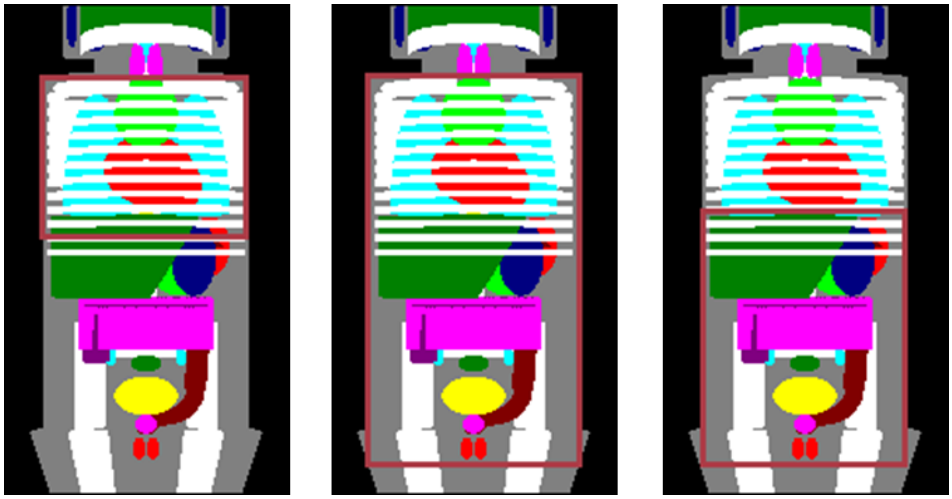


Figure 1: Standard field positions: from left to right: chest, combined chest-abdomen and abdomen examinations

The validity of PCXMC for the calculation of doses to premature new-borns was assessed by Smans (14).

For the three examination types, the position of the X-ray field for a standard radiograph was defined after consulting several physicians. This "standard" field position was thereafter applied to each individual examination and used as an input parameter in PCXMC for the calculation of organ doses. *Figure 1* gives an example of the standard field position for the three examination types considered in the study.

In a subset of hospitals (3 for chest examinations and 2 for combined chest-abdomen examinations), the size of the examination field and the field position relative to the patient were also measured in the PACS, using the measuring tools of the PACS management software. The differences in organ doses for the measured field sizes compared to the 'standard' field size were investigated.

Risk assessment

In order to give a better insight into the risk incurred by patients undergoing radiographs, the lifetime risk estimate for various cancer incidences resulting from the dose accumulated per complete stay in the NICU was evaluated. The values from Table 12D-1 of the BEIR VII report (15) were used. These estimates are intended to apply to a population with an age composition similar to the 1999 U.S. population. They are adjusted for risk reduction due to low dose and low dose rate by a dose and dose rate reduction factor of 1.5 (1 for leukaemia).

KAP-meter calibration

All KAP-meters are calibrated in the participating centres using the so-called "beam-area" method. A Diados E dosimeter connected to a solid state detector (PTW, Freiburg, Germany) was used to

measure the air kerma at a certain distance from the focus. The Diados E dosimeter is calibrated in the secondary calibration laboratory of the Belgian Nuclear Research Centre (SCK•CEN). The field area was measured at the same distance by irradiating a processor-less gafchromic film XR QA 2 (lot A1007-1003B). The exposed film was then analysed using a scanner and image processing software: the field area was calculated on the – inverted - image segmented with a threshold of half the maximum intensity of the irradiated area.

The respective calibration factor is determined as follows:

$k_{KAP} = KAP_{ref}/KAP_{meas}$ with $KAP_{ref} = D_{ref}$ x Field area, where D_{ref} is the air kerma measured with the Diados E dosimeter.

All KAP values collected during the study were corrected according to the determined calibration factors in each centre.

Results and Discussion

Overview of collected data

Distribution of the data

In total, data were collected for 830 examinations performed on 285 patients. Data were collected during 8 months (from April 2011 to November 2011). The exact duration of the data collection varied from one centre to another. The distribution and the number of collected examinations in terms of examination type at the national level are summarized in *Figure 2*. It can be observed that the most frequently performed procedure is the chest examination (60% of all examinations). The combined chest-abdomen examination amounts to 30% of all collected data and the least frequent examination is the abdomen examination (10% of all examinations). Due to the lower frequency of the abdomen examination, the amount of data collected for this particular examination may sometimes restrict the data analysis.

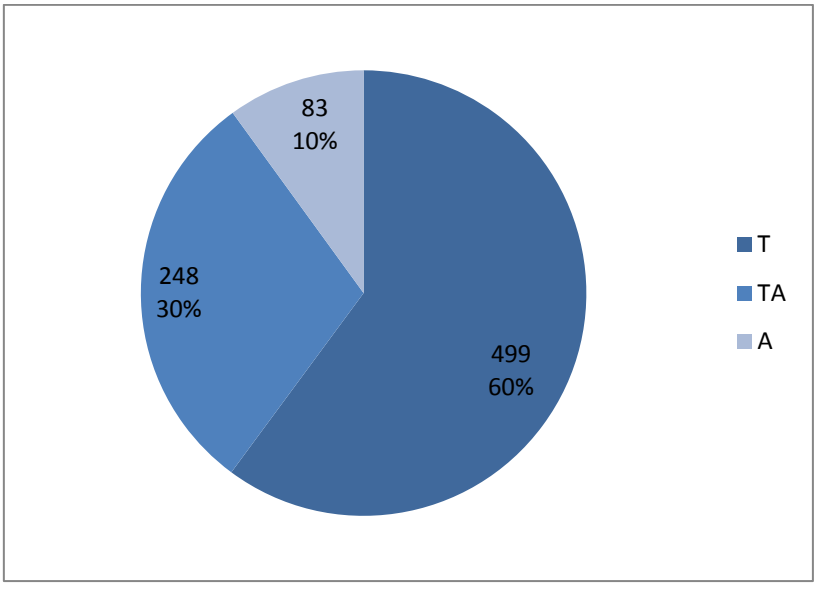


Figure 2: Distribution of collected data for the different types of examinations

The distribution of the examination type is given in detail for each weight category in *Figure 3* to *Figure* 5. These results show similar trends to those previously observed for all collected data[2] (*Figure 2*). With percentages ranging from 58 to 62% of all examinations, the chest examination is the most frequently performed procedure; the combined chest-abdomen examination, with percentages ranging from 28 to 35%, is the second procedure in terms of frequency; while the abdomen examination, with percentages ranging from 7 to 12%, is the least frequent procedure.

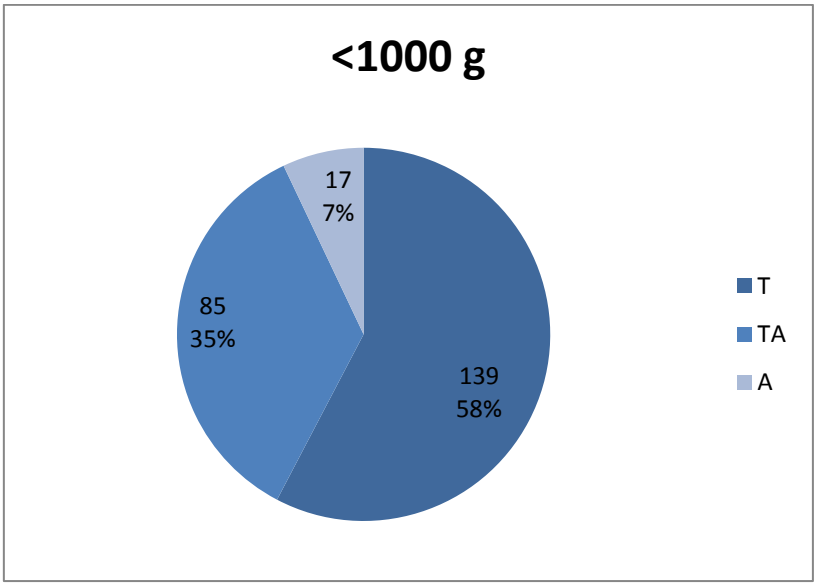


Figure 3: Distribution of collected data for the category "<1000 g"

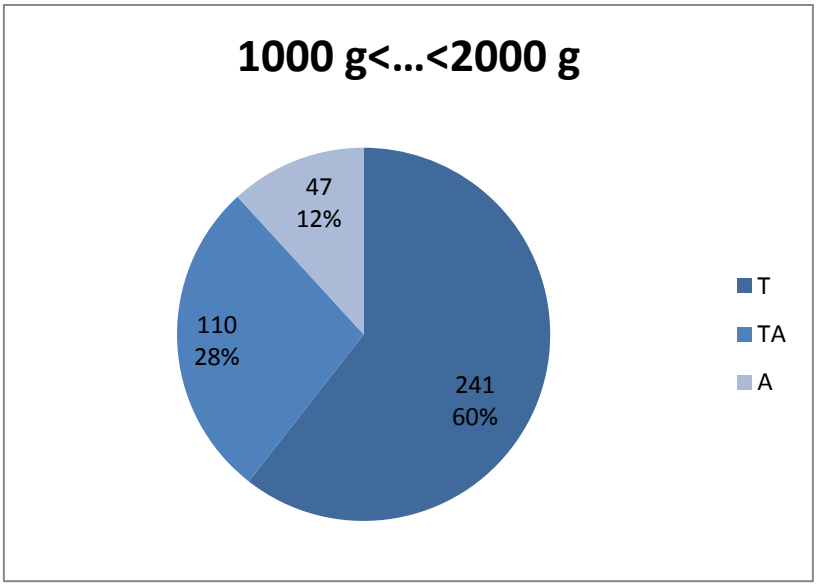


Figure 4: Distribution of collected data for the category "1000 g<...<2000 g"

[2] It must be mentioned that the sum of the number of examinations displayed in the three distributions relative to the weight of the patients is slightly smaller than the number of examinations displayed for the distribution of all data. This is due to the absence of the weight data for some examinations.

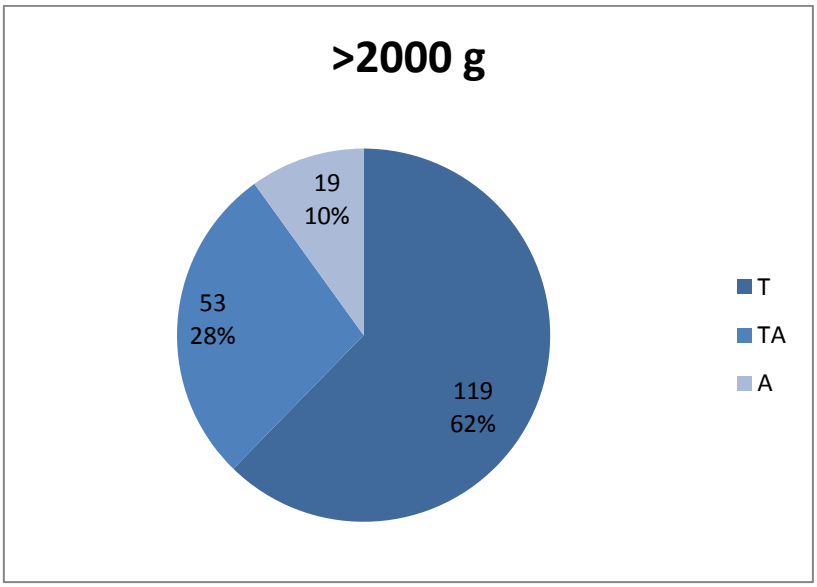


Figure 5: Distribution of collected data for the category ">2000 g"

In *Figure 6,* the absolute number of collected data is given per centre, and per type of examination. One can observe that, in most centres, the chest examination was the most common examination, except for centres B, G and J, where more combined thorax-abdomen examinations were performed. The abdomen examinations were least observed of all the examinations; in some centres even none were observed.

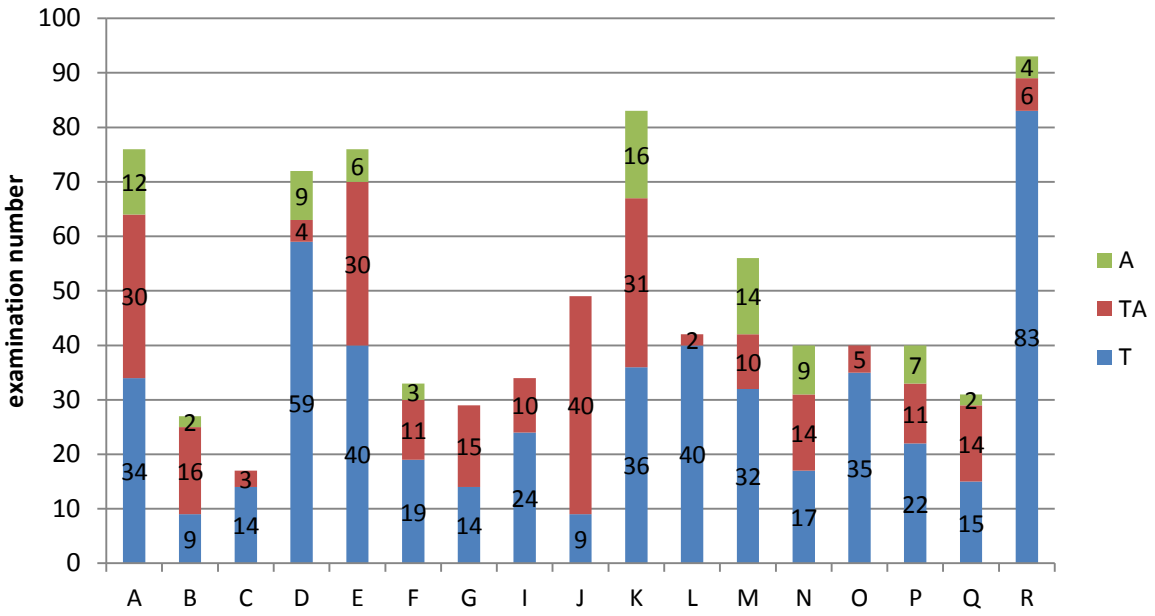


Figure 6: Number of collected data for the different types of examinations per centre

Equipment and examination protocols

In *Table 1*, the characteristics of the radiological systems used in the NICU's are given. The total filtration is the sum of the inherent filtration of the X-ray tube and any additional filtration, from the additional filters and the KAP meter. The filtration of the KAP meter was considered to be 0.2 mm Al, in all centres. Equipment characteristics of one centre that didn't participate in the data collection (S) were also collected. All X-ray systems listed below are mobile systems.

Hospital	XR-system	DAP meter	Total filtration (mm Al)
A	Siemens Polymobil III	Y	3,7
B	Philips Practix 33 Plus	Y	2.9
C	Philips Practix 33	Y	2.9
D	Siemens Mobilett Plus	Y	3
E	Siemens Mobilett XP Hybrid	Y	3.3
F	Philips Practix 33	N	2.7
G	Shimatsu Mobile dart	Y	3
I	Siemens Mobilett Plus	Y	3
J	Fuji FCR Go 2	Y	2.5
K	Philips Practix 33 Plus	Y	2.9
L	Siemens Polymobil III	Y	1.74
M	Siemens Mobilett XP Eco	Y	3.1
N	Siemens Mobilett Plus /E/M	N	3.9
O	Philips Practix 300	Y	2.9
P	Philips Practix 33 Plus	Y	2.9

Q	Philips Practix 33 Plus	Y	2.9
R	GE AMX 4 Plus	Y	2
S	Siemens Mobilett	N	2.8

Table 1: Overview of equipment used in the Belgian NICUs

Table 2 (*a* to *p*) gives the protocols used for the selection of the examinations settings. In these protocols the kVp and mAs which should be selected, are defined according to the patient's weight. In some protocols, settings are defined for weight intervals; while in other centres, the protocols are expressed for discrete weight values. The number of weight categories used in the protocols ranges from 1 to 8. Tube voltage and tube current range from 45 to 81 kVp and 0.32 to 2.8 mAs, respectively.

In centre C, no well-defined written protocol exists. The settings are selected according to a rule-of-thumb. If the parameters seem to result in acceptable images, the same settings will be used for the subsequent examinations of that specific patient.

In centre B and P, if any protocol exists, these were not obtained.

In centres A and L, different protocols are used according to the detector position; the detector is either directly put in contact with the patient, either inserted into the bucky table. In centre E, different settings are used for chest or abdomen examinations and combined chest-abdomen examinations; in centre K, different settings are used for chest and abdomen examinations. In addition, in centres I, J, L, N, R and Q, a fixed focus-detector distance is used.

Hospital A		
Detector plate under the baby		
weight (g)	**kVp**	**mAs**
<500	50	0.8
>500	50	1
>1000	55	1.6
Detector plate inside the bucky table		
weight (g)	**kVp**	**mAs**
<500	52	1
>500	52	1.25
>1000	57	2

(a)

Hospital D		
weight (g)	kVp	mAs
500-800	66	0.71
800-2000	70	0.71
2000-4500	73	0.71

(b)

Hospital E		
Chest or abdomen examination		
weight (g)	**kVp**	**mAs**
<1000	60	1.4
1000-2000	60	1.6
>2000	60	1.6
Combined chest-abdomen examination		
weight (g)	**kVp**	**mAs**
<1000	60	1.6
1000-2000	60	1.8
>2000	60	1.8

(c)

Hospital F		
weight (g)	**kVp**	**mAs**
500	60	0.56
800	60	0.63
1100	60	0.63
1300	61.5	0.8
1700	64.5	0.8
2000	66	0.8

(d)

Hospital G		
weight (g)	**kVp**	**mAs**
All	60	0.8

(e)

Hospital I		
weight (g)	**kVp**	**mAs**
500	63	0.71
800	63	0.8
1100	63	0.8
1300	66	1
1700	70	1
2000	70	1
2500	70	1
2800	70	1
3000	73	1
4000	73	1.25

(f)

Hospital J		
weight (g)	kVp	mAs
/	65	0.5

(g)

Hospital K		
Chest		
weight (g)	**kVp**	**mAs**
600	48	1.6
800	50	1.6
1000-1400	51	1.6
1500-1600	52	1.6
1700-1800	53	1.6
2000-3000	54	1.6
3000-4000	54	2
Abdomen		
weight (g)	**kVp**	**mAs**
600	50	1.6
800	50	1.6
1000-1400	50	1.6
1500-1600	52	1.6
1700-1800	53	1.6
2000-3000	54	1.6
3000-4000	56	1.6

(h)

Hospital L		
Detector plate under the baby		
weight (g)	**kVp**	**mAs**
500	63	0.32
1250	63	0.4
2250	63	0.5
Detector plate inside the bucky table		
weight (g)	**kVp**	**mAs**
500	66	0.4
1500	66	0.5
2250	70	0.64

(i)

Hospital M		
weight (g)	**kVp**	**mAs**
<1000	63	0.7
1000-2000	77	0.7
2000-3000	81	0.9
>3000	81	1

(j)

Hospital N		
weight (g)	**kVp**	**mAs**
<1000	48	0.5
1000-1500	50	0.5
1500-2000	52	0.5
2000-3000	56	0.5
>3000	60	0.5

(k)

Hospital O		
weight (g)	**kVp**	**mAs**
800	64	0.64
1000	64	0.8
1250	66	0.8
1500	68	0.64
1750	68	0.8
2000	70	0.64
2300	70	0.8

(l)

Hospital Q		
weight (g)	**kVp**	**mAs**
<600	55	1
600-800	58	1
800-1000	60	1
>1000	60	1.3

(m)

Hospital R		
weight (g)	**kVp**	**mAs**
<1000	50-55	0.5
1000-2000	55-60	0.5
2000-3000	60-65	0.5
>3000	65	0.5

(n)

Hospital S		
weight (g)	**kVp**	**mAs**
1000-1250	60	1.25
1500-1750	60	1.40
2000-2250	60	1.60
2500-2750	60	1.80
3000	60	2.2
3100	60	2.5
3250	60	2.8
3500	60	3.2

(o)

Table 2: Overview of the examination protocols

Tube output measurements

Figure 7 to *Figure* 9 give an overview of the tube output measurements for every centre. The criterion of acceptability of the tube output is also reported (16; 17). The measurements were realized for kVp and mAs settings close to the values defined in the examination protocols. For the sake of clarity, the data are grouped per region. If measurements were executed for more than one mAs value[3], a mean value is used.

[3] In theory, tube output measurements are independent of the tube load; however, small discrepancies can be observed in reality, particularly for low mAs values.

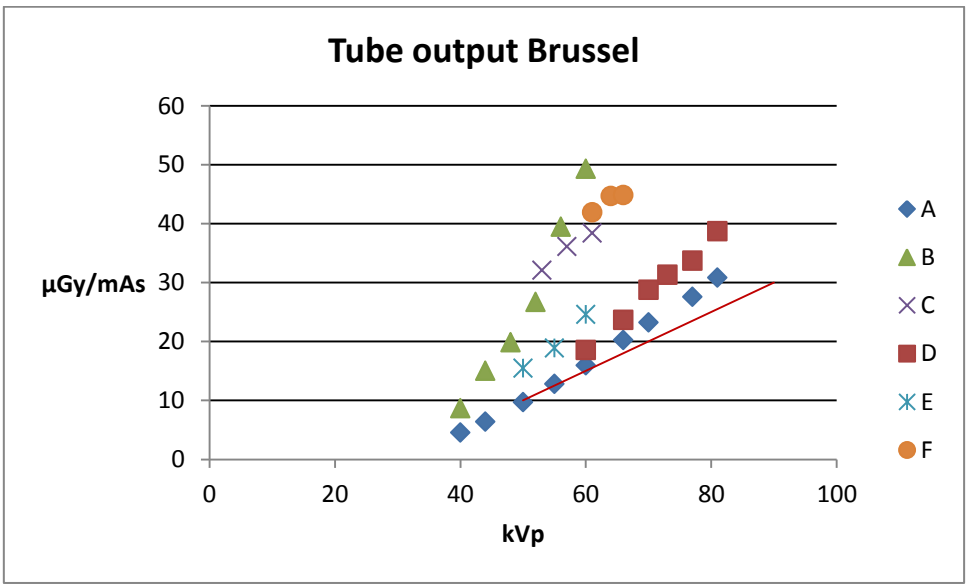


Figure 7: Overview of the tube output for Brussels. The inferior limit of acceptability of the tube output is reported (red line).

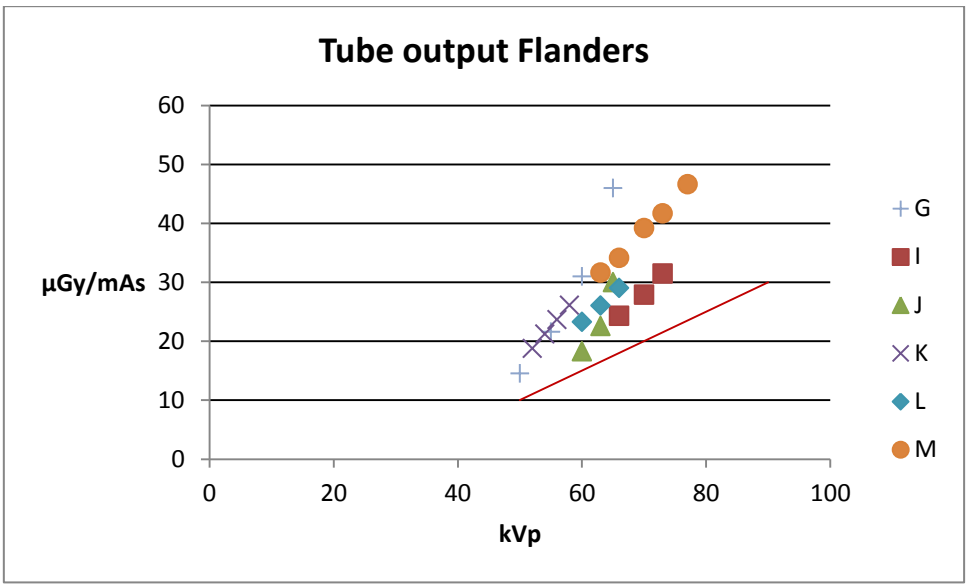


Figure 8: Overview of the tube outputs for Flanders. The inferior limit of acceptability of the tube output is reported (red line).

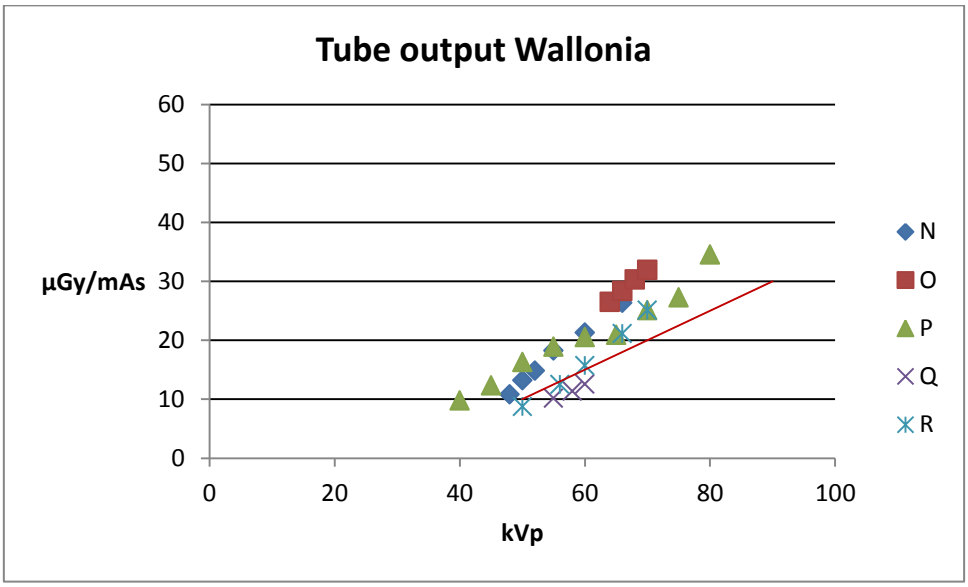


Figure 9: Overview of the tube outputs Wallonia. The inferior limit of acceptability of the tube output is reported (red line).

In *Table 3*, the tube output of all centres is compared for 60 kVp; the criterion of acceptability is also reported. One can notice that a ratio of more than 4 is observed between the maximum (49.3 µGy/mAs) and the minimum value (12.6 µGy/mAs). This latter also fails to comply with the criterion of acceptability established by the Belgian Hospital Physicists Association (17).

Hospital	**Tube output at 60 kVp** [µGy/mAs]
A	16.0
B	49.3
C	37.9
D	18.6
E	24.6
F	41.6
G	31.0
I	17.9
J	18.2
K	28.5
L	23.3
M	28.1

N	21.3
O	22.9
P	20.6
Q	12.6
R	15.7
Criterion of acceptability (17)	15

Table 3: Overview of the tube output at 60 kVp

KAP-meter calibrations

The calibration of the KAP meters used during the data collection was calculated for all centres. As discussed previously for the tube output measurements, the tube voltage values were chosen according to the examination protocols implemented in the participating centres.

In most centres, the measured calibration factors are within the range [0.8; 1.2]. In centres M, O and Q, values slightly inferior to 0.8 were observed. All recorded KAP values were corrected according to the calibration factor.

Overview of technical parameters: Tube load (mAs) and tube voltage (kVp)

We investigated if the local staff properly followed the protocols. Deviations up to 3 kVp and 0.2 mAs for the tube voltage and tube load settings respectively were tolerated. Only 2 hospitals (J and O) followed the protocol completely, for kVp and for mAs. It should be noted that hospital J applies the same kVp and mAs value for all patients. In hospitals I, L and N, no kVp and mAs data were collected, as they stated to strictly follow the values listed in the protocol. Therefore, the protocol settings are used in the study and any deviation could not be evaluated.

Hospital E follows the protocol for kVp-values, but a lot of deviations (60%) were observed in terms of mAs. For hospital R, the protocol is correctly applied for mAs settings (they only have one value for all patients), but not for kVp.

In general, it can be concluded that it is not common practice to always strictly follow the protocols. It is interesting to note that, in hospitals A, E and Q, the deviations of the tube load – from the protocol - consist of slightly smaller mAs values. While in hospital F, these deviations consist of considerably higher mAs settings (nearly twice the value defined in the protocol). On average, the observed deviations of the tube voltage consist of the use of slightly higher settings (a few kVp). For hospital M, however, deviations were mainly observed in the lowest weight category and amount up to an increase of 13 kVp on average. In hospital R, the kVp settings defined in the protocol seem to have been increased by 5 kVp in practice. On the contrary, , the average deviations in hospital F are of the order of 7 kVp lower than the values as defined in the protocol.

In centre M, where numerous deviations from the protocol were observed for the tube voltage and tube load, corrective measures were taken by the responsible physician. During the data collection, the technical staff was urged to more strictly follow the registered protocol.

In *Figure 10*, an overview is given of the median values of the collected tube loads for all participating centres, separately for each examination type. In a same centre, similar settings are observed for all examination types. A large spread of the median tube loads is observed, these values varying from 0.3 to 4 mAs, 0.3 to 3.6 mAs and from 0.5 to 1.6 mAs for chest, combined chest-abdomen and abdomen examinations, respectively. It is worth mentioning that retrieving centre B from the analysis would result in a considerable shrinkage of the median spread (median values varying from 0.3 to 1.6 mAs for chest and combined chest-abdomen examinations). In centre C, where no protocol was defined, for most collected examinations tube loads and tube voltages equal to 53 kVp and 0.3 mAs, were used.

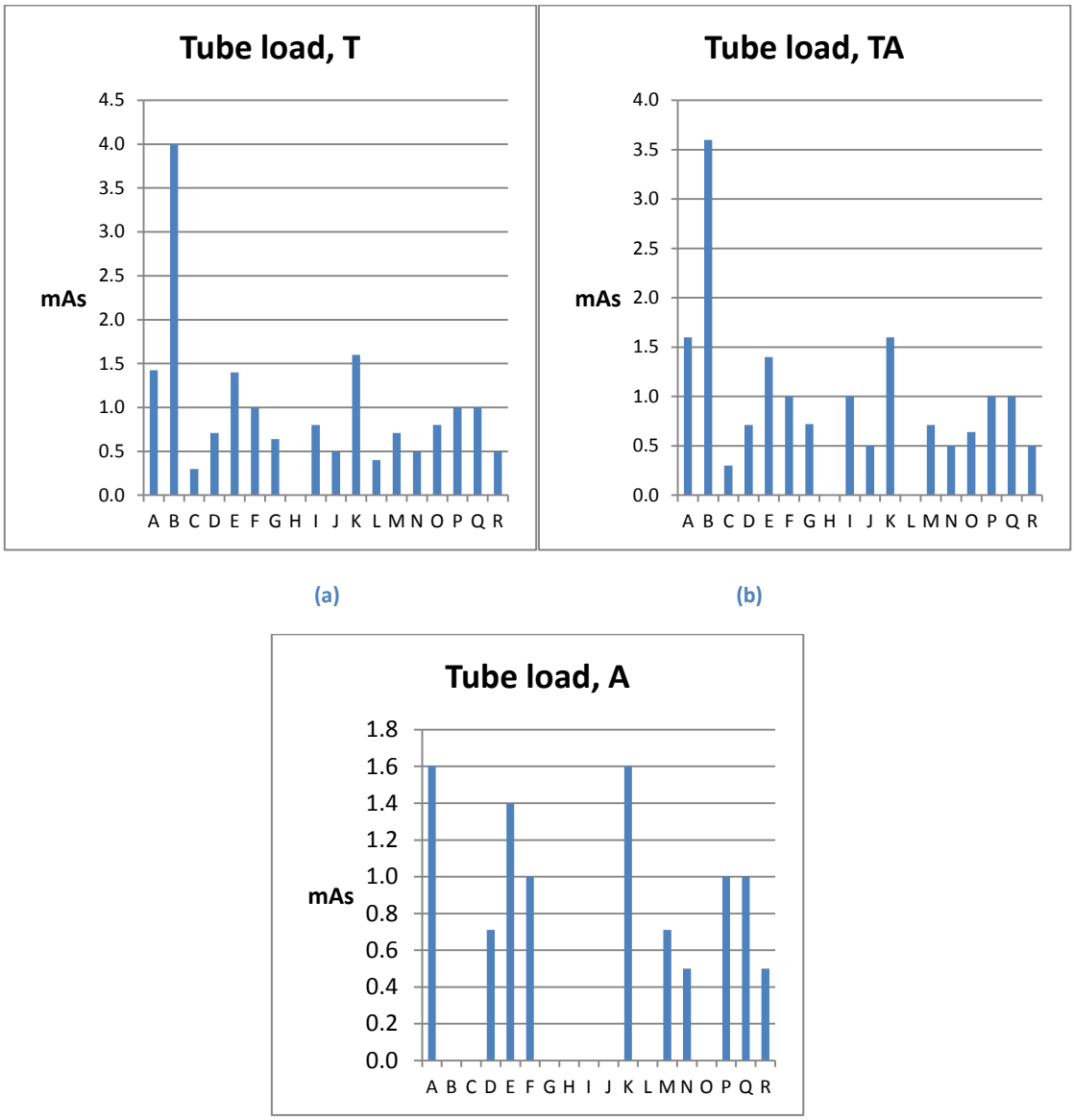
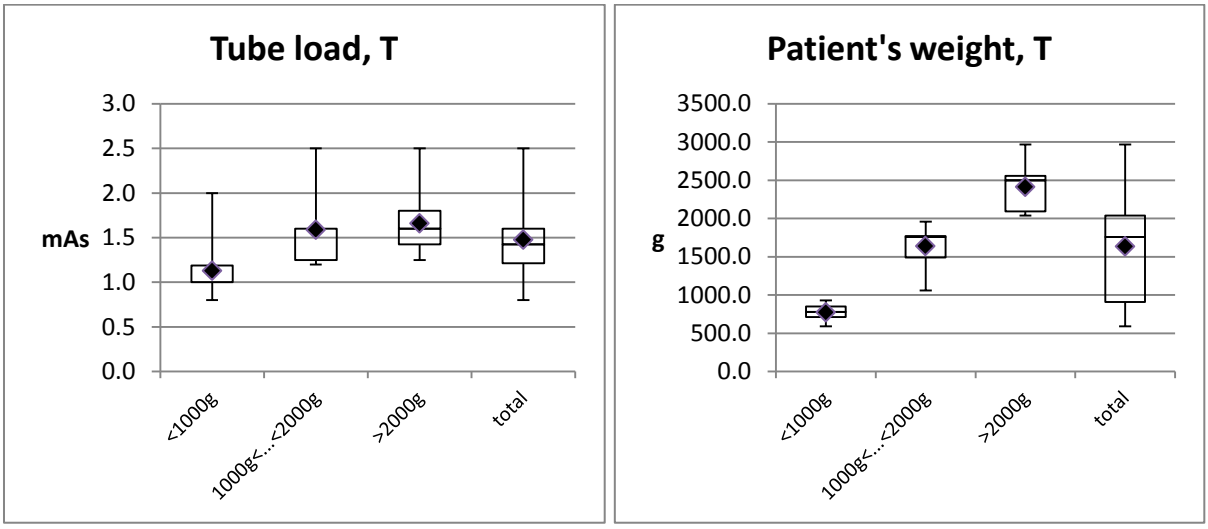


Figure 10: Overview of the tube load (median values) for chest (a), combined chest-abdomen (b) and abdomen examination (c).

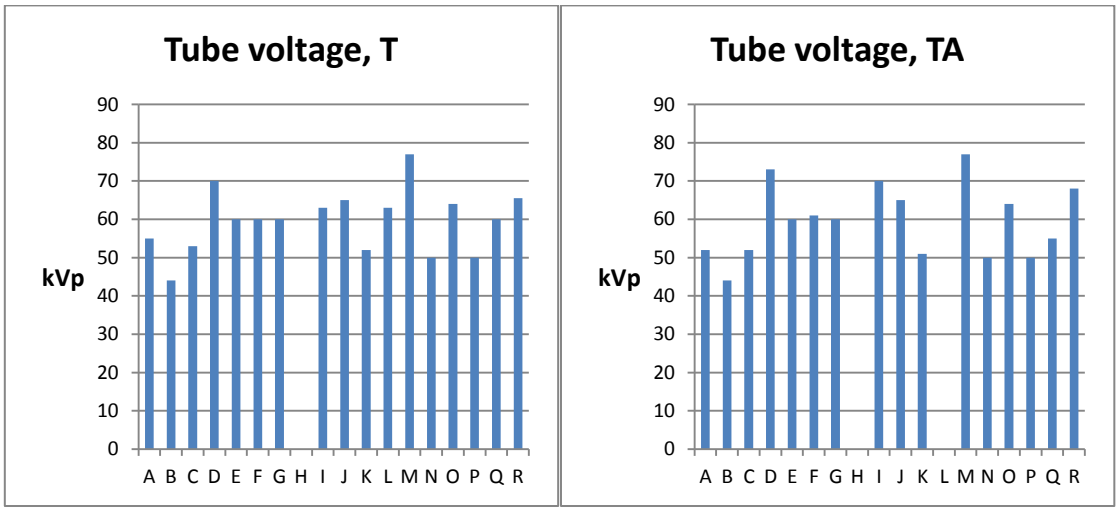
In some centres, the weight of the patient is obviously considered, when the tube load is selected. On the one hand it can be confirmed by the protocol, in which a range of mAs values are defined in terms of patient weight. On the other hand, it can also be confirmed by the collected data in some hospitals. A nice example is shown in *Figure 11* for hospital A, where we can observe a similar increasing trend both for selected tube load and patient weight.



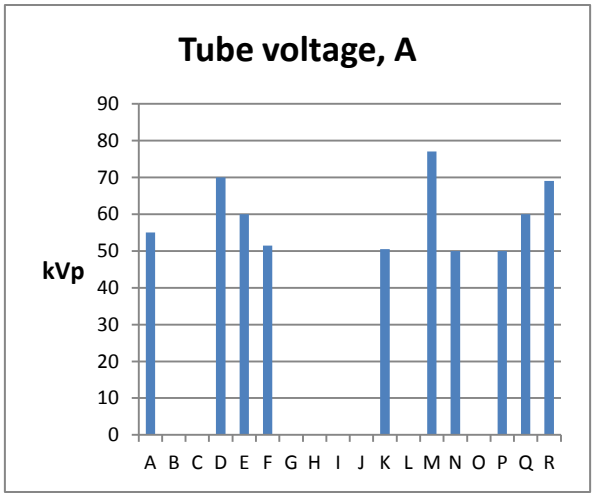
(a) (b)

Figure 11: Tube load (a) and patient's weight (b) in hospital A for chest examinations

In *Figure 12*, the median values of the tube voltages are given for all participating centres. As observed for the tube load, the tube voltage is similar for the three examination types. The median values vary from 44 to 77 kVp (for chest and combined chest-abdomen examinations) and from 50 to 77 kVp for abdomen examinations. In most centres, the tube voltage is within the range [50, 70] kVp. In hospital B and M, values considerably lower and higher were found.



(a) (b)



(c)

Figure 12: Overview of the tube voltage (median values) for chest, combined chest-abdomen and abdomen examinations No data for combined chest-abdomen examinations were collected in hospital L

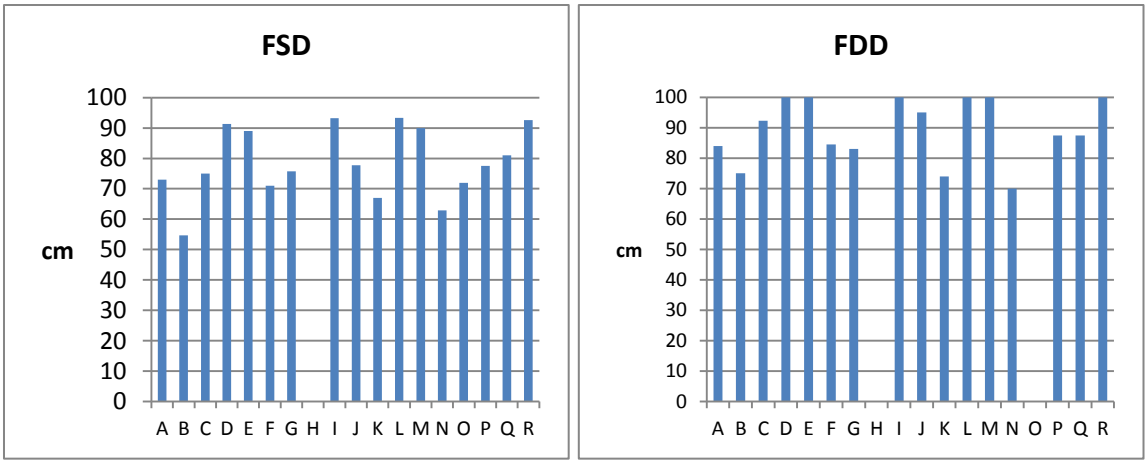
Figure 13 gives the distribution of the median FSD and FDD for all participating centres; all data are presented together for all examination types. As can be observed neither the FDD, nor the FSD are defined for a specific examination type. The FSD and FDD median values range from 55 to 93 cm and from 70 to 100 cm, with minimum and maximum values of 25 and 97 cm and 40 and 107 cm, respectively.

In centres I, J, L, N and R, a fixed FDD was used for all examinations. In some other centres, the FDD was usually set by a rule of thumb based on the maximal opening of the patient's incubator or maximal settable height of the X-ray-machine. No fixed FSD was observed in any of the participating centres.

In half of the centres (B, D, G, I, J, L, N, Q and R), no FSD values were collected. Therefore the FSD was directly estimated from the FDD and patient's characteristics. By definition, the FDD is the sum of the FSD, the patient's thickness and the distance between the patient's back and the detector. The patient's thickness was calculated from the patient's height and weight, following the formula used to scale the phantom thickness in PCXMC:

$$9.8 \times \sqrt{(\frac{50.9 \times height}{weight \times 3400})}.$$

The information with regard to the distance between the patients' back and detector was requested at the respective centres.



(a) (b)

Figure 13: Median focus to skin distance (a) and focus to detector distance (b) for all collected data

Doses

ESK, KAP and organ doses per examination

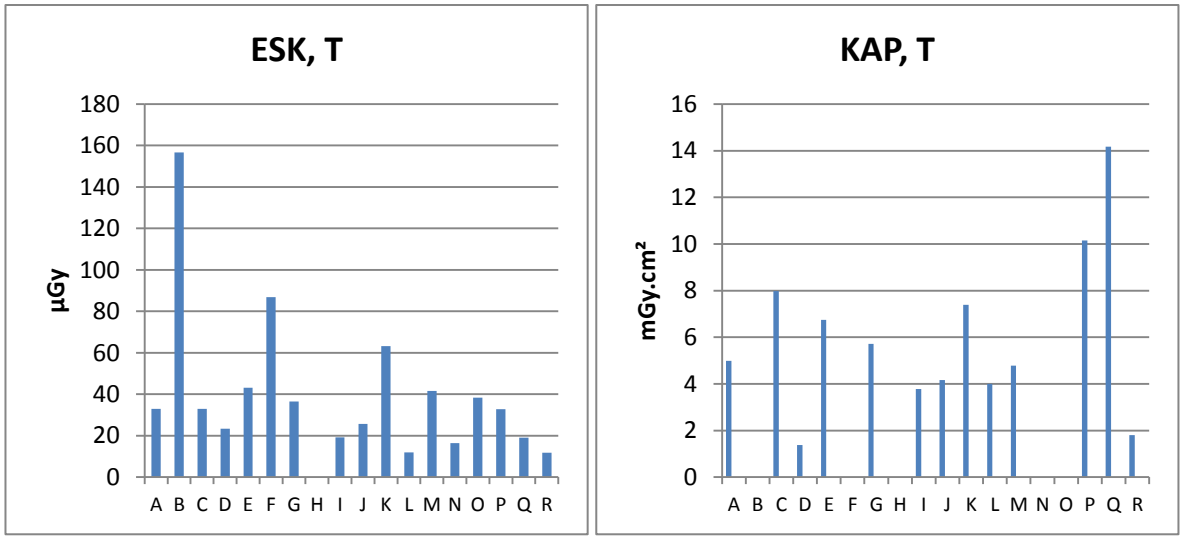
The current section details the ESK, KAP and organ doses observed in each centre. For the sake of clarity, the section is divided into three parts, each of them specifically dedicated to one of the examination types.

In some hospitals, the amount of collected data in particular weight categories was insufficient to calculate complete box plot representations. In those cases, only the average or no value at all is given.

Chest examinations

In *Figure 14*, a comparison of the median ESK and KAP is presented for all centres. In agreement with the large differences observed in the protocol settings and tube output measurements, a large spread of ESK is found. The median ESK ranges from 12 to 157 µGy, which represents a ratio of 13 between the extremes of the median interval. Minimum and maximum ESK with values of 7 and 272 µGy for a single chest examination are found in hospitals R and B, respectively.

The median KAP ranges from 1 to 14 mGy.cm². Comparison of centres can vary whether the doses are expressed in terms of KAP or ESK; for example, a ratio of about 3 is observed between centres A and L in terms of ESK, while this ratio decreases to 1.25 if the comparison is expressed in terms of KAP. This can be explained by the fact that KAP is not only related to the selected technical parameters – as is the case for ESK – but also takes into account the actual field size used.

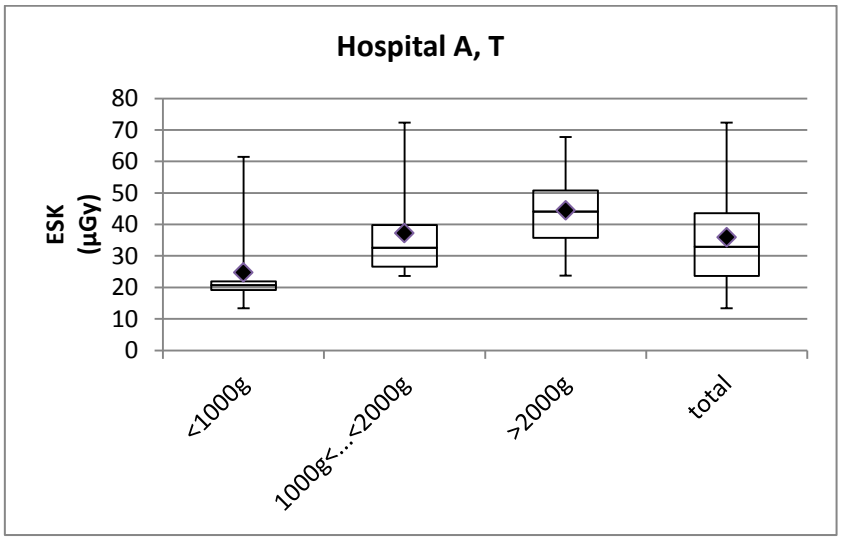


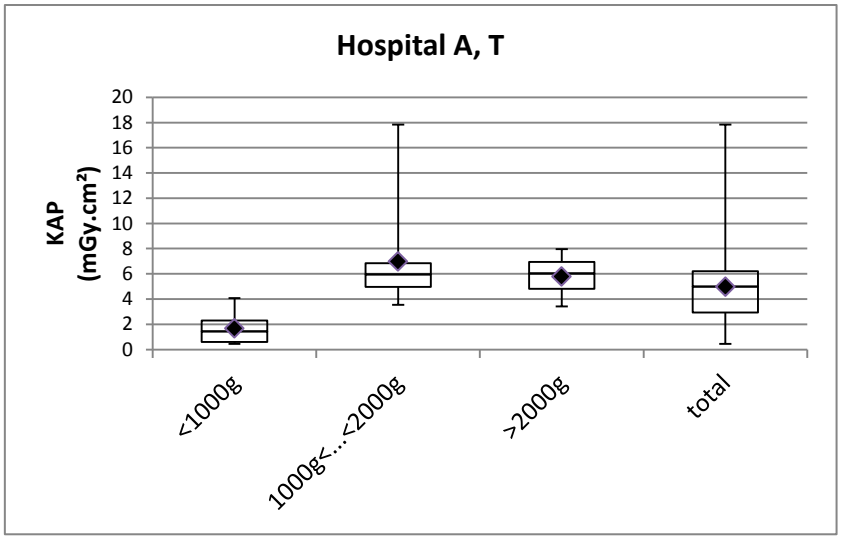
(a) (b)

Figure 14: Median ESK (a) and KAP (b) for chest examinations in the Belgian NICU's

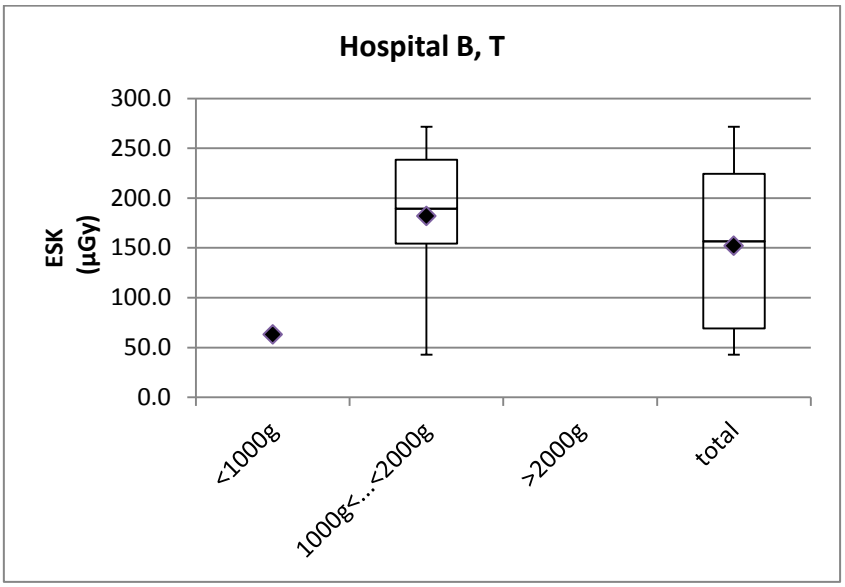
Secondly, in *Figure 15*, an overview of the ESK and KAP is given for each hospital and each weight category separately. The results are given in terms of boxplots, representing the average, median, 25th and 75th percentiles and minima and maxima values.

In some hospitals, an increase of the ESK with the weight category can be observed. This increase is particularly marked in hospitals A, M and R. An increase of the KAP values coupled with the weight category is also observed in some centres. This trend is particularly marked in hospitals L, M and R. In hospitals M and R, this trend is seen for the KAP, as well as for the ESK. For centres C and K, high ESK values correspond to high KAP values.

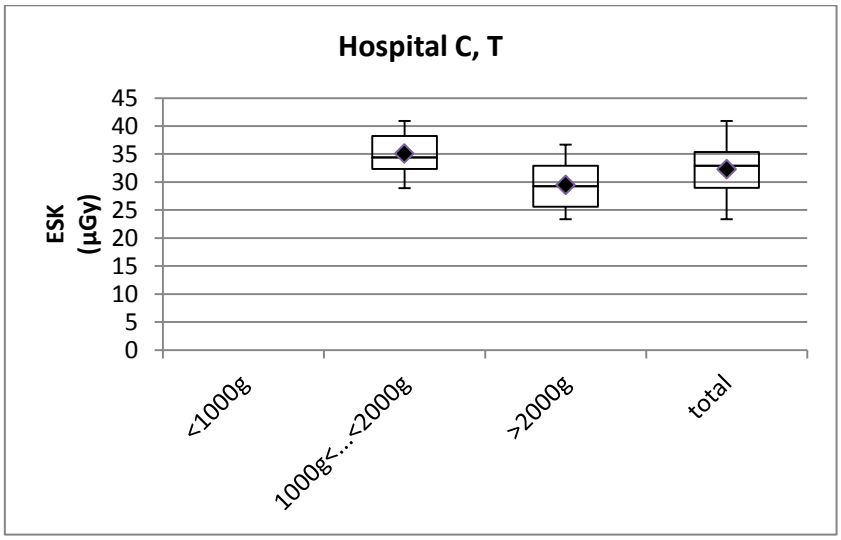


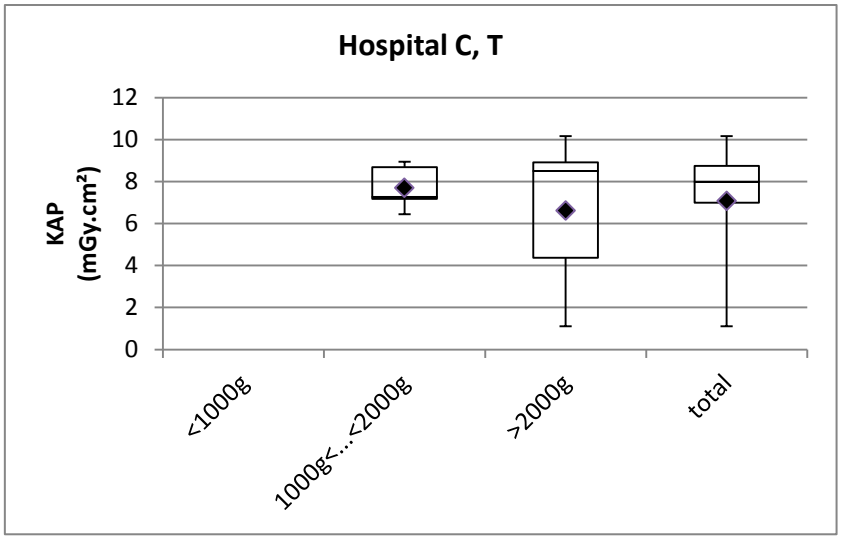

Hospital A, T
KAP (mGy.cm²)
20
18
16
14
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

(a)

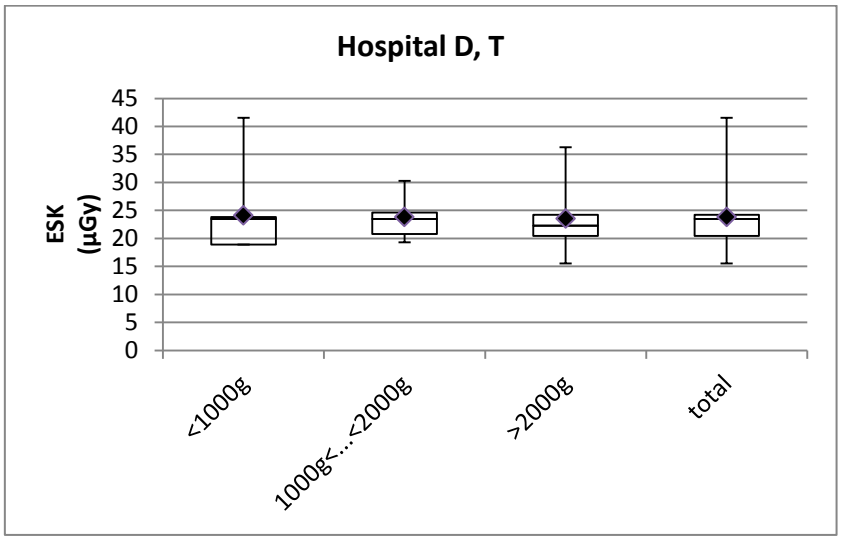

Hospital B, T
ESK (µGy)
300.0
250.0
200.0
150.0
100.0
50.0
0.0
<1000g
1000g<...<2000g
>2000g
total

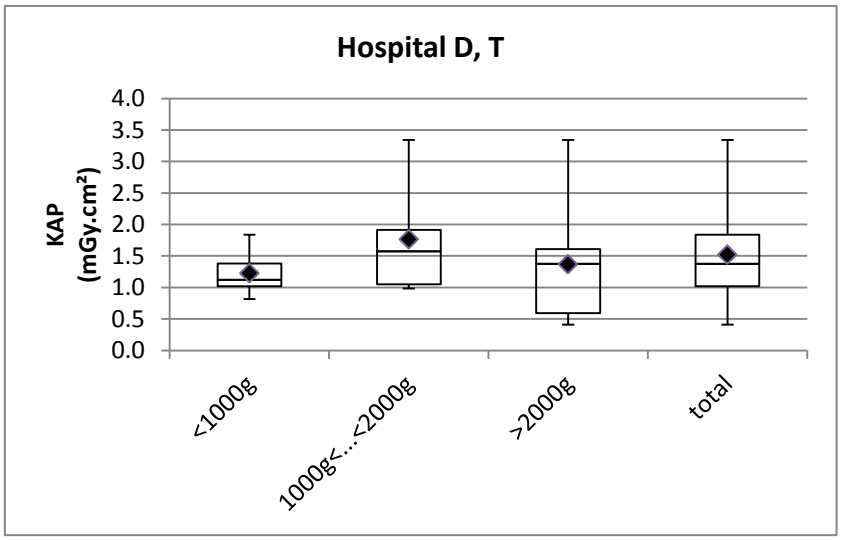
(b)


Hospital C, T
ESK (µGy)
45
40
35
30
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

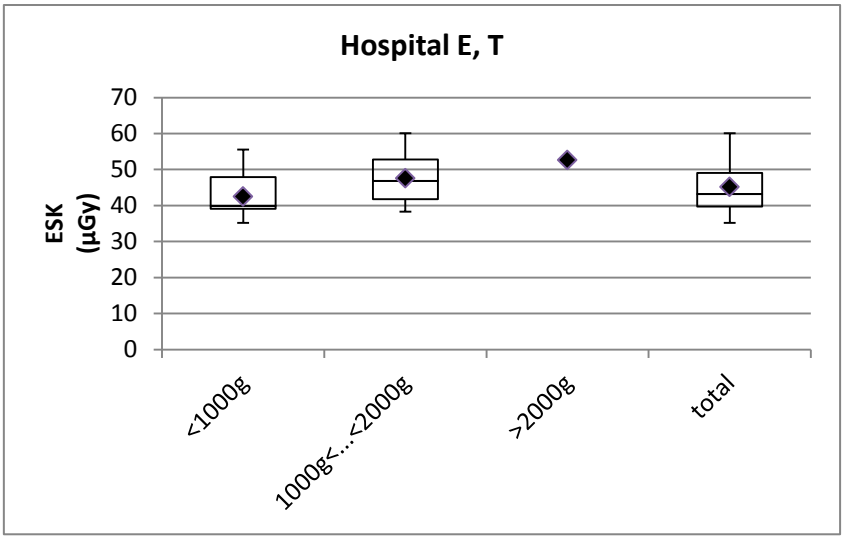

Hospital C, T
KAP (mGy.cm²)
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

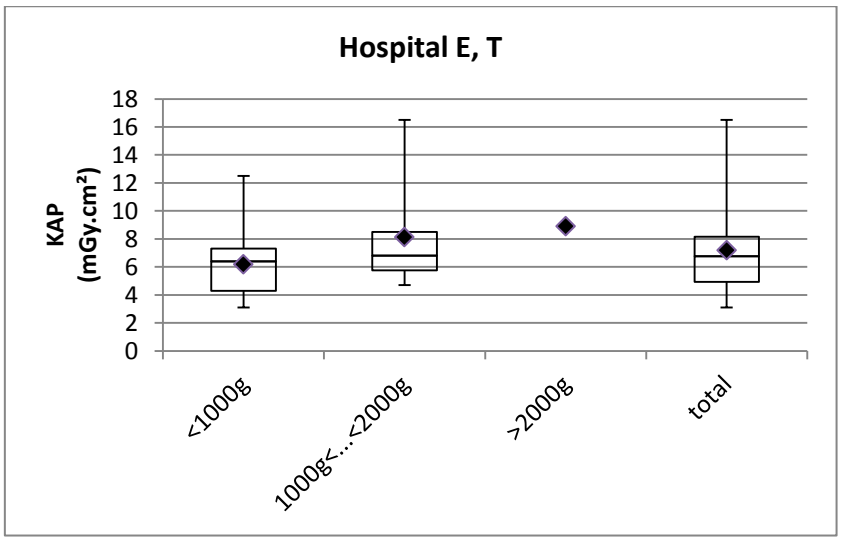
(c)


Hospital D, T
ESK (µGy)
45
40
35
30
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

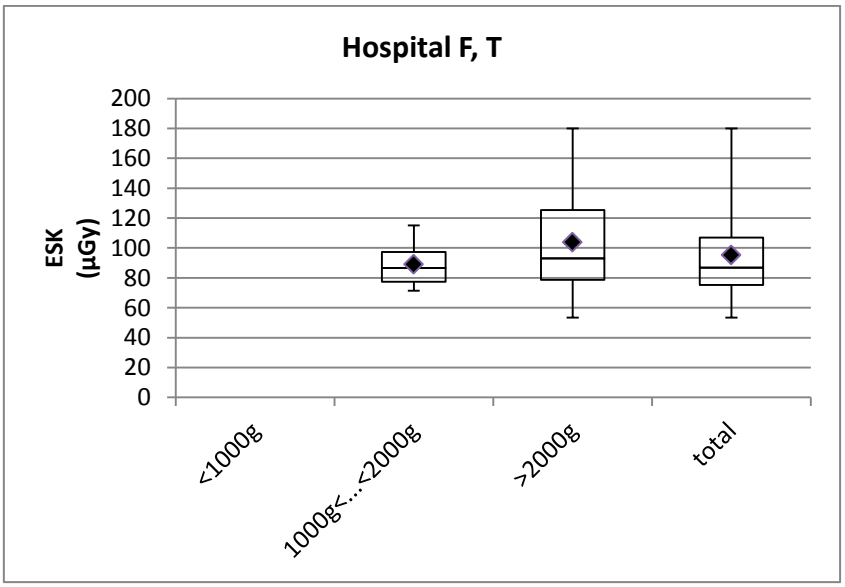

Hospital D, T
KAP (mGy.cm²)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
<1000g
1000g<...<2000g
>2000g
total

(d)

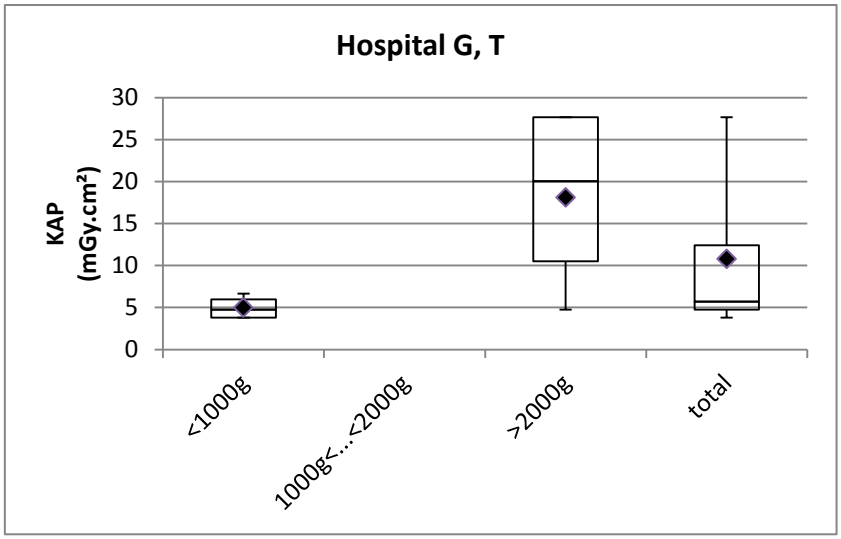

Hospital E, T
ESK (µGy)
70
60
50
40
30
20
10
0
<1000g
1000g<...<2000g
>2000g
total

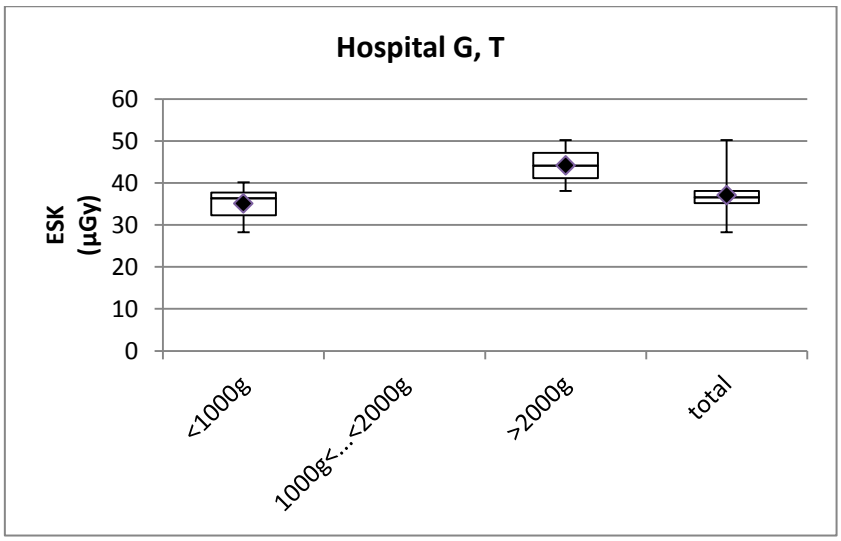

Hospital E, T
KAP (mGy.cm²)
18
16
14
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

(e)

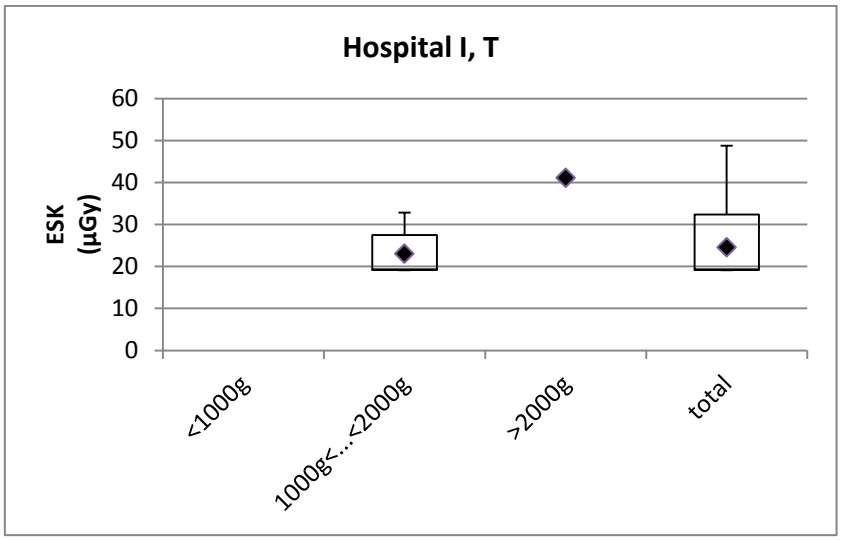

Hospital F, T
ESK (µGy)
200
180
160
140
120
100
80
60
40
20
0
<1000g
1000g<...<2000g
>2000g
total

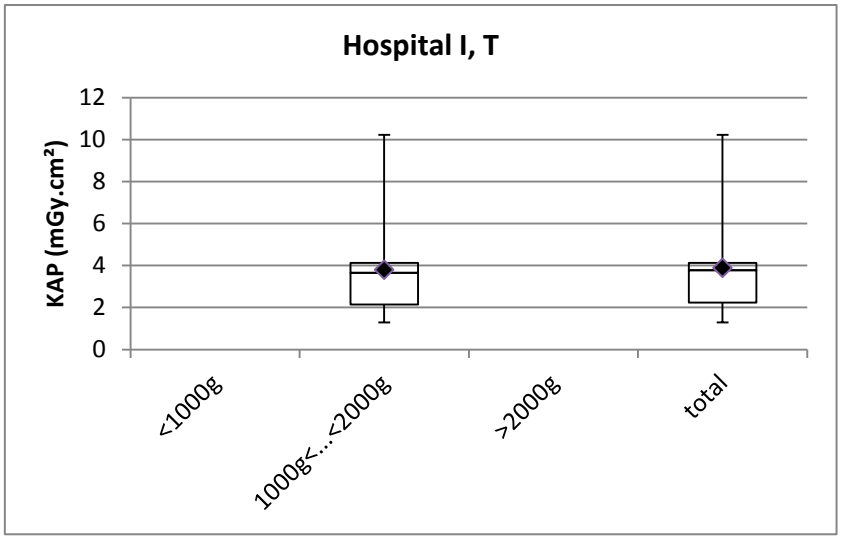
(f)


Hospital G, T
KAP (mGy.cm²)
30
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

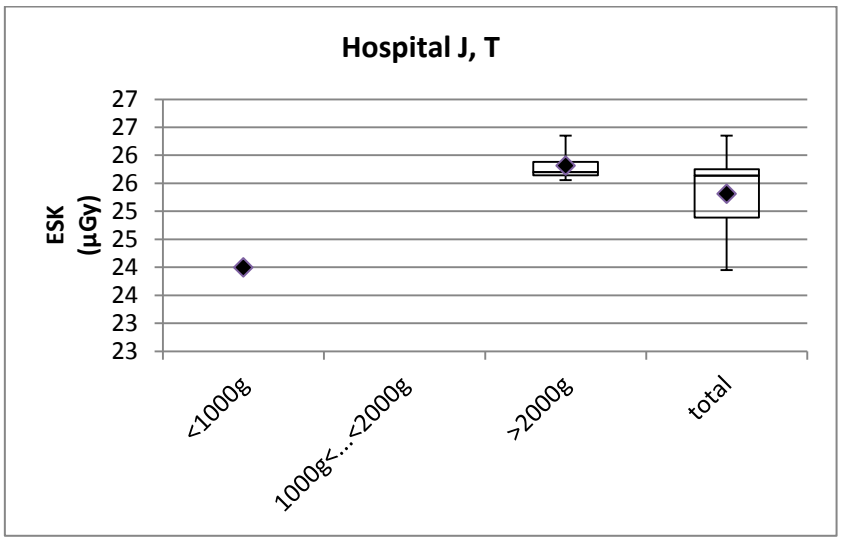

Hospital G, T
ESK (µGy)
60
50
40
30
20
10
0
<1000g
1000g<...<2000g
>2000g
total

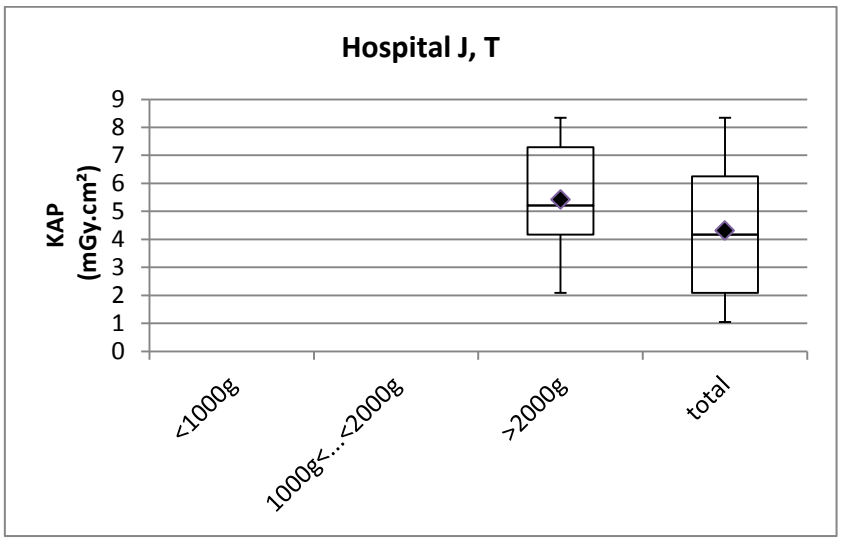
(g)


Hospital I, T
ESK (µGy)
60
50
40
30
20
10
0
<1000g
1000g<...<2000g
>2000g
total

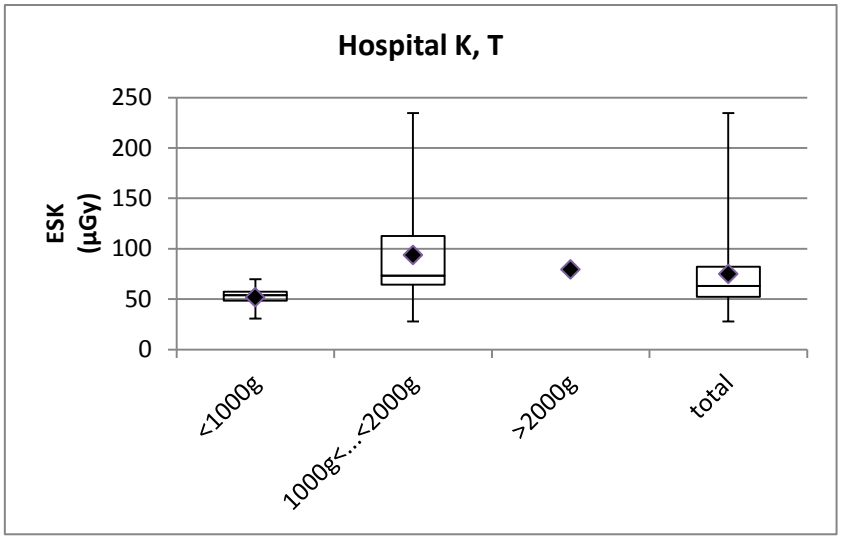

Hospital I, T
KAP (mGy.cm²)
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

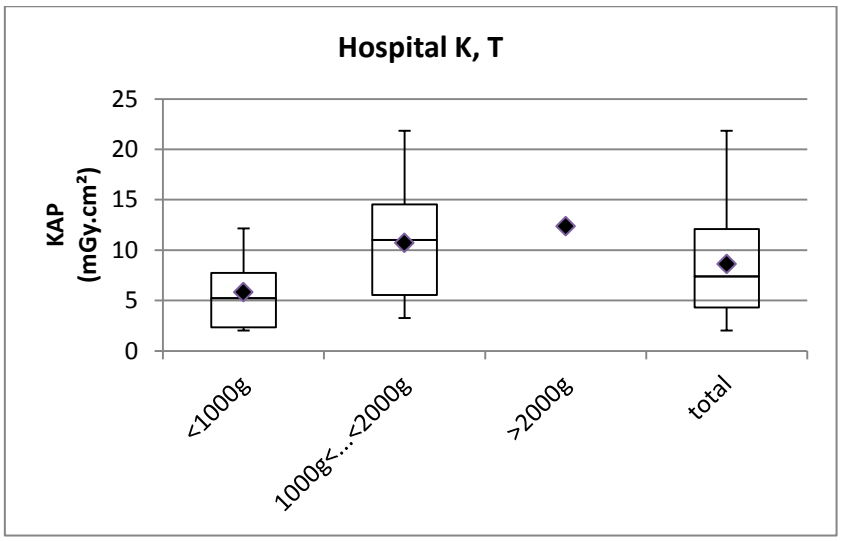
(h)


Hospital J, T
ESK (µGy)
27
27
26
26
25
25
24
24
23
23
<1000g
1000g<...<2000g
>2000g
total

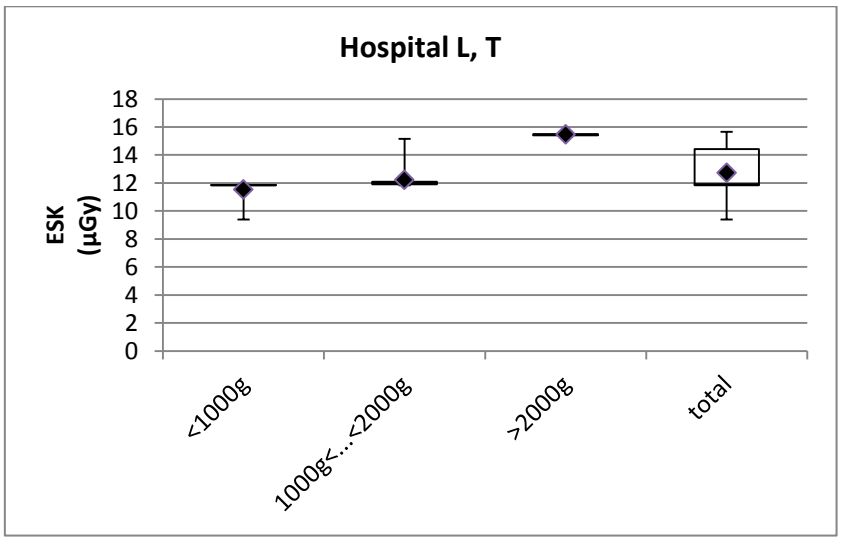

Hospital J, T
KAP (mGy.cm²)
9
8
7
6
5
4
3
2
1
0
<1000g
1000g<...<2000g
>2000g
total

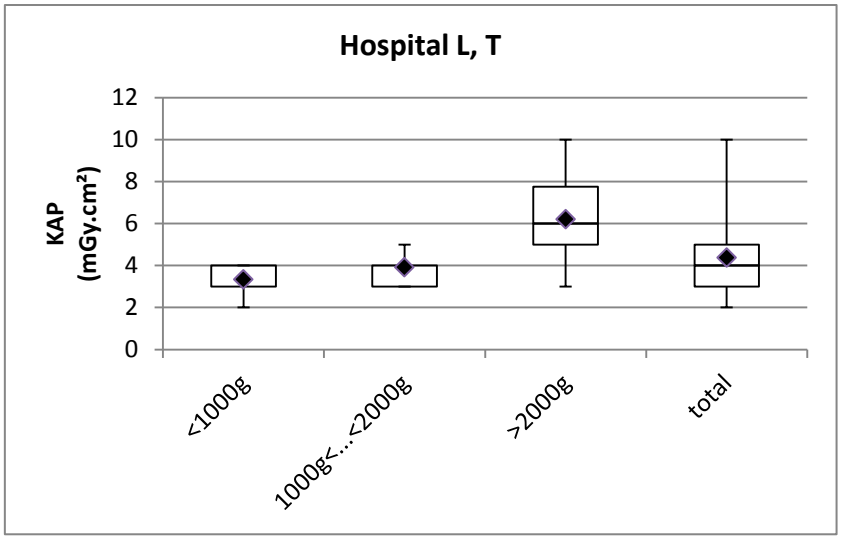
(i)


Hospital K, T
ESK (µGy)
250
200
150
100
50
0
<1000g
1000g<...<2000g
>2000g
total

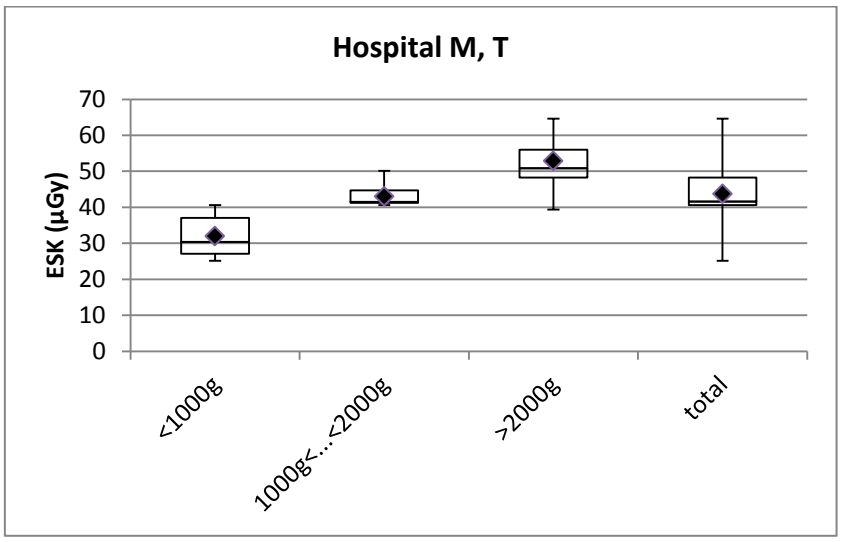

Hospital K, T
KAP (mGy.cm²)
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

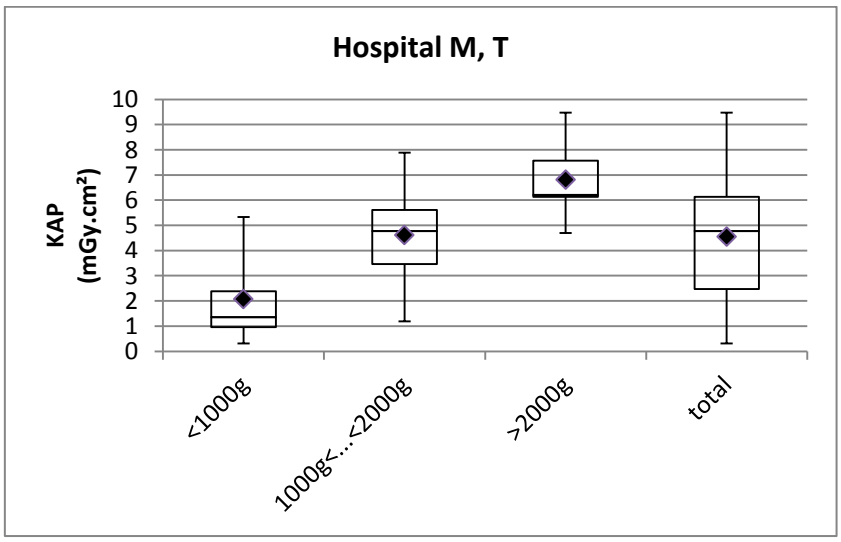
(j)


Hospital L, T
ESK (µGy)
18
16
14
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

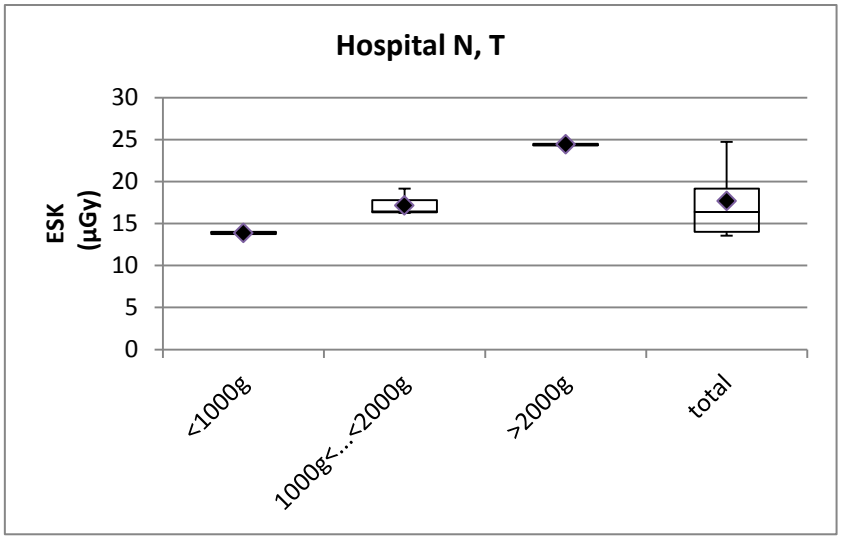

Hospital L, T
KAP (mGy.cm²)
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

(k)

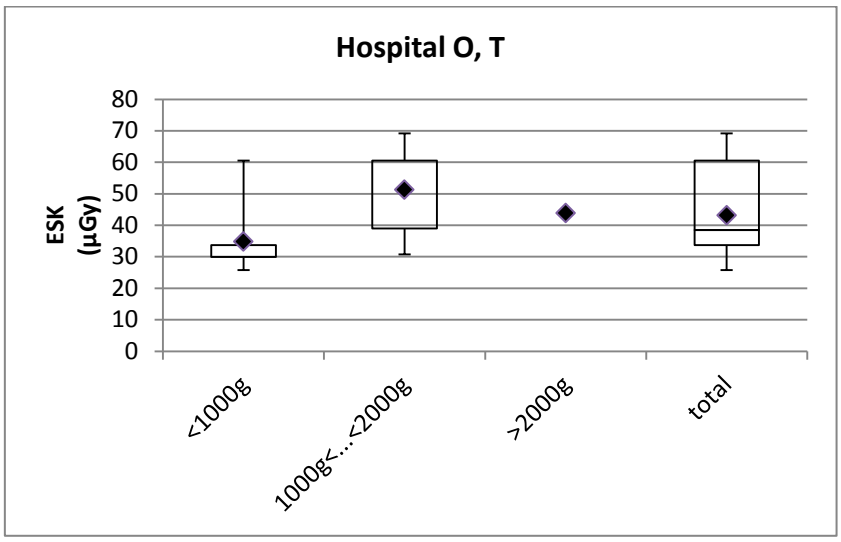

Hospital M, T
ESK (µGy)
70
60
50
40
30
20
10
0
<1000g
1000g<...<2000g
>2000g
total


Hospital M, T
KAP (mGy.cm²)
10
9
8
7
6
5
4
3
2
1
0
<1000g
1000g<...<2000g
>2000g
total

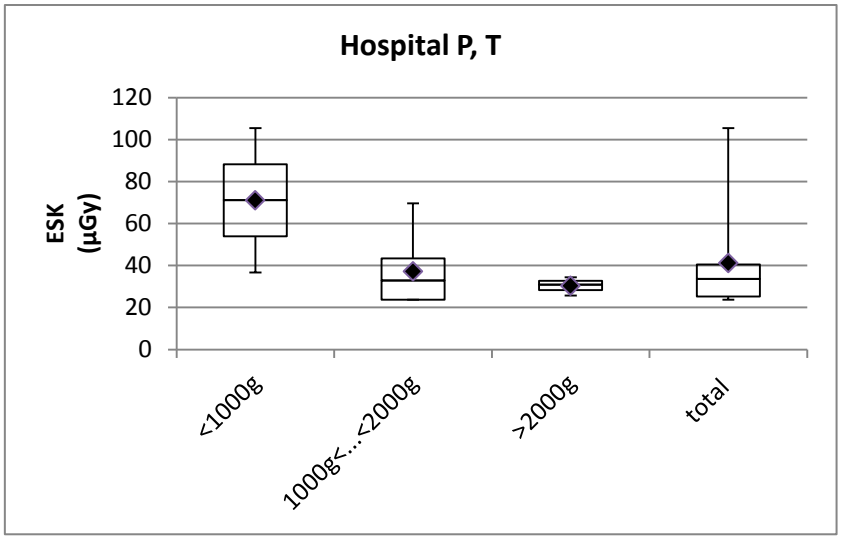
(l)

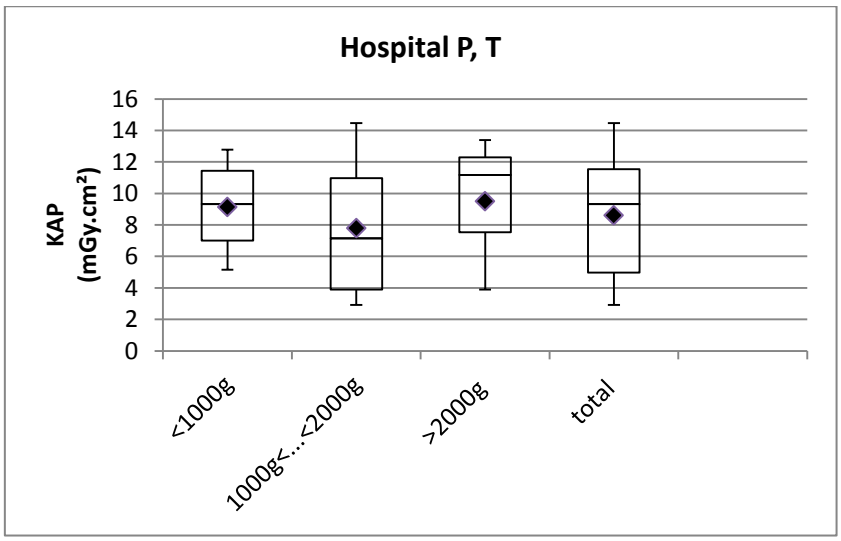

Hospital N, T
ESK (µGy)
30
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

(m)

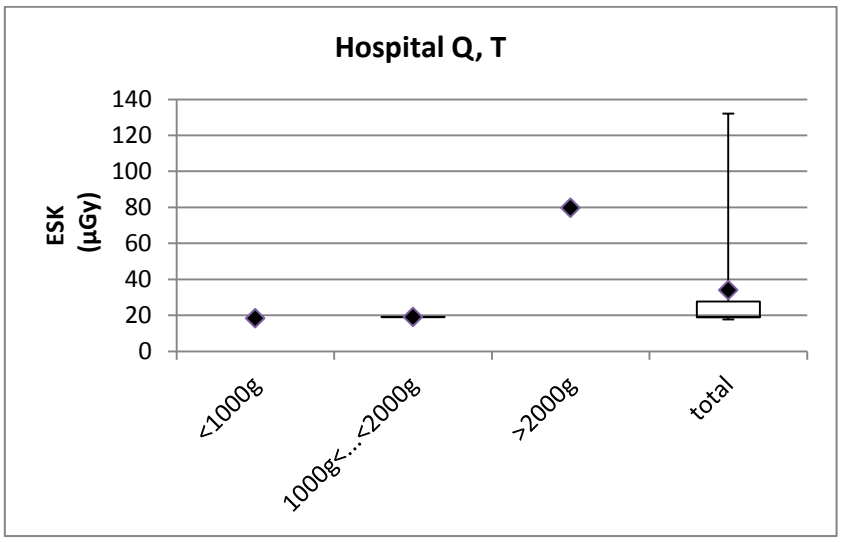

Hospital O, T
ESK (µGy)
80
70
60
50
40
30
20
10
0
<1000g
1000g<...<2000g
>2000g
total

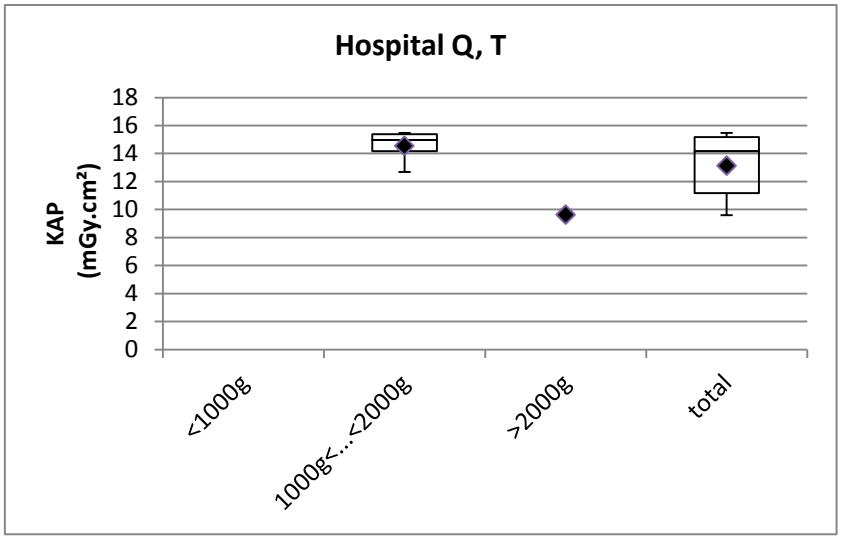
(n)


Hospital P, T
ESK (µGy)
120
100
80
60
40
20
0
<1000g
1000g<...<2000g
>2000g
total

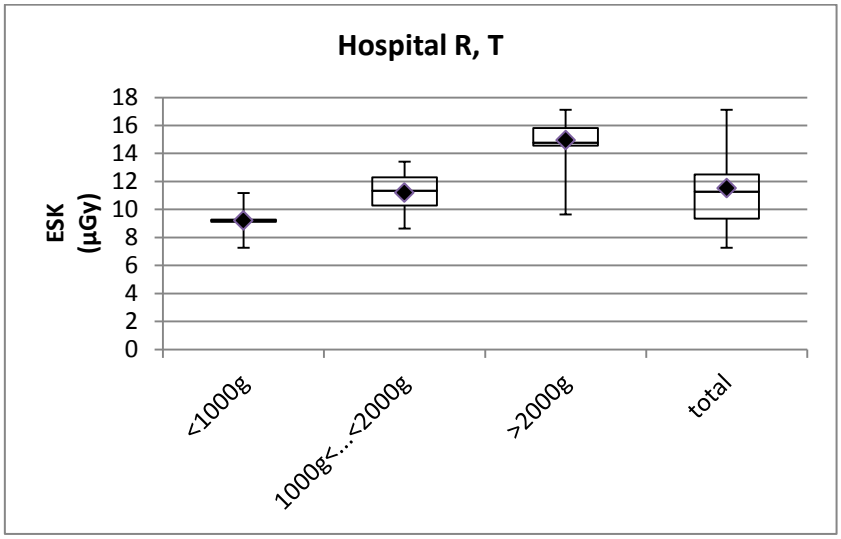

Hospital P, T
KAP (mGy.cm²)
16
14
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

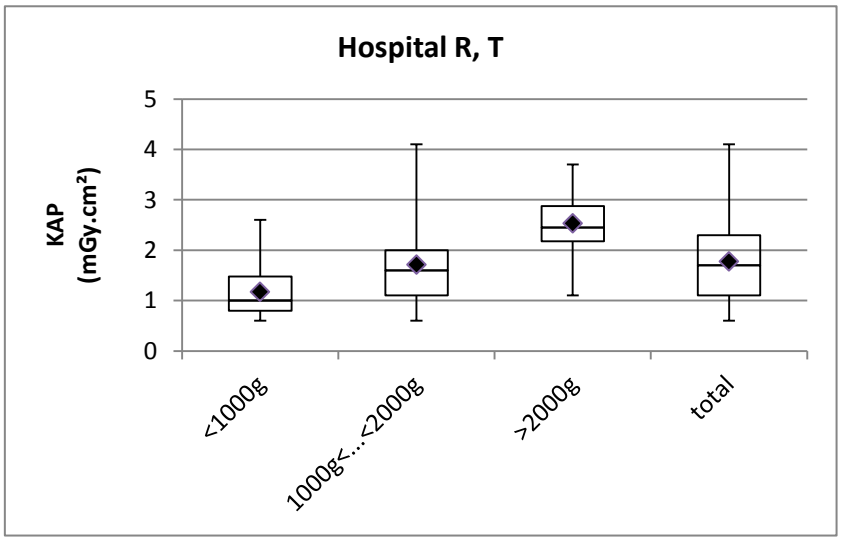
(o)


Hospital Q, T
ESK (µGy)
140
120
100
80
60
40
20
0
<1000g
1000g<...<2000g
>2000g
total



(p)





(q)

Figure 15: Overview of the ESK and the KAP per hospital for chest examinations

Thirdly, organ doses are calculated with the ESK and technical parameters as input using the PCXMC software for all hospitals, except for hospital B. In *Figure 16*, an overview of the organ doses for the active red bone marrow, breast, lungs, thymus and thyroid are given for the whole of Belgium. As no noticeable variations were observed between the different weight categories, only the results for the total sample are displayed.

As expected from the observed ESK, a large spread of the organ doses is also found. For the active red bone marrow, the average organ dose range from 1 to 7 µGy, for breast from 13 to 90 µGy, for lungs from 7 to 43 µGy, for thymus from 10 to 69 µGy and for thyroid from 1 to 6 µGy. Minimum and maximum average values are found in hospital R and K respectively. A ratio of 7, the same order as the ratio found for the ESK, can be observed between the extremes of the average organ doses. We stress again that these organ doses were calculated with a standard field size. The latter usually underestimates the actual field size and doesn't take into account the field position error (see *Field Size and Position Analysis*).

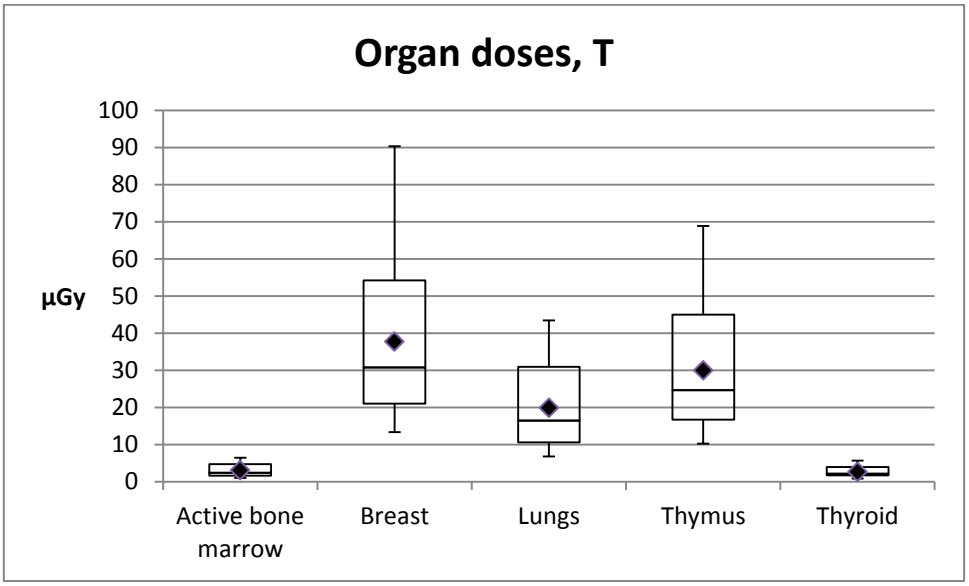


Figure 16: Overview of the organ doses for the active red bone marrow, breast, lungs, thymus and thyroid for the whole of Belgium

Combined chest-abdomen examinations

In *Figure 17*, a comparison between the median ESK and KAP is presented for all centres. In agreement with the large differences observed in the protocol settings and tube output measurements, a large spread of ESK is found. This is coherent with the spread observed for the chest examinations, as the protocols are usually not specifically defined for a specific type of examination. The median ESK ranges from 14 to 117 µGy. Minimum and maximum ESK with values of 8 and 866 µGy for a single chest-abdomen examination are found in hospitals R and B, respectively.

The median KAP ranges from 4 to 17 mGy.cm².

In hospital E, the high ESK values observed correspond with the high KAP values.

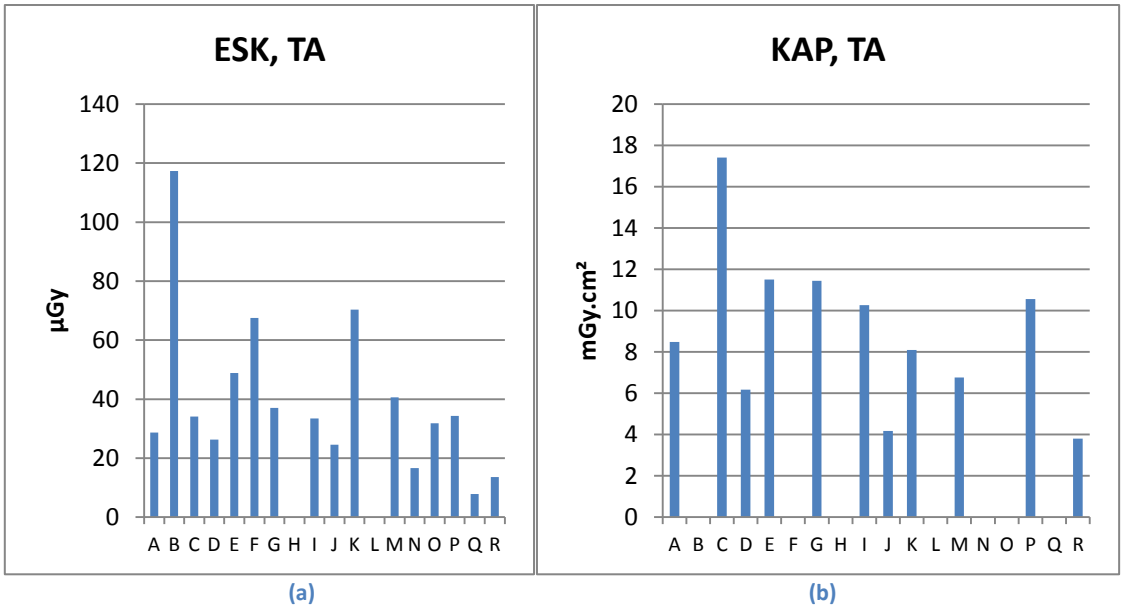
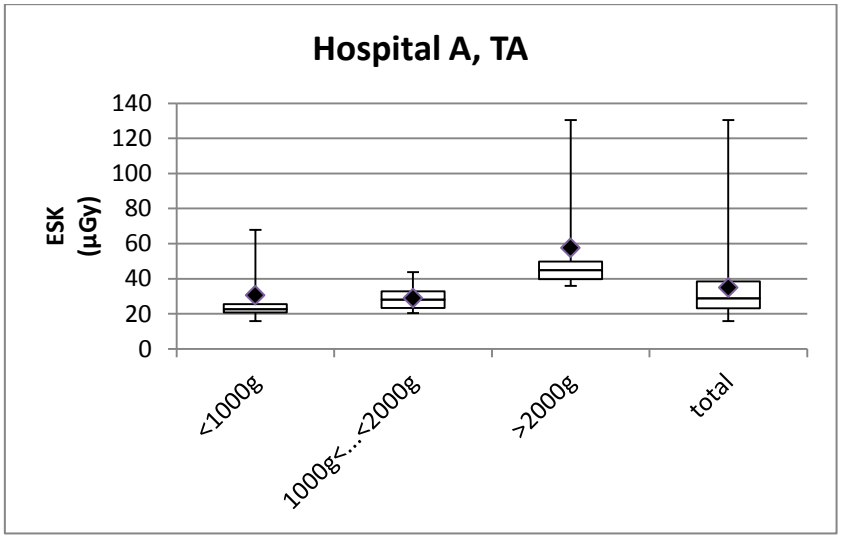


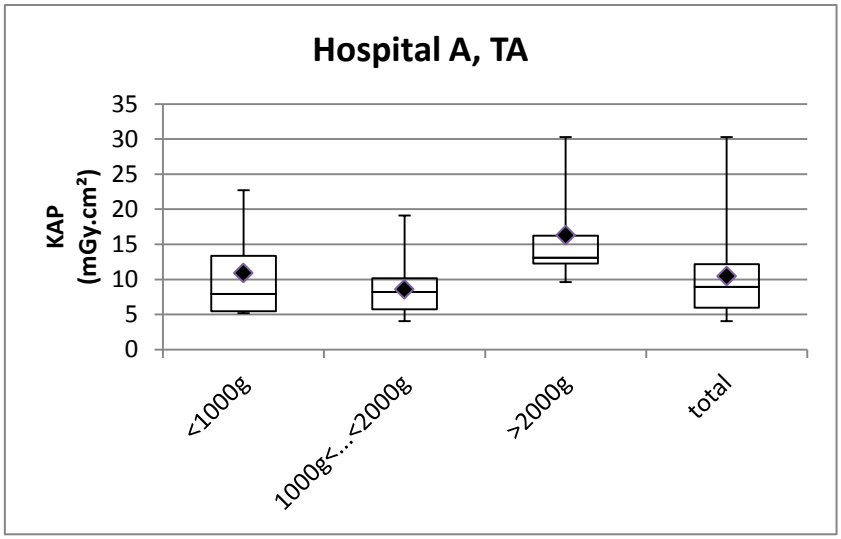
Figure 17: Median ESK (a) and KAP (b) for combined chest-abdomen examinations in the Belgian NICU's

Secondly, in *Figure 18* (*a* to *o*), an overview of the ESK (a) and KAP (b) is given for each hospital and for each weight category separately. The results are given in terms of boxplots, representing the average, median, 25th and 75th percentiles and minima and maxima values.

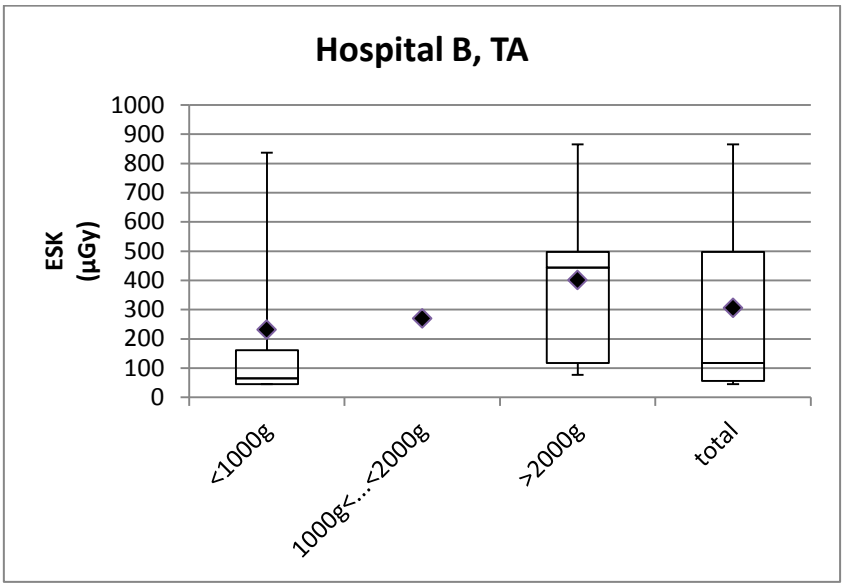
In the hospitals E, N and R, the ESK increases with the weight category.
An increase in the KAP values can be observed with the increasing weight category – and the ESK - in hospital E.

In hospitals L and O, an insufficient amount of combined chest-abdomen examinations were collected. Therefore, no boxplots are shown.

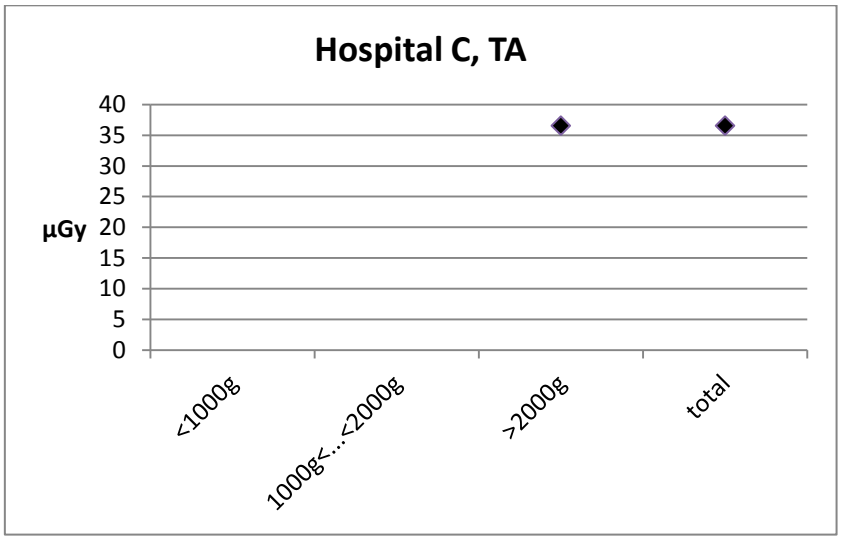


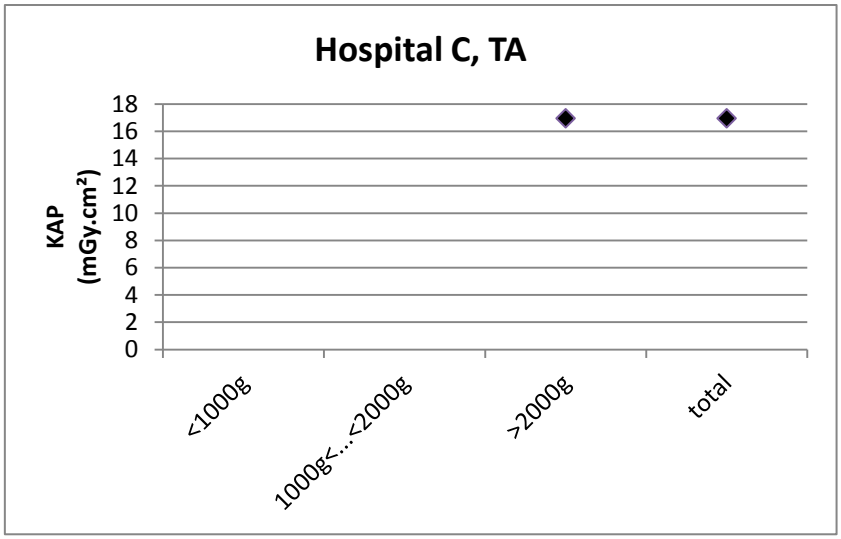

Hospital A, TA
KAP (mGy.cm²)
35
30
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

(a)

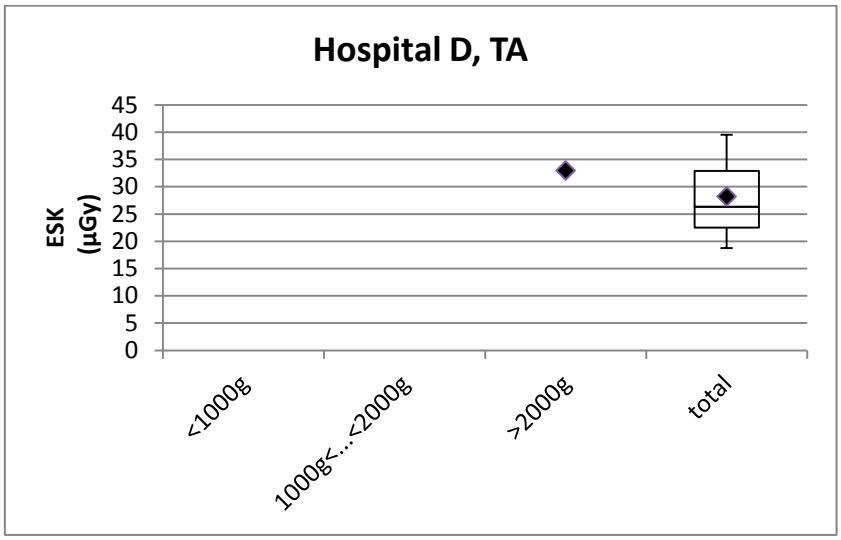

Hospital B, TA
ESK (µGy)
1000
900
800
700
600
500
400
300
200
100
0
<1000g
1000g<...<2000g
>2000g
total

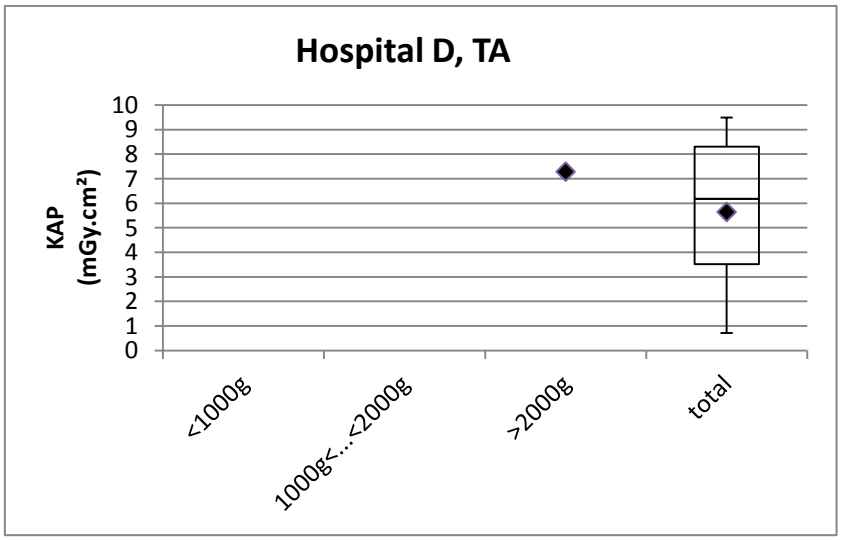
(b)


Hospital C, TA
µGy
40
35
30
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

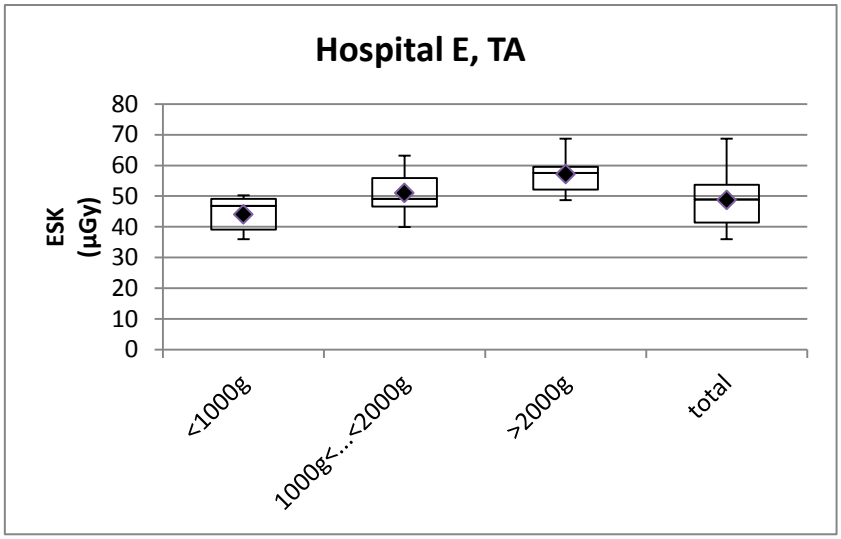

Hospital C, TA
KAP (mGy.cm²)
18
16
14
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

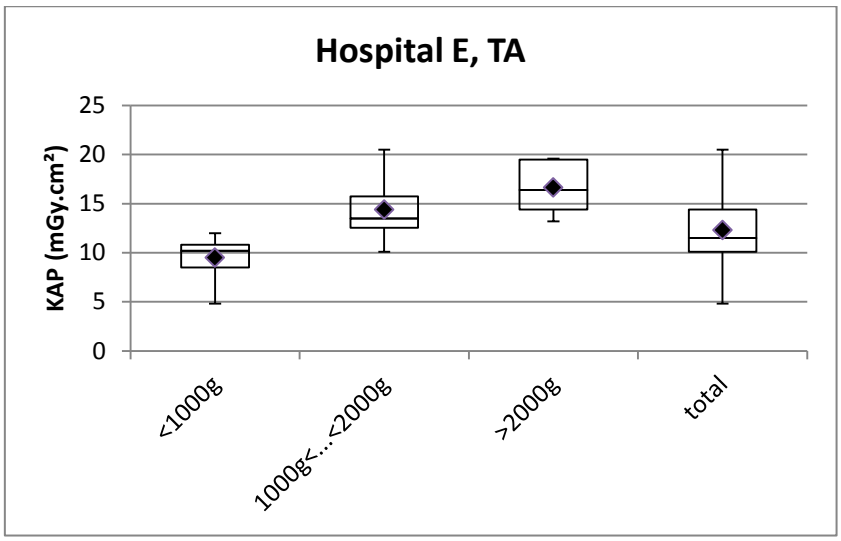
(c)


Hospital D, TA
ESK (µGy)
45
40
35
30
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

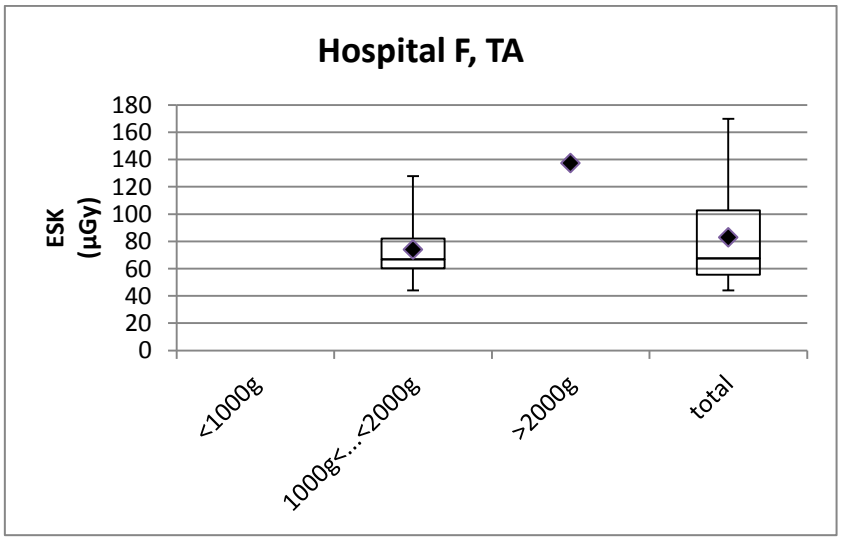

Hospital D, TA
KAP (mGy.cm²)
10
9
8
7
6
5
4
3
2
1
0
<1000g
1000g<...<2000g
>2000g
total

(d)

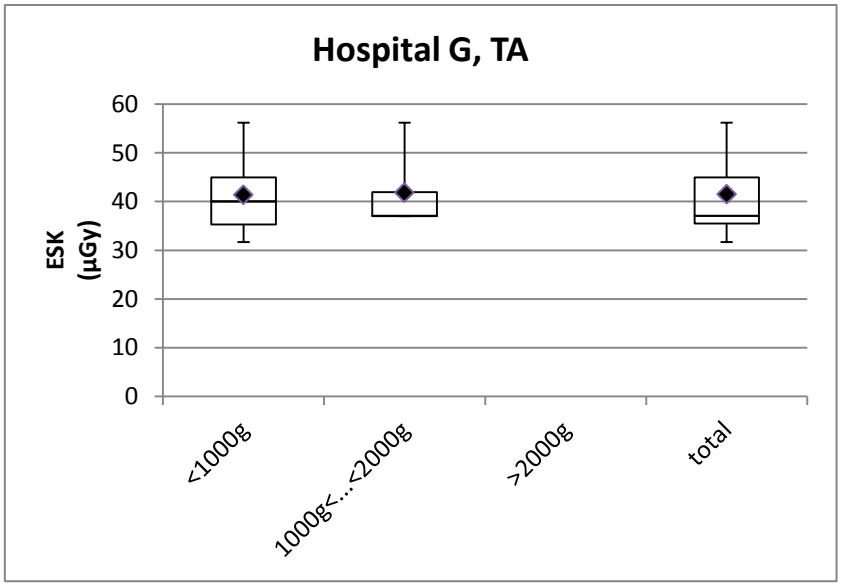

Hospital E, TA
ESK (µGy)
80
70
60
50
40
30
20
10
0
<1000g
1000g<...<2000g
>2000g
total

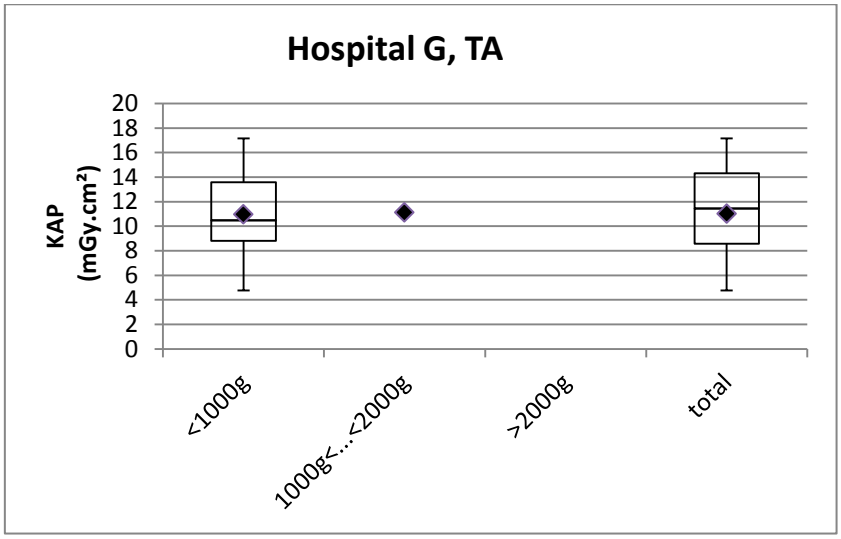

Hospital E, TA
KAP (mGy.cm²)
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

(e)

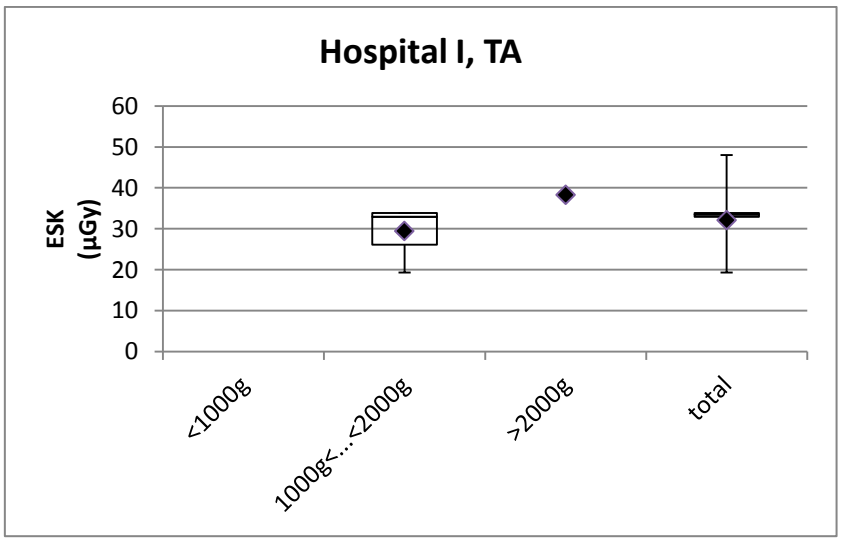

Hospital F, TA
ESK (µGy)
180
160
140
120
100
80
60
40
20
0
<1000g
1000g<...<2000g
>2000g
total

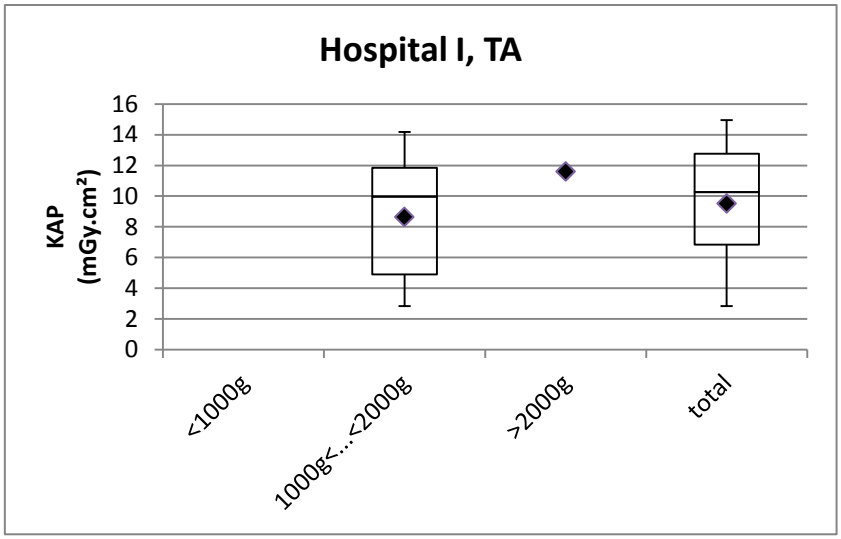
(f)


Hospital G, TA
ESK (µGy)
60
50
40
30
20
10
0
<1000g
1000g<...<2000g
>2000g
total

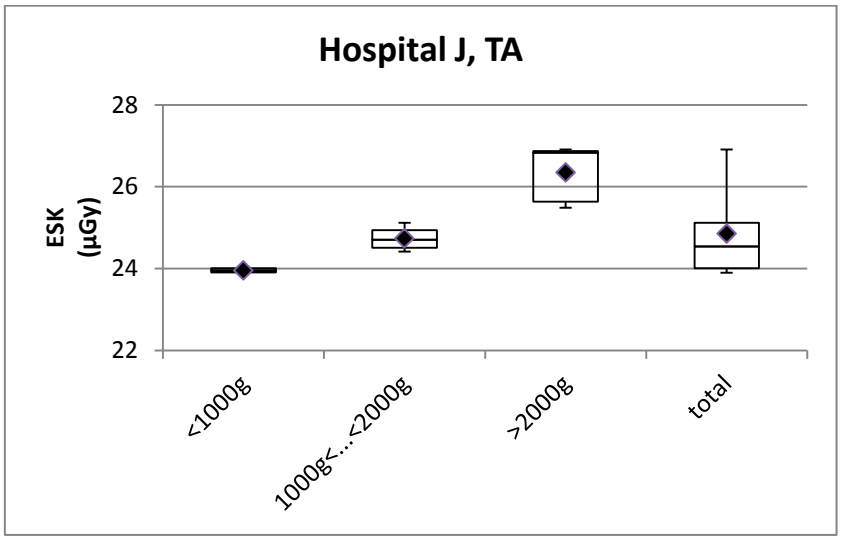

Hospital G, TA
KAP (mGy.cm²)
20
18
16
14
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

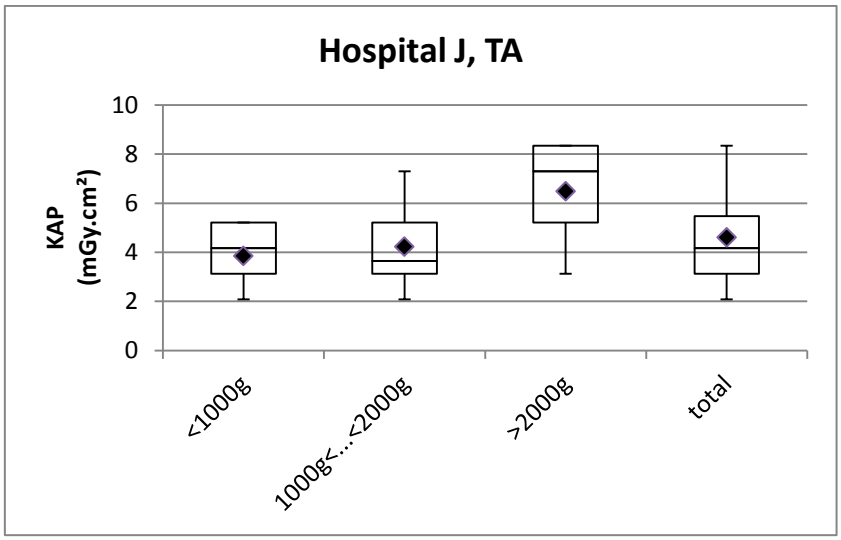
(g)


Hospital I, TA
ESK (µGy)
60
50
40
30
20
10
0
<1000g
1000g<...<2000g
>2000g
total

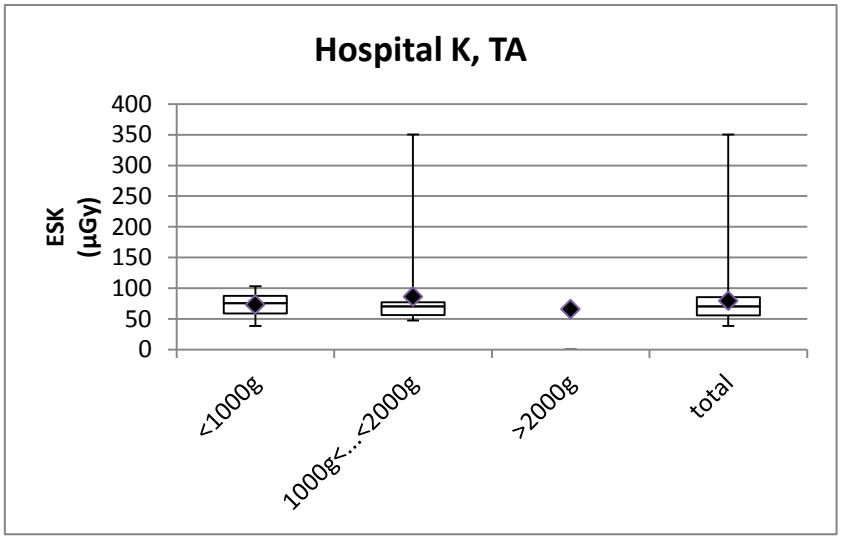

Hospital I, TA
KAP (mGy.cm²)
16
14
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

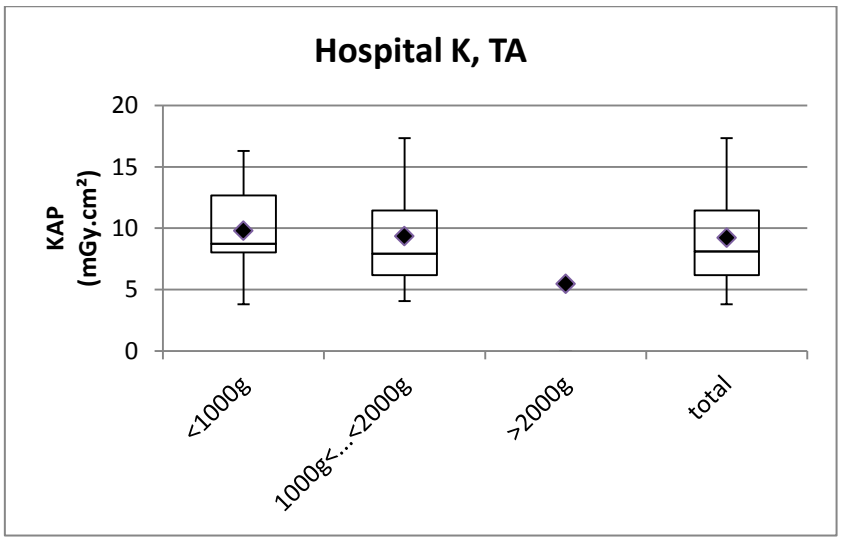
(h)


Hospital J, TA
ESK (µGy)
28
26
24
22
<1000g
1000g<...<2000g
>2000g
total

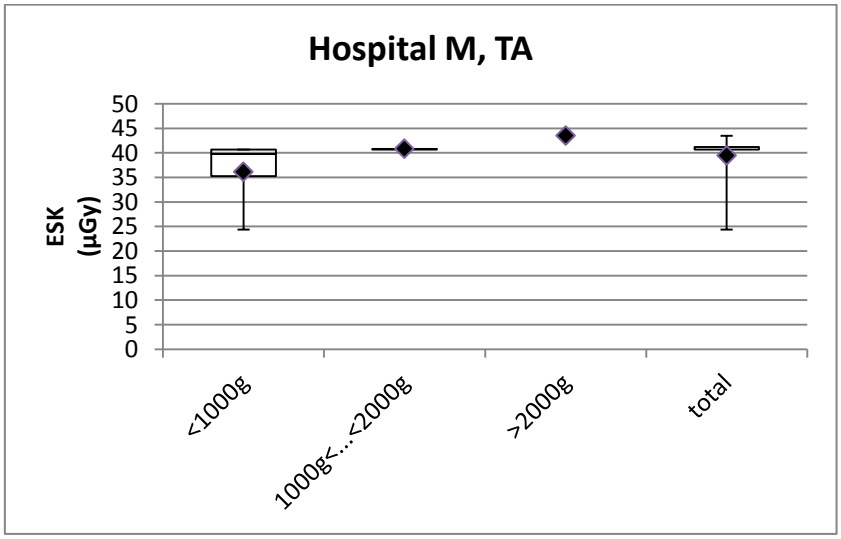

Hospital J, TA
KAP (mGy.cm²)
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

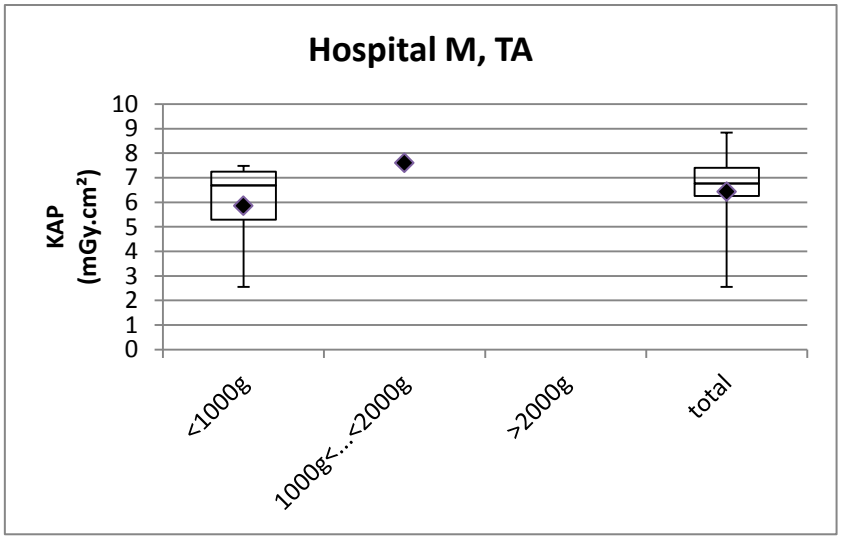
(i)


Hospital K, TA
ESK (µGy)
400
350
300
250
200
150
100
50
0
<1000g
1000g<...<2000g
>2000g
total

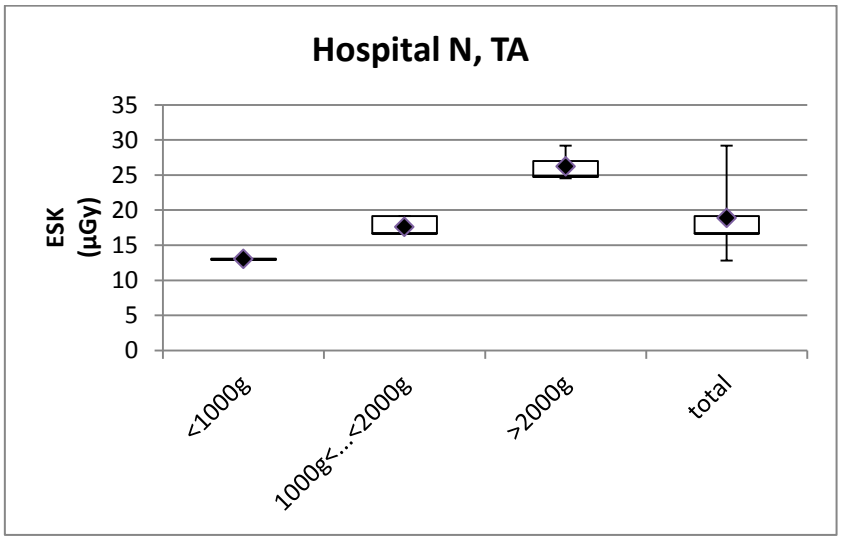

Hospital K, TA
KAP (mGy.cm²)
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

(j)

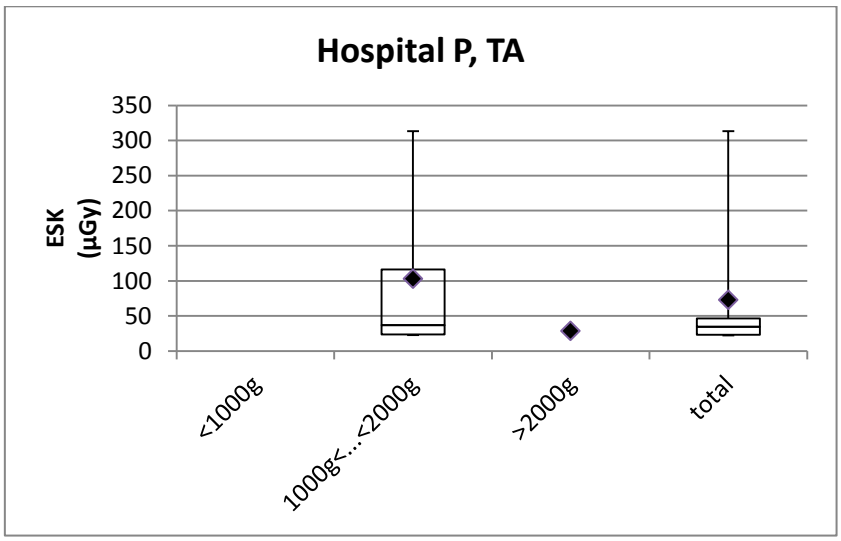

Hospital M, TA
ESK (µGy)
50
45
40
35
30
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

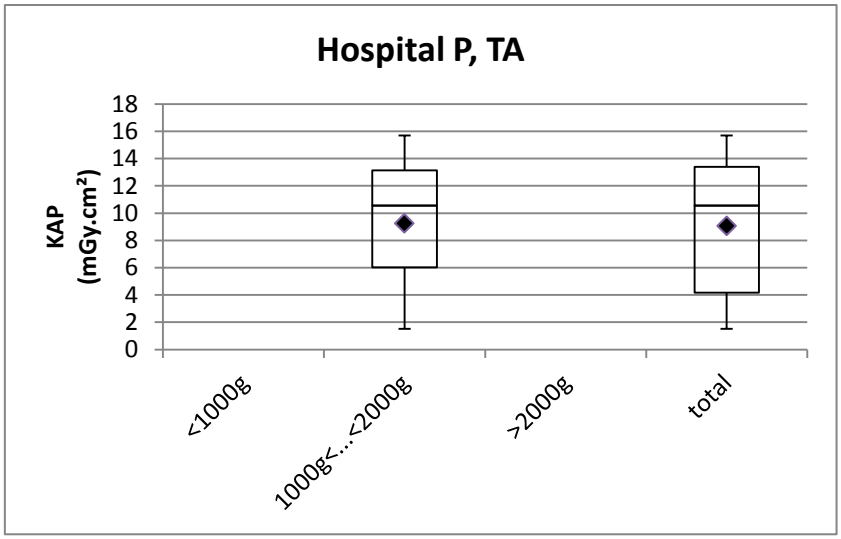

Hospital M, TA
KAP (mGy.cm²)
10
9
8
7
6
5
4
3
2
1
0
<1000g
1000g<...<2000g
>2000g
total

(k)

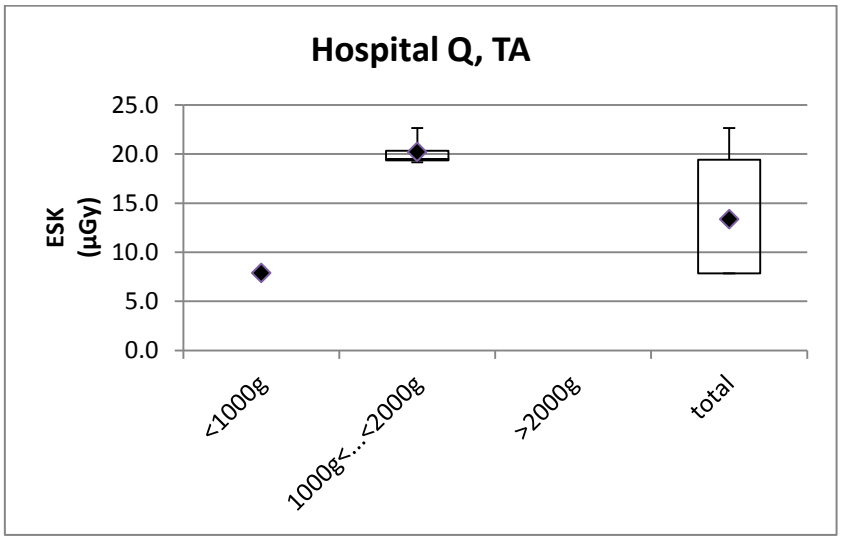

Hospital N, TA
ESK (µGy)
35
30
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

(l)

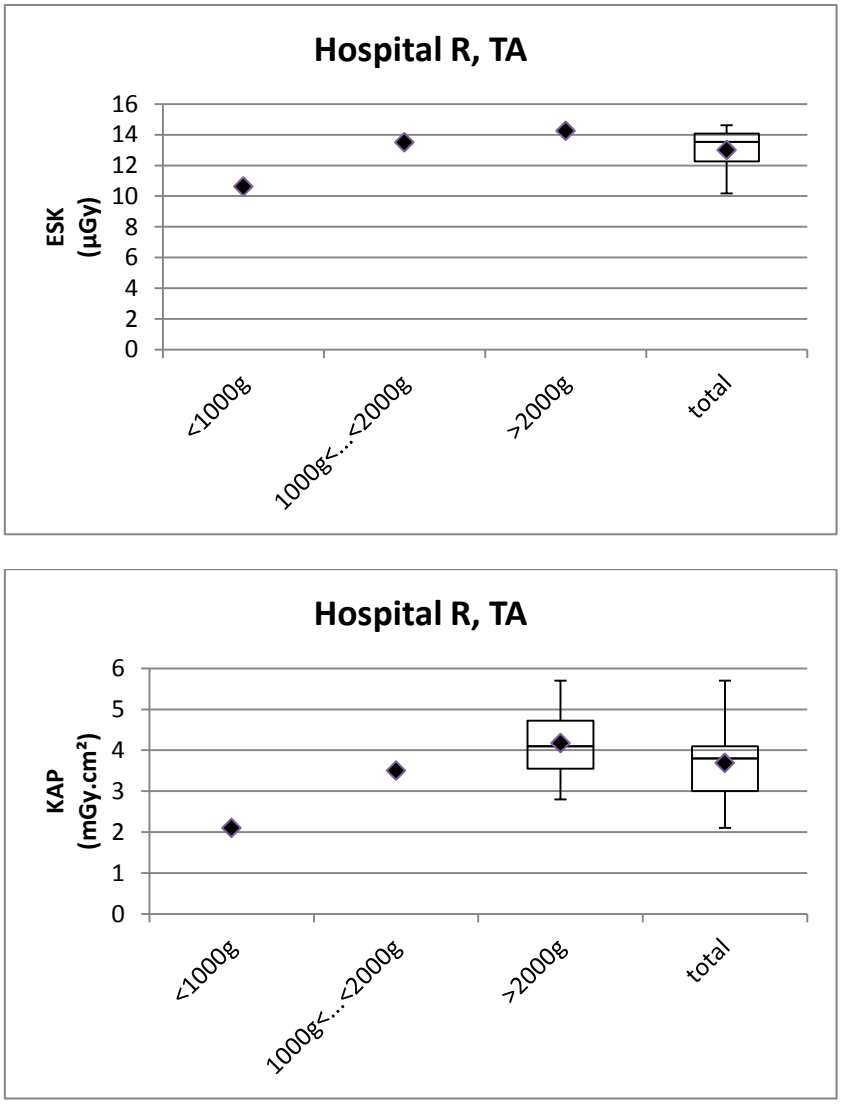

Hospital P, TA
ESK (µGy)
350
300
250
200
150
100
50
0
<1000g
1000g<...<2000g
>2000g
total


Hospital P, TA
KAP (mGy.cm²)
18
16
14
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

(m)


Hospital Q, TA
ESK (µGy)
25.0
20.0
15.0
10.0
5.0
0.0
<1000g
1000g<...<2000g
>2000g
total

(n)



(o)

Figure 18: Overview of the ESK and the KAP per hospital for combined chest-abdomen examinations

Thirdly, organ doses are calculated with the ESK and technical parameters as input by means of the PCXMC software tool, for all hospitals. In *Figure 19*, an overview of the organ doses for the active red bone marrow, breast, colon, lungs, stomach, thymus and thyroid are given for the whole of Belgium, except for centre B. As no noticeable variations were observed between the different weight categories, only the results for the total sample are displayed.

As it was expected from the observed ESK, a large spread of the organ doses is also found. For the active bone marrow, the average organ doses range from 2 to 12 µGy, for breast from 17 to 95 µGy, for colon from 4 to 47 µGy, for lungs from 8 to 47 µGy, for stomach from 7 to 61 µGy, for thymus from 13 to 72 µGy and for thyroid from 1 to 7 µGy. Minimum and maximum average values are found in hospital J and K respectively. A ratio of 7, the same order as the ratio found for the ESK, can be observed. We stress again that these organ doses were calculated with a standard field size.

Contrarily to the chest examinations, the standard field size used for combined chest-abdomen examinations usually overestimates the actual field size (see *Field Size and Position Analysis*).

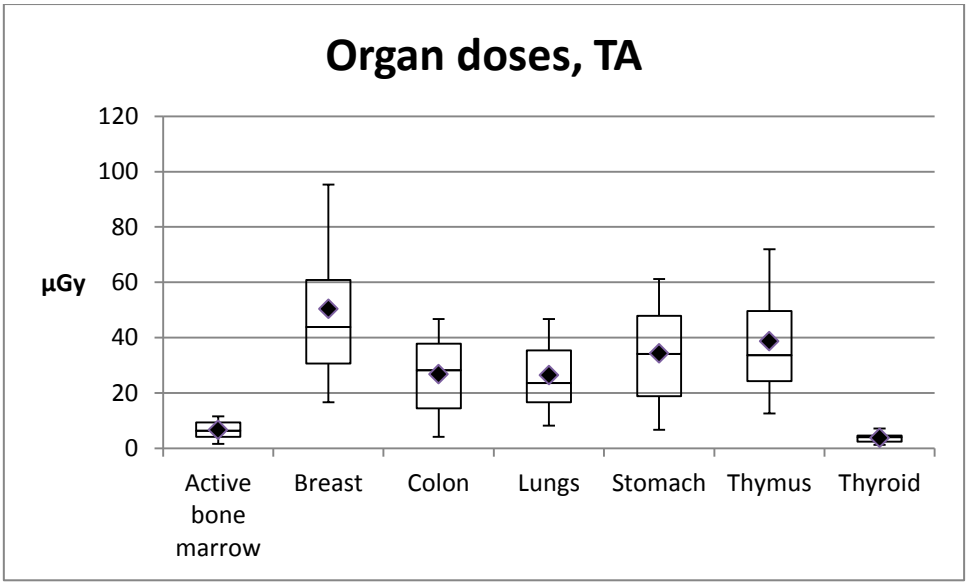


Figure 19: Overview of the organ doses for the active red bone marrow, breast, colon, lungs, stomach, thymus and thyroid for the whole of Belgium

Abdomen examinations

As mentioned earlier, the abdomen examination is performed less frequently. As a result, the amount of collected data for the abdomen examinations was not sufficient to realise a representative analysis in all the centres. In *Figure 20*, a comparison between the median ESK and KAP is presented for those centres where sufficient abdomen examinations were performed. ESK were calculated for 7 centres (A, D, E, K, M, N and R); KAP values are only available for 5 centres (A, D, E, K and M).

In agreement with the large differences observed in the protocol settings and tube output measurements, a large spread of ESK is found. This is coherent with the spread observed for the chest and chest-abdomen examinations, as the protocols are usually not specifically defined for one type of examination. The median ESK ranges from 14 to 65 µGy and were found in hospitals R and K respectively.

The median KAP ranges from 3 to 9 mGy.cm².

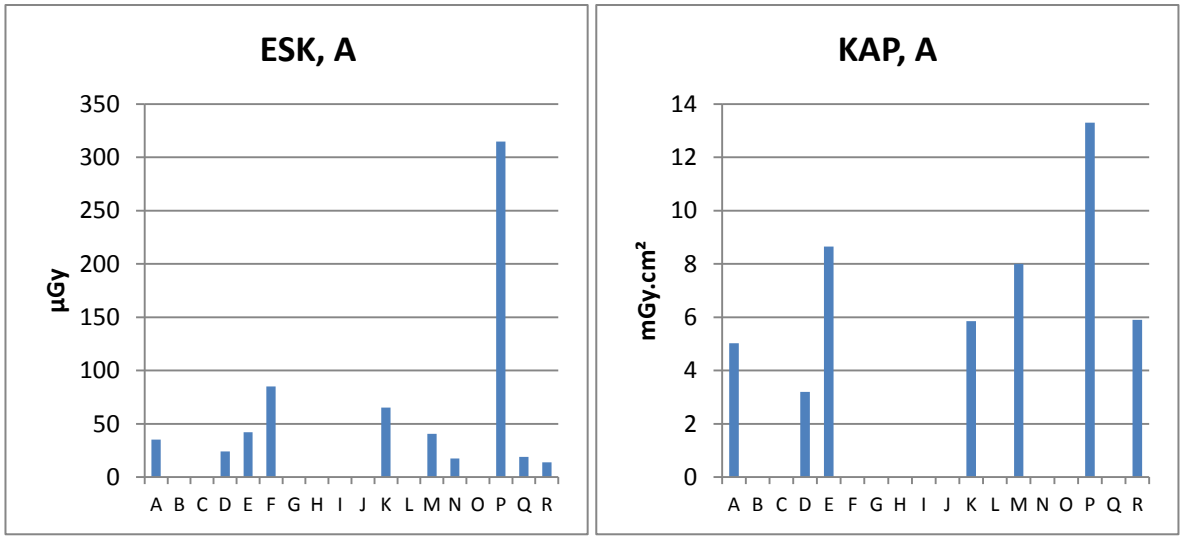
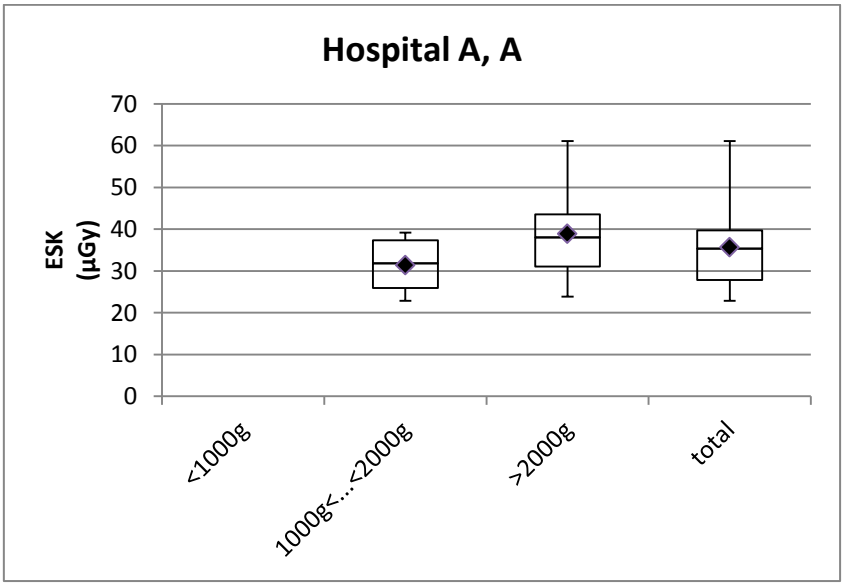
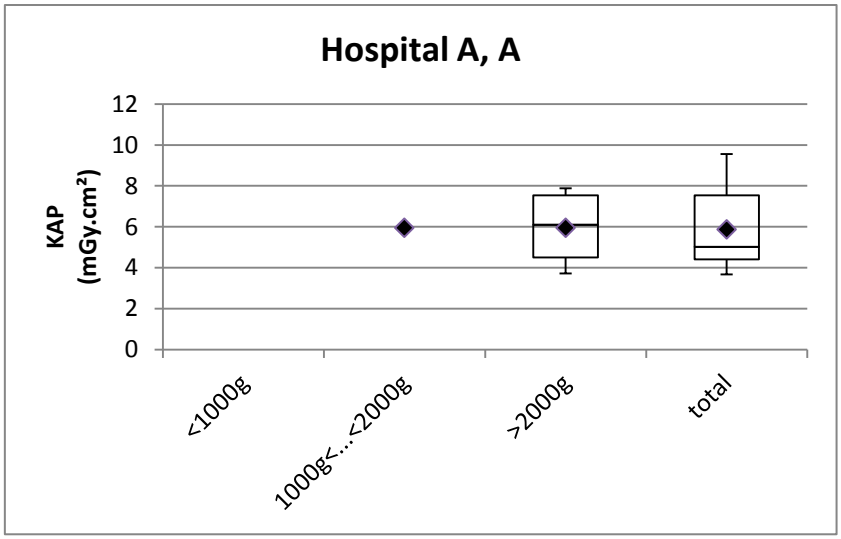


Figure 20: Median ESK (a) and KAP (b) for abdomen examinations in the Belgian NICU's

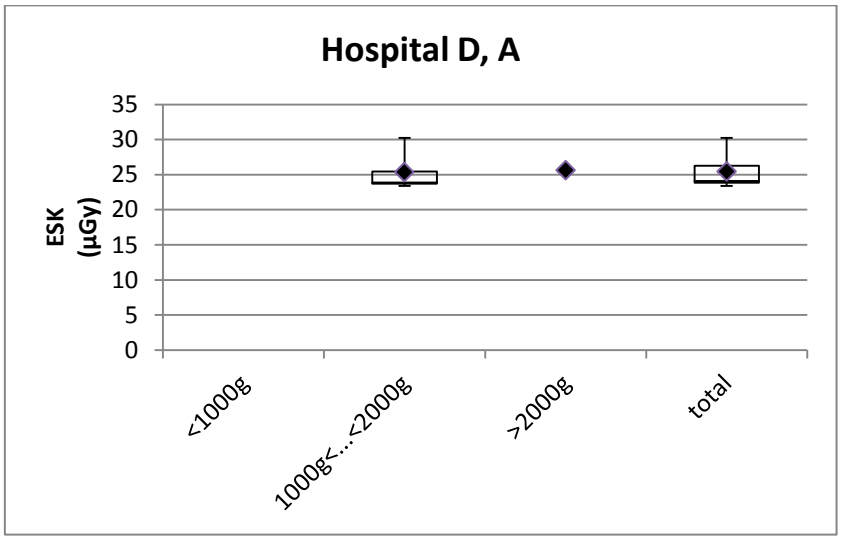
Secondly, in *Figure 21*, an overview of the ESK (a) and KAP (b) is given for each weight category separately in some of the hospitals. The results are given in terms of boxplots, representing the average, median, 25th and 75th percentiles and minima and maxima values.

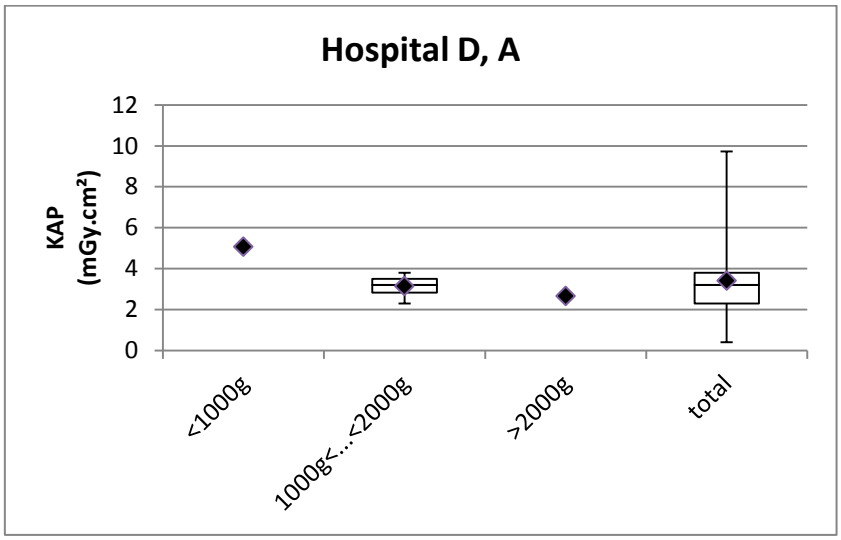
One can observe that, in hospital N, the ESK seems to increase with the weight.



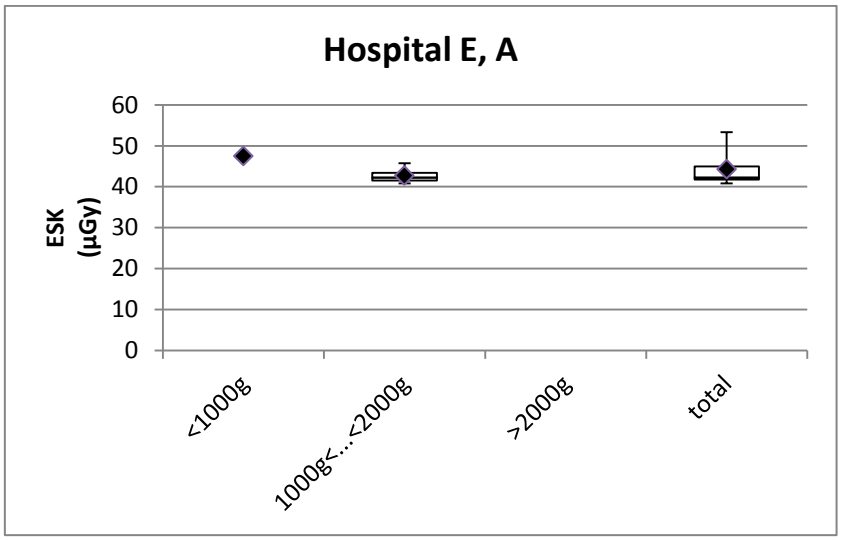

Hospital A, A
KAP (mGy.cm²)
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

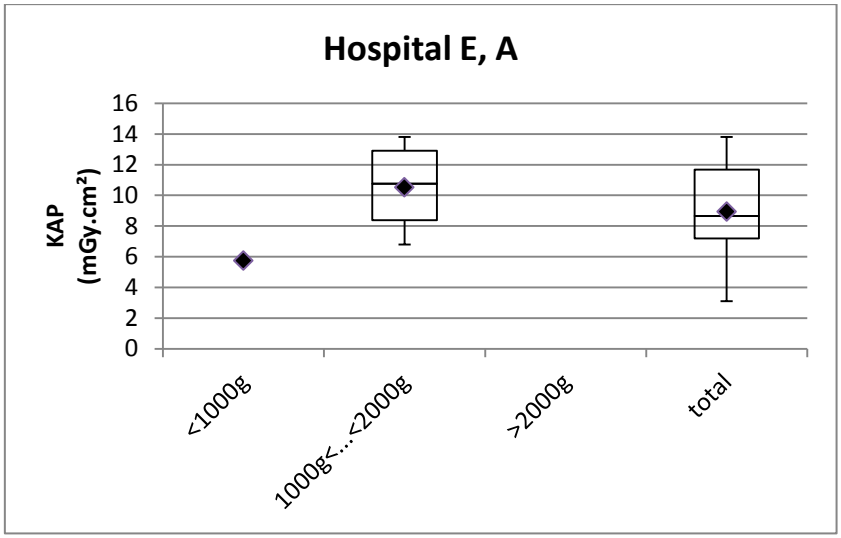
(a)


Hospital D, A
ESK (µGy)
35
30
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

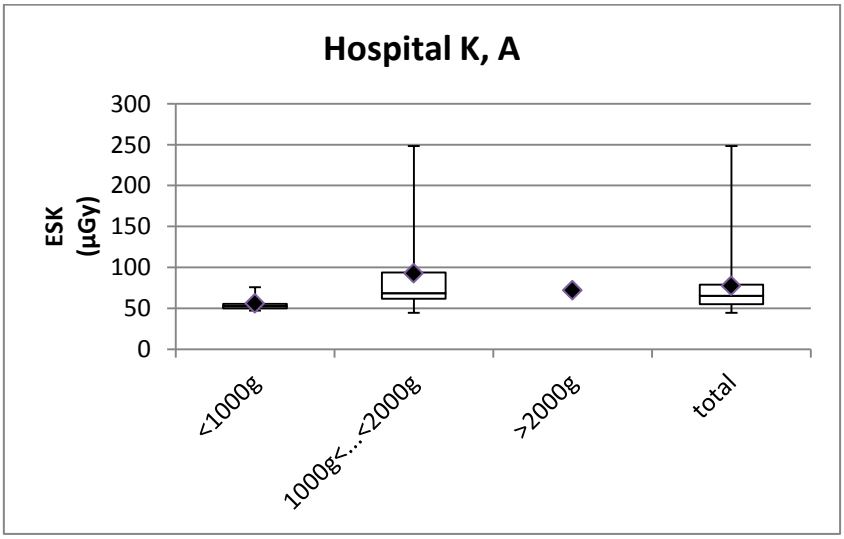

Hospital D, A
KAP (mGy.cm²)
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

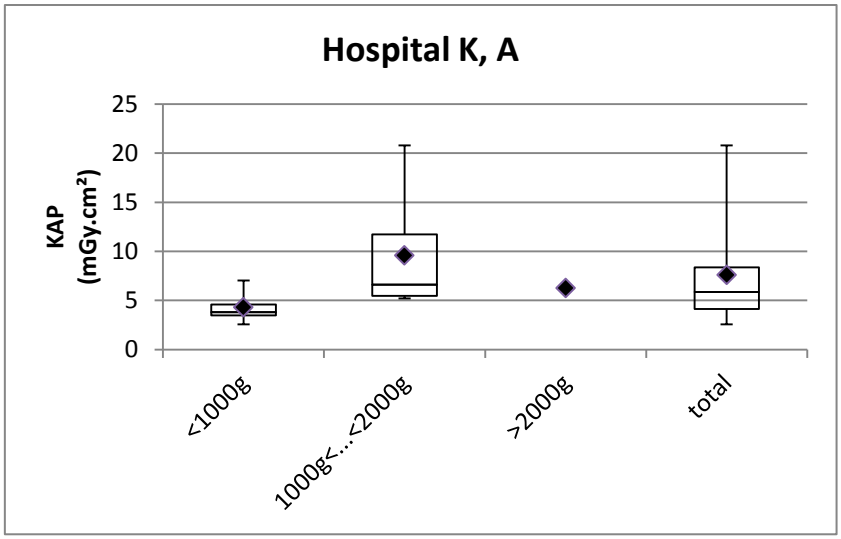
(b)


Hospital E, A
ESK (µGy)
60
50
40
30
20
10
0
<1000g
1000g<...<2000g
>2000g
total

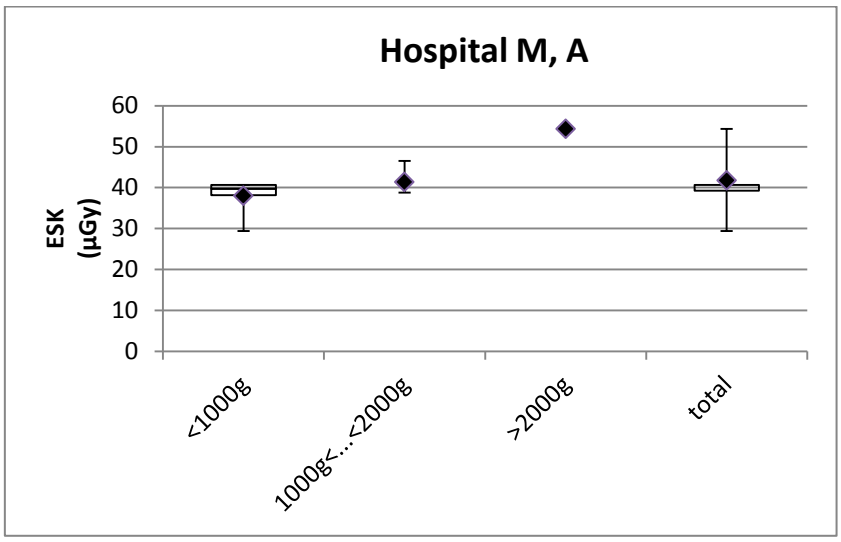

Hospital E, A
KAP (mGy.cm²)
16
14
12
10
8
6
4
2
0
<1000g
1000g<...<2000g
>2000g
total

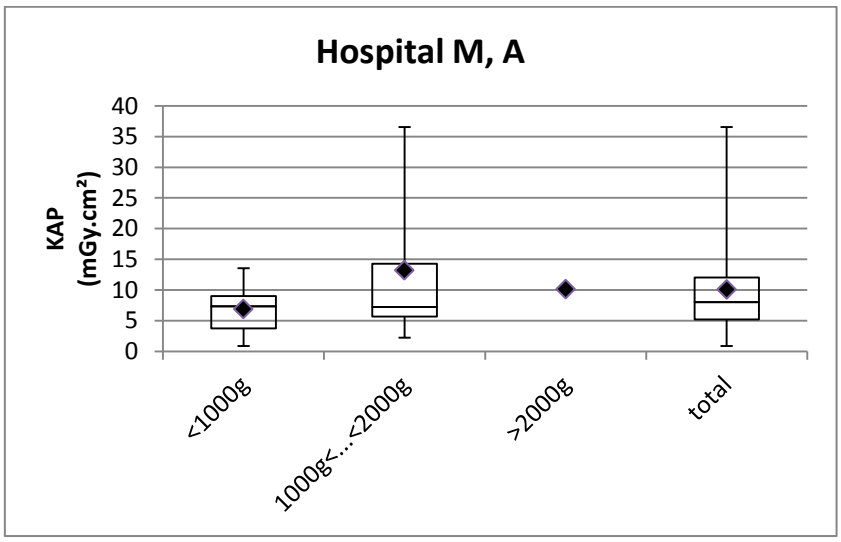
(c)


Hospital K, A
ESK (µGy)
300
250
200
150
100
50
0
<1000g
1000g<...<2000g
>2000g
total

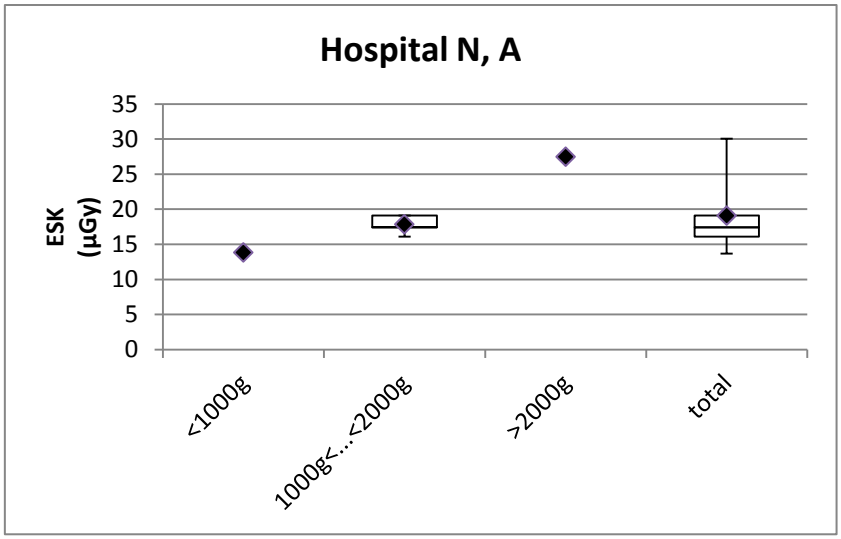

Hospital K, A
KAP (mGy.cm²)
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

(d)

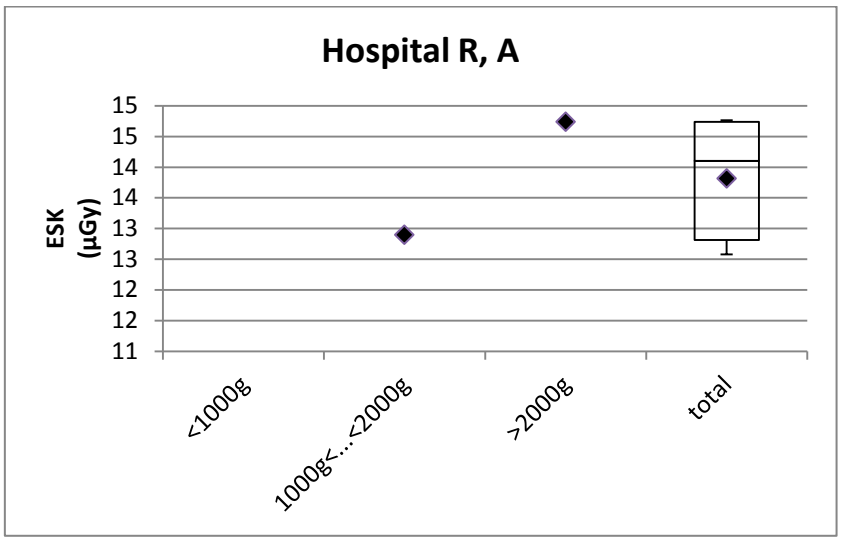

Hospital M, A
ESK (µGy)
60
50
40
30
20
10
0
<1000g
1000g<...<2000g
>2000g
total


Hospital M, A
KAP (mGy.cm²)
40
35
30
25
20
15
10
5
0
<1000g
1000g<...<2000g
>2000g
total

(e)



(f)



(g)

Figure 21: Overview of the ESK and the KAP per hospital for abdomen examinations.

Thirdly, organ doses are calculated with the ESK and technical parameters as input using the PCXMC software tool for all hospitals. In *Figure 22*, an overview of the organ doses for the active red bone marrow, colon and stomach are given for the whole of Belgium. As no noticeable variations were observed between the different weight categories, only the results of the total sample is displayed.

For the active red bone marrow, the average organ doses range from 1 to 6 µGy, for colon from 8 to 45 µGy and for stomach from 10 to 57 µGy.

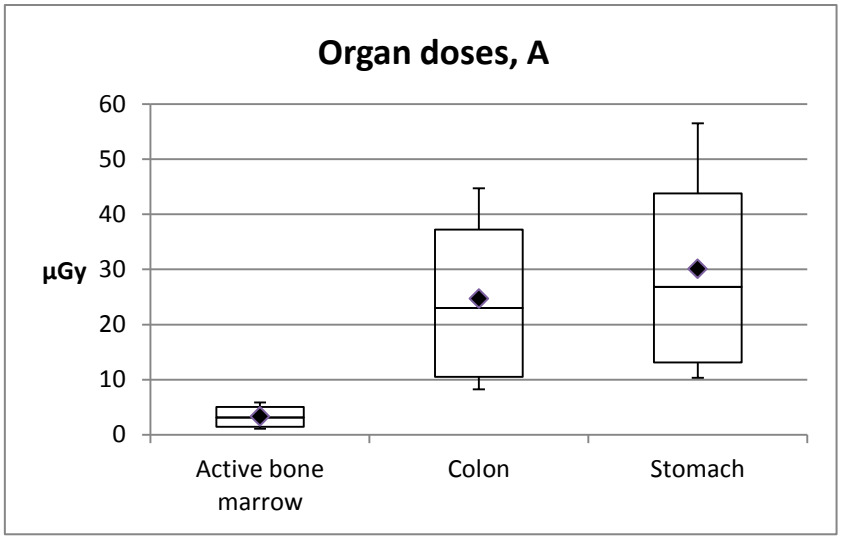
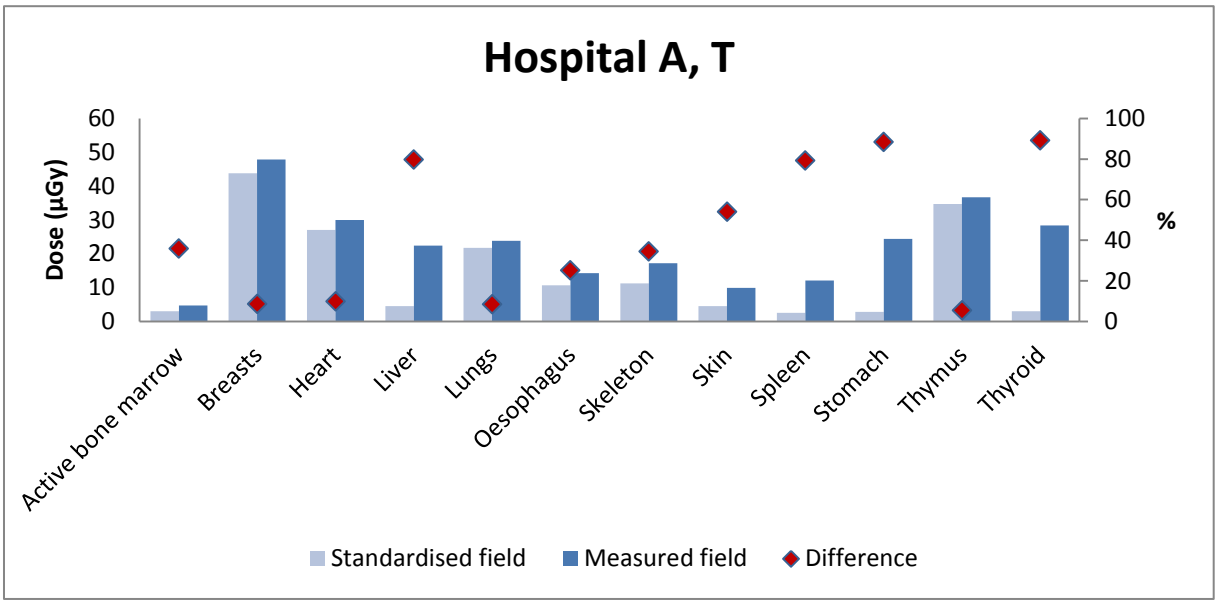
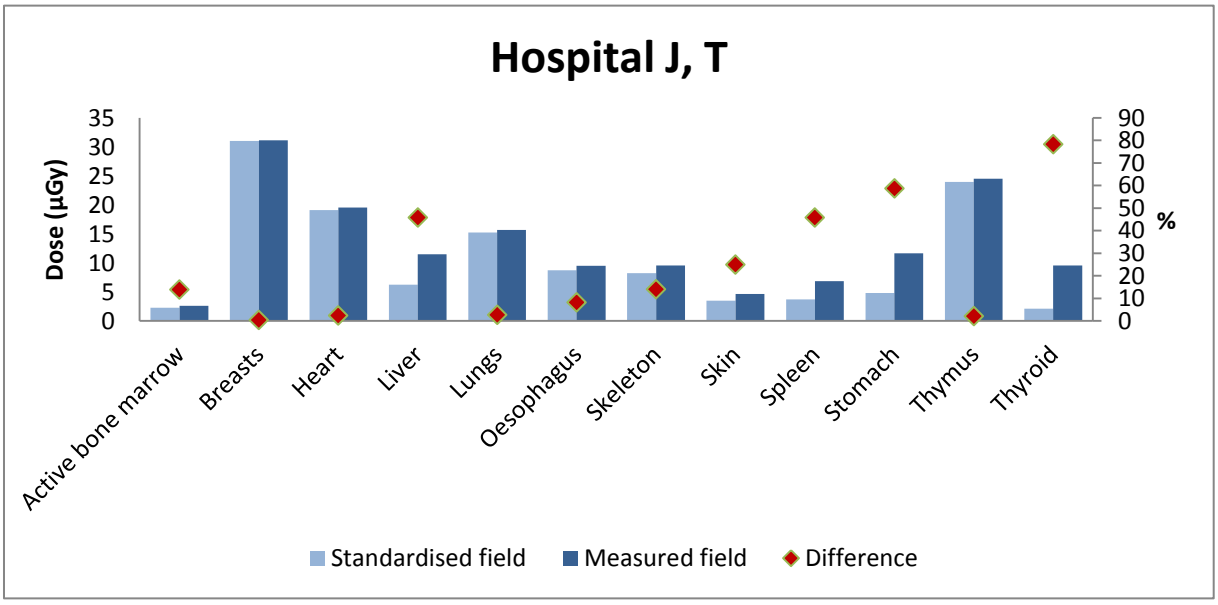


Figure 22: Overview of the organ doses for the active red bone marrow, colon and stomach for the whole of Belgium

Field Size and Position Analysis

Numerous field size measurements, in different hospitals, have confirmed that the standard field size used in the study for chest examinations usually underestimates the actual field size, and doesn't take into account the inappropriate field positioning. Organ dose calculations were also performed for actual field sizes measured in hospital A, J and R. *Figure 23* shows, on average, the effects of the field size and position on the organ doses for chest examinations. The standard field size, used for the calculation of the organ doses, is compared to the actual field size, measured in the hospitals. A minor influence on the doses to the breast, the heart, the lungs and the thymus is observed (less than 9, 10, 8 and 5 %, respectively), as these organs are completely situated in the radiation field for most chest examinations, even with an excessive field size or an inappropriate position/collimation. Doses to organs partially situated in the radiation field, on the edges or distributed over the whole body are considerably more sensitive to field position and size. This observation is of particular interest for organs such as the liver, the stomach, the active red bone marrow and the thyroid. For the latter, the largest variations are found with doses from 5 to 10 times larger as compared to the dose resulting from the use of the standard field.


Hospital A, T
Dose (µGy)
60
50
40
30
20
10
0
100
80
60
40
20
0
%
Active bone marrow
Breasts
Heart
Liver
Lungs
Oesophagus
Skeleton
Skin
Spleen
Stomach
Thymus
Thyroid
Standardised field
Measured field
Difference


Hospital J, T
Dose (µGy)
35
30
25
20
15
10
5
0
90
80
70
60
50
40
30
20
10
0
%
Active bone marrow
Breasts
Heart
Liver
Lungs
Oesophagus
Skeleton
Skin
Spleen
Stomach
Thymus
Thyroid
Standardised field
Measured field
Difference

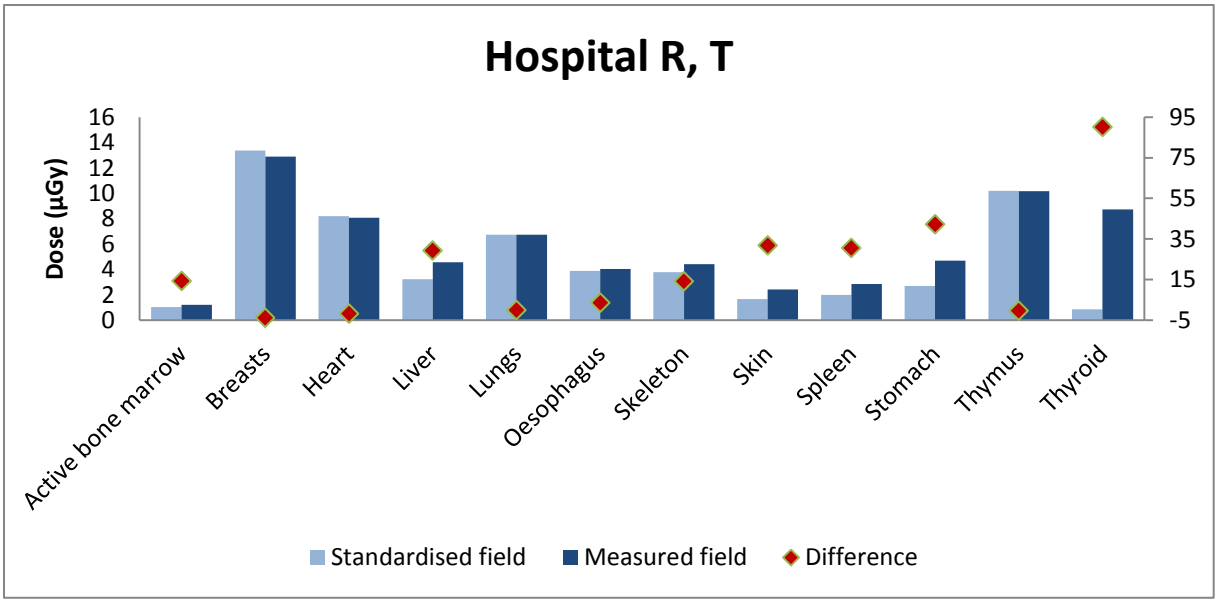
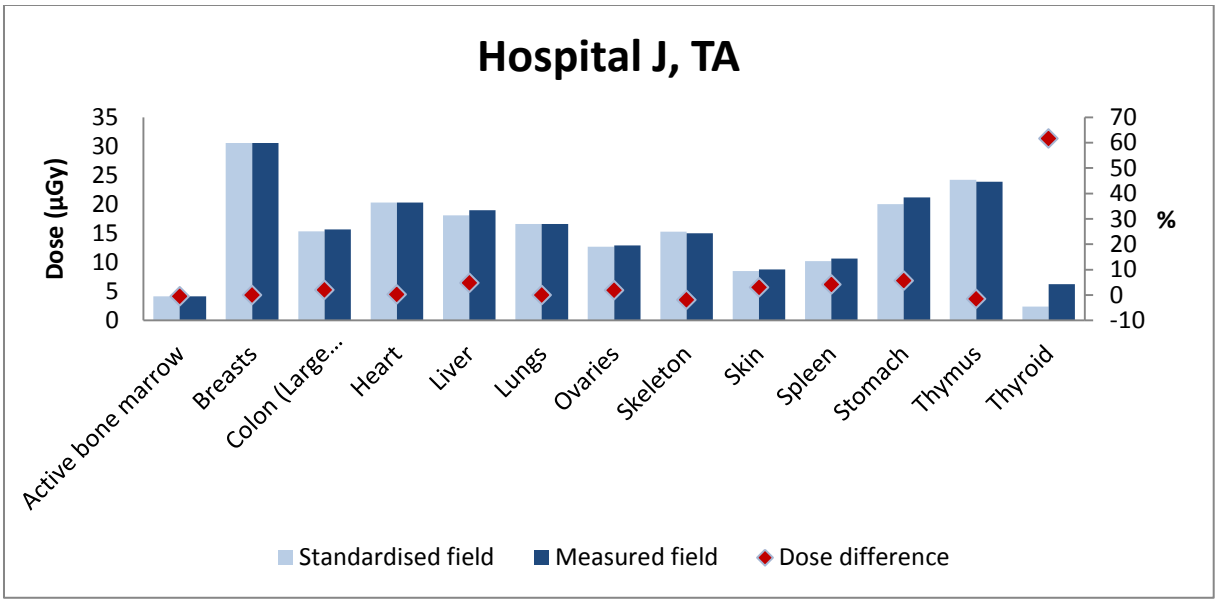


Figure 23: Doses difference (red diamonds) between the average doses for chest examinations. In grey, doses simulated with a standard field size, in blue doses simulated with the measured field size.

For the combined chest-abdomen examinations, it appears that the size of the standard field as used in this study is usually larger than the real size of the measured field in different hospitals. This is explained by the way the standard field is defined, as the maximal field size possible. The large differences in the observed field sizes could be partially explained by specific request of the referring doctor. This particularly affects organs situated at the border of the actual field. For the thyroid, a variation of 62% is found in hospital J, while in hospital E the variation was much larger (84%). Nevertheless, for organs included as a whole within the field, such as the lungs, the liver and the stomach, the estimated doses obtained with the standard field are not affected, when using the actual fields.



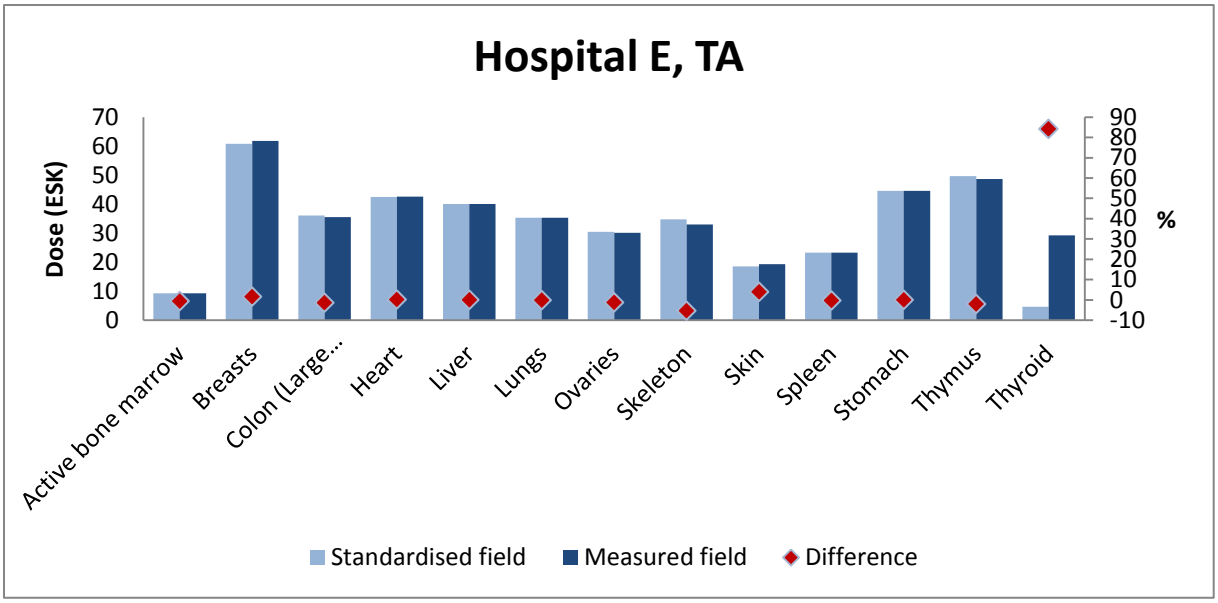


Figure 24: Doses difference (red diamonds) between the average doses for combined chest-abdomen examination. In grey, doses simulated with a standard field size, in blue doses simulated with the measured field size.

Diagnostic reference levels

The diagnostic reference levels for the chest examinations and combined chest–abdomen examinations are given in *Table 4*. ; the values of 25th percentiles are also added for informative purposes. These values are given in terms of ESK and KAP, for each weight category and for the complete sample. They are calculated from the median dose distribution in each hospital. For the complete sample, all patients are included. For the different weight categories only a median is calculated if at least 3 patients are included per weight category and per hospital. For chest examinations, the DRLs for the total sample are 39 µGy and 7.4 mGy.cm², in terms of ESK and KAP respectively. For combined chest-abdomen examinations, the DRLs for the total sample are 39 µGy and 11.0 mGy.cm², in terms of ESK and KAP respectively. It can be noted that the DRL for chest examinations, in terms of ESK, is half the value of the reference level for a new-born of 1000 g (80 µGy) given in the guidelines of the European Commission in 1996 (18).

As the amount of data collected for abdomen examinations usually proven to be insufficient, a DRL could not be established for each weight category separately. A DRL is calculated on the total sample, but this should be considered preliminary, as only data from 10 hospitals are included for ESK and from 7 hospitals for KAP. Moreover, the number of patients per hospital can be relatively small.

It can be observed that the DRL in terms of ESK are quite similar for chest and combined chest-abdomen examinations, the preliminary DRL for abdomen is higher.

ESK (µGy)

	<1000g		*1000g<…<2000g*		*>2000g*		***total***	
	25th	*75th*	*25th*	*75th*	*25th*	*75th*	***25th***	***75th***
Chest	21	40	19	47	25	51	**19**	**42**
Chest-abdomen	24	47	27	51	27	58	**26**	**43**
Abdomen	/	/	/	/	/	/	**20***	**59***

(a)

KAP (mGy.cm²)

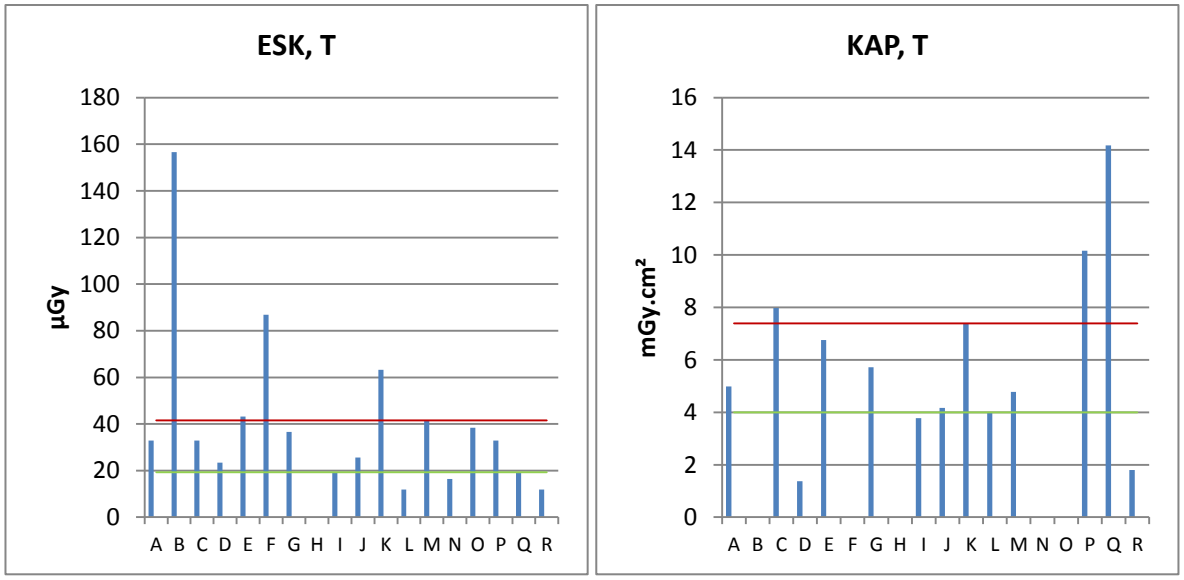
	<1000g		*1000g<…<2000g*		*>2000g*		***total***	
	25th	*75th*	*25th*	*75th*	*25th*	*75th*	***25th***	***75th***
Chest	1.1	5.1	3.7	7.1	5.4	9.6	**4.0**	**7.4**
Chest-abdomen	5.8	9.8	7.7	11.5	7.6	14.5	**6.5**	**11.0**
Abdomen	/	/	/	/	/	/	**5.4***	**8.3***

(b)

Table 4: Diagnostic reference levels and 25th percentile of the dose distribution for chest and combined chest-abdomen examinations in terms of ESK (a) and KAP (b). A preliminary diagnostic reference level is also given for abdomen examinations.

In *Figure 25* and *Figure* 27, the median ESKs and median KAPs of the participating centres are compared to the corresponding DRLs, calculated for the total sample for chest and combined chest-abdomen examinations, respectively. Specific recommendations, adapted to the situation observed in the participating hospitals, are available in a separate document.

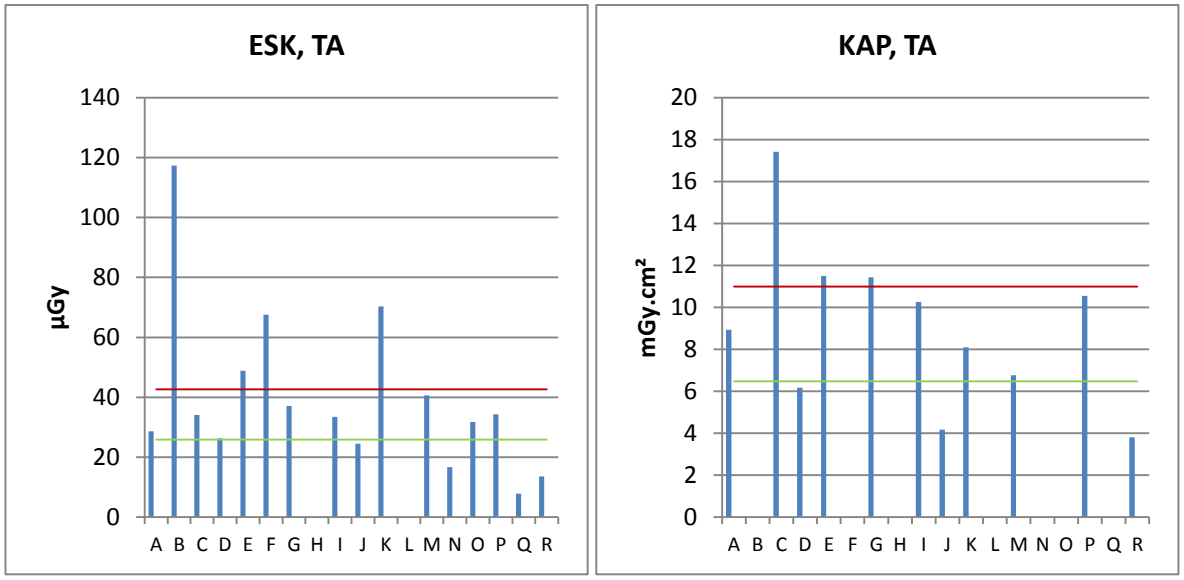
For chest examinations, centres C, E, K and P exceed or are close to the DRLs both for ESK and KAP. Centres B, F, M and O exceed the DRL in terms of ESK (no KAP data are collected in centres B, F and O). Centre G is close to the DRL in terms of ESK, but further from the DRL in terms of KAP. Centres A, D, I, J, L, N and R are below the DRLs, both in terms of ESK and KAP.



(a) (b)

Figure 25: DRLs, median ESKs (a) and KAPs (b) for chest examinations in the Belgian NICU's; 75th percentile reported in red, 25th percentile reported in green.

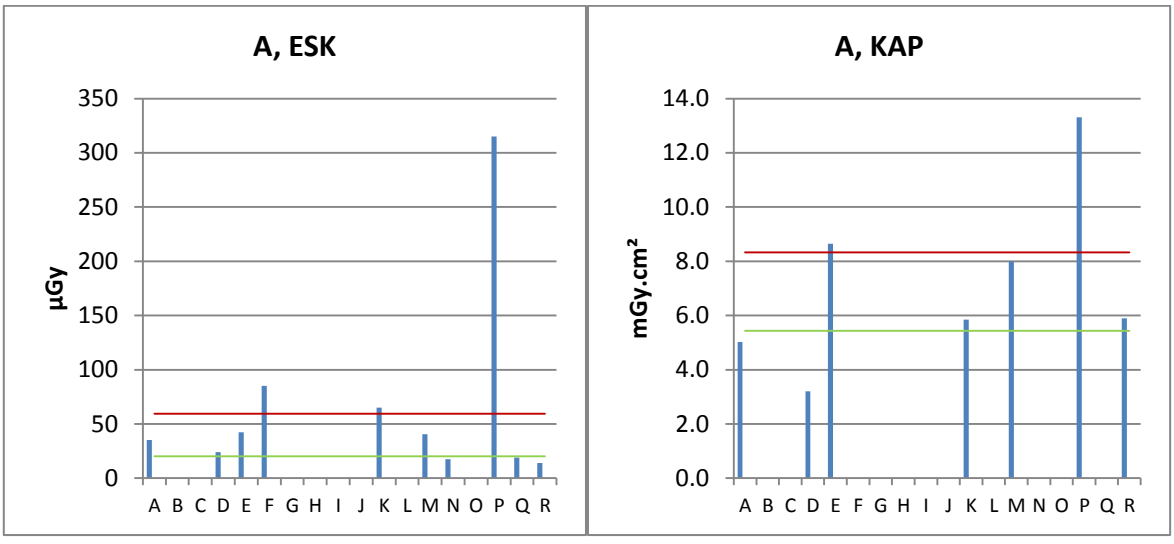
For combined chest-abdomen examinations, centres A, D, J and R are below the DRLs both in terms of ESK and KAP. Centres N, O and Q are also below the DRL in terms of ESK (no KAP data have been collected). Centres E, G, I and P exceed or are close to the DRL both in terms of ESK and KAP. Centre C exceeds the DRL in terms of KAP significantly, although, in terms of ESK, the DRL is not reached. While in centres K and M the opposite is observed: the average ESK exceeds or is close to the DRLs; although in terms of KAP, the DRL is not reached. Centres B and F exceed the DRL significantly in terms of ESK (no KAP data are collected).



(a) (b)

Figure 26: DRLs, median ESKs (a) and KAPs (b) for combined chest-abdomen examinations in the Belgian NICU's; 75th percentile reported in red, 25th percentile reported in green.

For abdomen examinations, centres A, D and R are below the preliminary DRLs both in terms of ESK and KAP. Centres N and Q are also below the DRL in terms of ESK (no KAP data have been collected). Centre M is close to the DRLs both in terms of ESK and KAP. Centre K exceeds the DRL in terms of ESK, although in terms of KAP the DRL is not attained. While in centre E we observe the opposite: the average KAP exceeds the DRL, although in terms of ESK the DRL is not attained. Centre F exceeds the DRL significantly in terms of ESK (no KAP data are collected), while centre P exceeds both DRLs significantly.



(a) (b)

Figure 27: DRLs, median ESKs (a) and KAPs (b) for combined chest-abdomen examinations in the Belgian NICU's; 75th percentile reported in red, 25th percentile reported in green.

In *Figure 25* and *Figure* 27, one can observe centres that exceed the DRL in terms of ESK for chest or combined chest-abdomen examinations, but do not exceed the DRL in terms of KAP, and vice-versa. This can be due to the fact that the field size is taken into account for the KAP, while this is not the case for the ESK. In the centres exceeding only the DRL in terms of KAP, relatively large field sizes are probably being used. As a result of this lack of collimation, some organs are unnecessarily irradiated.

It can be noted that centres B and K, which exceed DRLs for chest, combined chest-abdomen and abdomen examinations, in terms of ESK, work with high mAs settings (observed in the protocol for centre K (*Table 2)* as well as in the collected data (*Figure 10*)). In contrast, in centre A, where similar mAs settings are observed as in centre K, the doses don't exceed any of the DRLs. This can be explained by the considerably smaller tube output measured in centre A (*see Table 3*).

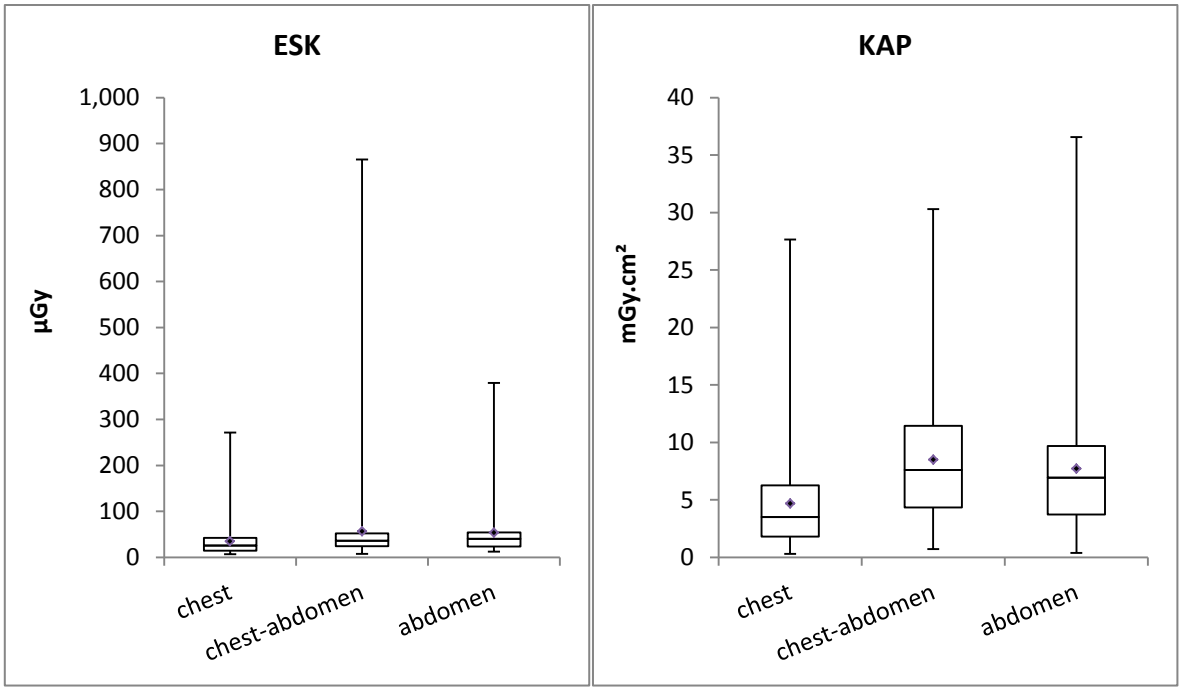
In addition, for centre K, where the doses are amongst the highest, the observed FSD (*see Figure 13*) is also one of the smallest. Surprisingly, in centre N, a lower FSD value is observed without exceeding the DRL. This can be explained by the mAs settings used in this centre, which are more than three times lower than in centre K.

For centre F, the reason for the high doses, exceeding the DRL for chest, combined chest-abdomen and abdomen examinations, is linked to the high tube output of the X-ray system. In centre C, comparable values of tube output are counterbalanced by the use of lower mAs settings and slightly higher FSD.

In centre P, the DRLs are always almost reached or exceeded, one reason is the frequent use of low FSDs. Also a relatively high mAs value contributes to this. As for all 3 examinations the DRL in terms of KAP is mostly exceeded, possibly due to the larger field sizes used.

Comparison of examination types

In *Figure 28*, a direct comparison is made between the 3 types of examinations in terms of ESK as well as in terms of KAP. We can see that for ESK, the median and average doses are comparable for all 3 types. In terms of KAP, slightly higher doses are observed for the combined chest-abdomen examinations, due to a larger field size. The field size used for the abdomen examinations also appears to be larger than the one used for the chest examinations, as confirmed in *Figure 1.*



(a) (b)

Figure 28: Comparison of the three types of examination in terms of ESK (a) and KAP (b)

Total number of examinations

In *Figure 29*, the distribution of the total number of examinations performed on the patients included in the study, during their stay in the NICUs is given for the whole of Belgium.

A large variation in the total number of examinations per patient is observed, even within the same hospital. For most hospitals the maximum number of examinations did not exceed 21, except in hospital E and N, where a maximum of 71 and 46 examinations respectively are observed. Moreover, one can observe that centre E, with 10 patients observed, includes two of the most frequently exposed patients, with 71 and 56 examinations, respectively. From the national distribution, it appears that about half of the patients (47%) underwent less than 5 examinations during their stay. Three-quarter of the patients underwent less than 10 examinations.

To explain the considerable variation in the number of examinations performed between the different centres, an analysis of the underlying pathology of the patients would be of particular interest. Nevertheless, the characterisation of the pathology wasn't collected for all the patients and would probably require the collection of complementary data.

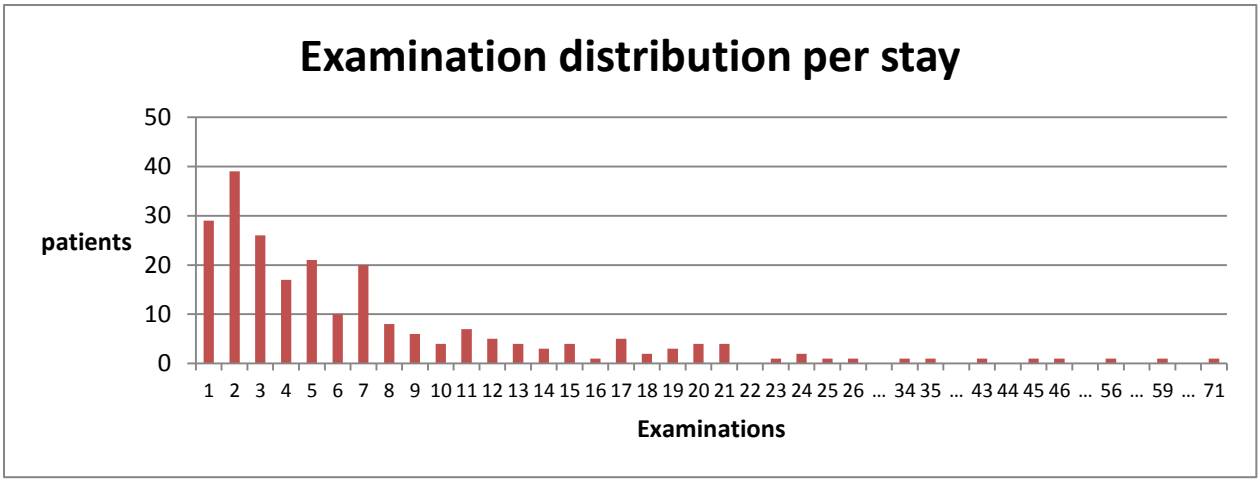


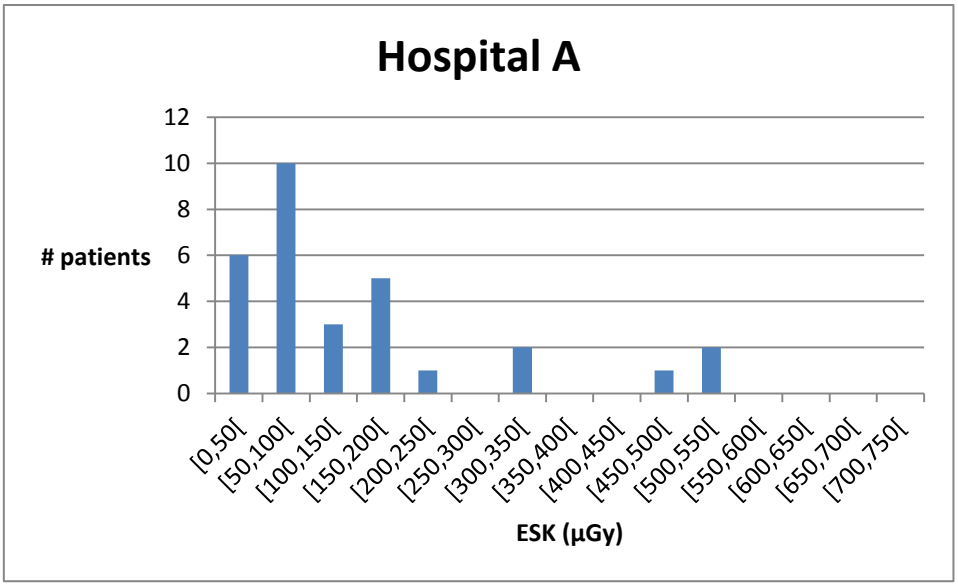
Figure 29: Overview of the total number of examinations per individual stay in all hospitals

Cumulative ESK (ESK_{tot})

The information from *Figure 29* is used to estimate the cumulative ESK for the patients included in the study. As expected, a wide spread in the cumulative ESK is found. Median values per hospital range from 39 up to 540 µGy.

As the cumulative ESK is based on the total number of examinations per stay and on the ESK per individual examination, it can be expected that hospitals showing high doses per examinations and/or high examination frequency will have high values of cumulative ESK. Logically, this is observed in hospitals E and K, which show the highest cumulative doses. In hospital E, the number of examinations is the highest; while in hospital K one of the highest ESK was estimated per procedure. Contrary to that, hospitals D, Q and R, where low ESK per examination and low examination frequencies are found, show low cumulative doses. In hospital A, the relatively high ESK per examination is compensated by a low examination frequency, resulting in relatively low cumulative ESK. In *Figure 30* (a to l), the distribution of the cumulative ESK per hospital is given.

The percentage of patients receiving a cumulative ESK inferior to 50 µGy, amounts to 22%; for a cumulative ESK inferior to 150 µGy, this percentage increases to 52%. Less than 6% (13 out of the 232 patients), received a cumulative ESK superior or equal to 1 mGy.


Hospital A
patients
12
10
8
6
4
2
0
[0,50[
[50,100[
[100,150[
[150,200[
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[250,300[
[300,350[
[350,400[
[400,450[
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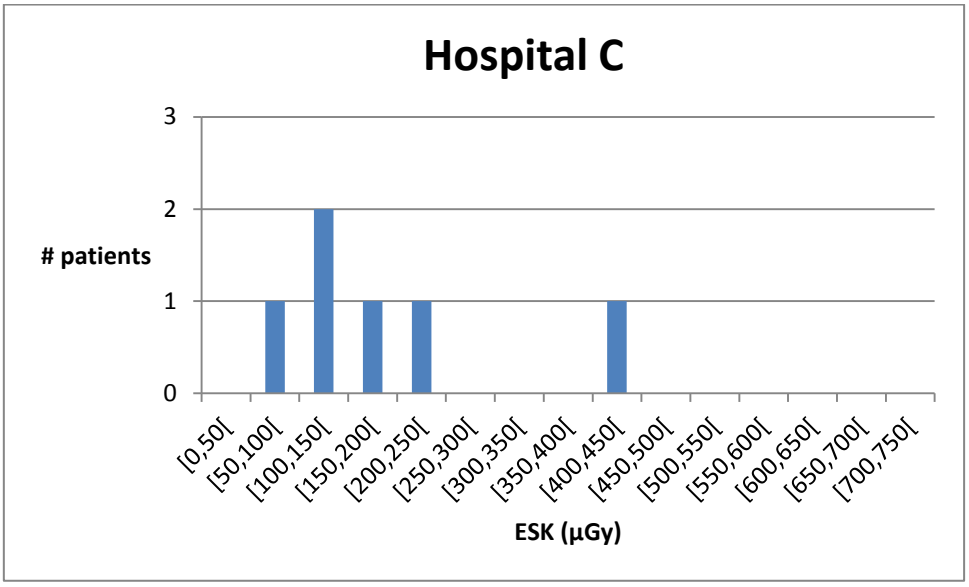
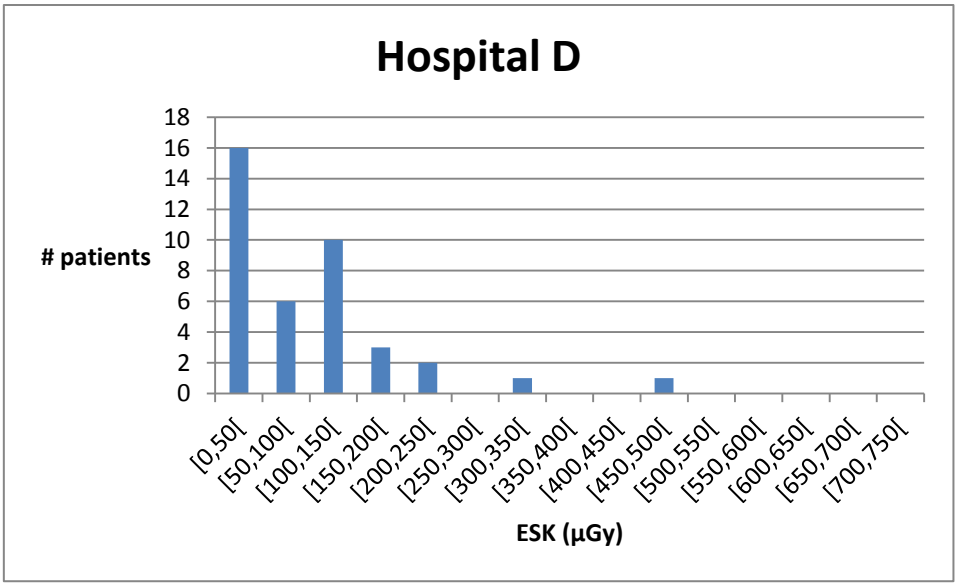
[650,700[
[700,750[
ESK (µGy)

(a)


Hospital C
patients
3
2
1
0
[0,50[
[50,100[
[100,150[
[150,200[
[200,250[
[250,300[
[300,350[
[350,400[
[400,450[
[450,500[
[500,550[
[550,600[
[600,650[
[650,700[
[700,750[
ESK (µGy)

(b)


Hospital D
patients
18
16
14
12
10
8
6
4
2
0
[0,50[
[50,100[
[100,150[
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[350,400[
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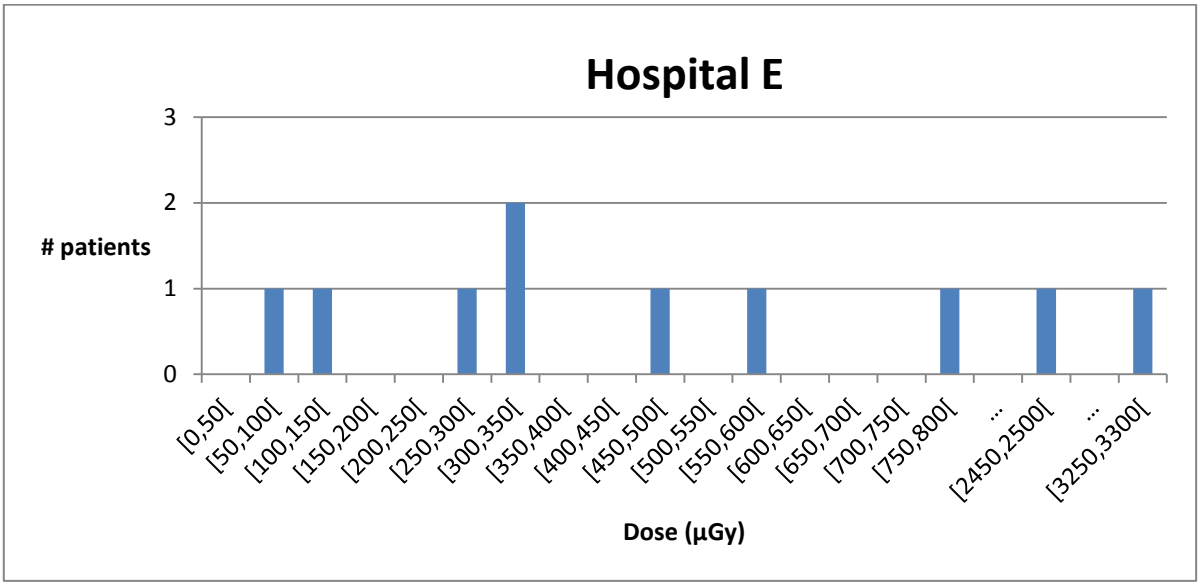
[650,700[
[700,750[
ESK (µGy)

(c)


Hospital E
patients
3
2
1
0
[0,50[
[50,100[
[100,150[
[150,200[
[200,250[
[250,300[
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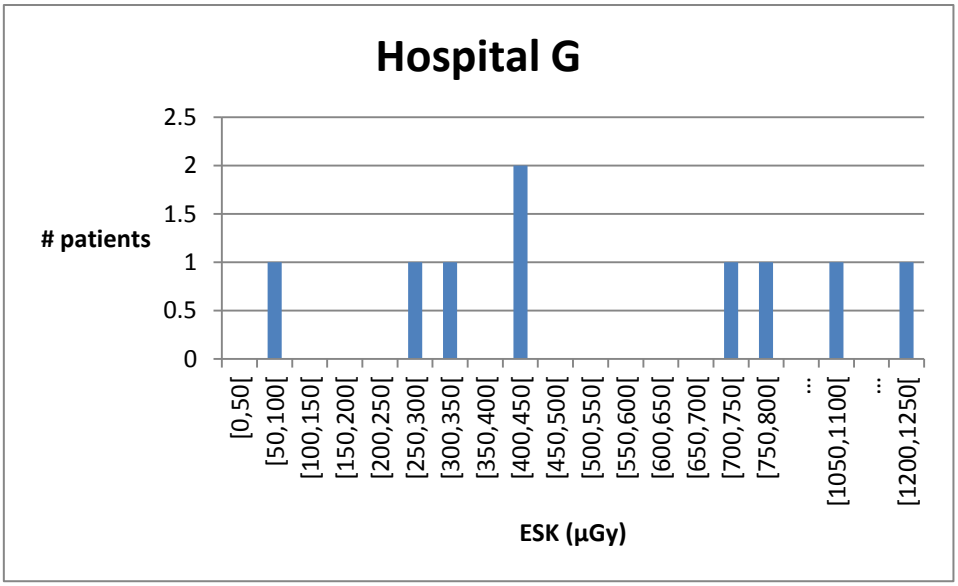
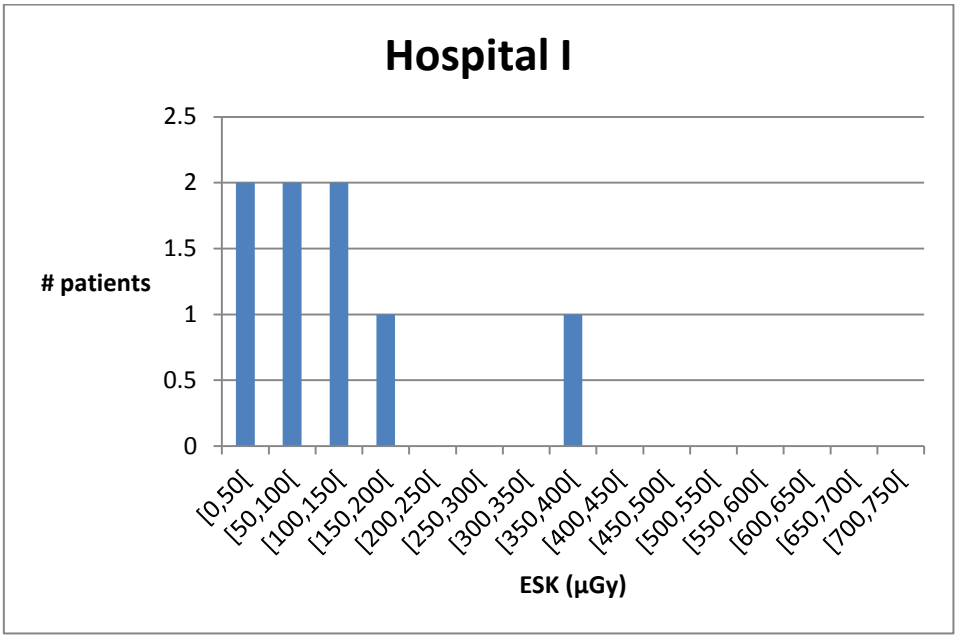
[400,450[
[450,500[
[500,550[
[550,600[
[600,650[
[650,700[
[700,750[
[750,800[
...
[2450,2500[
...
[3250,3300[
Dose (µGy)

(d)


Hospital G
patients
2.5
2
1.5
1
0.5
0
[0,50[
[50,100[
[100,150[
[150,200[
[200,250[
[250,300[
[300,350[
[350,400[
[400,450[
[450,500[
[500,550[
[550,600[
[600,650[
[650,700[
[700,750[
[750,800[
...
[1050,1100[
...
[1200,1250[
ESK (µGy)

(e)


Hospital I
patients
2.5
2
1.5
1
0.5
0
[0,50[
[50,100[
[100,150[
[150,200[
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[250,300[
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[350,400[
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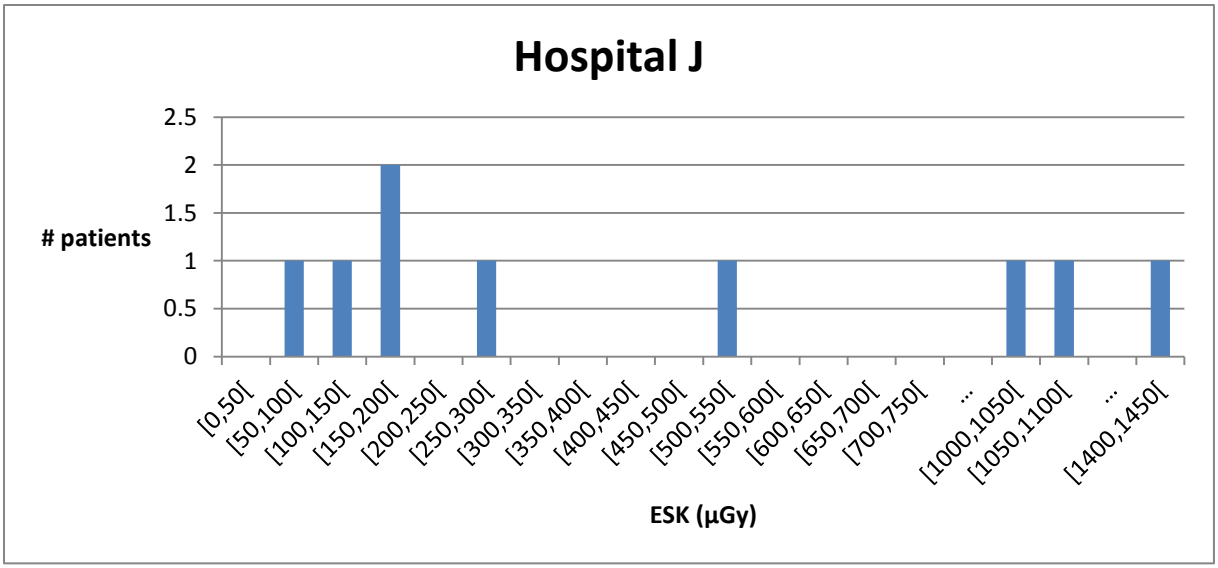
[650,700[
[700,750[
ESK (µGy)

(f)


Hospital J
patients
2.5
2
1.5
1
0.5
0
[0,50[
[50,100[
[100,150[
[150,200[
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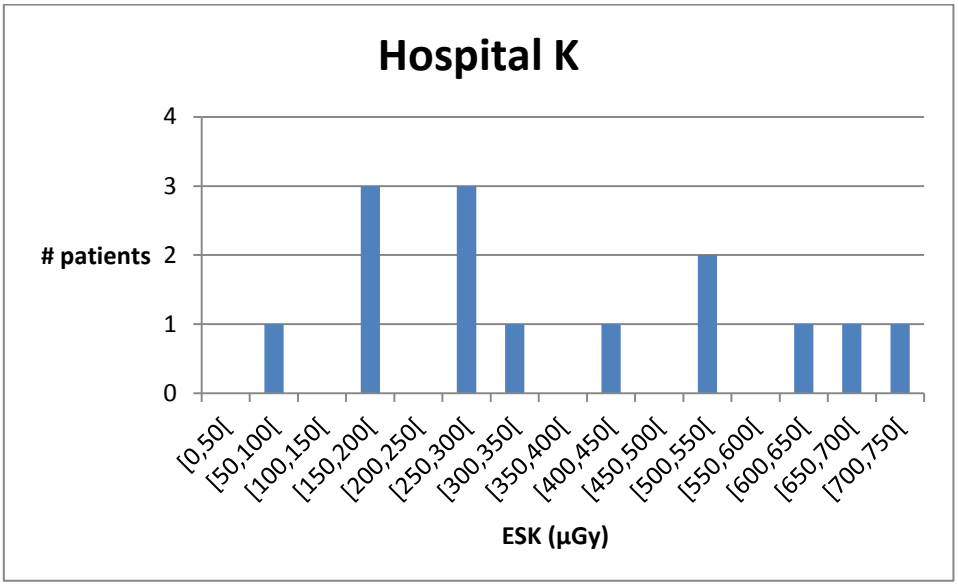
[450,500[
[500,550[
[550,600[
[600,650[
[650,700[
[700,750[
...
[1000,1050[
[1050,1100[
...
[1400,1450[
ESK (µGy)

(g)


Hospital K
patients
4
3
2
1
0
[0,50[
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[100,150[
[150,200[
[200,250[
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[350,400[
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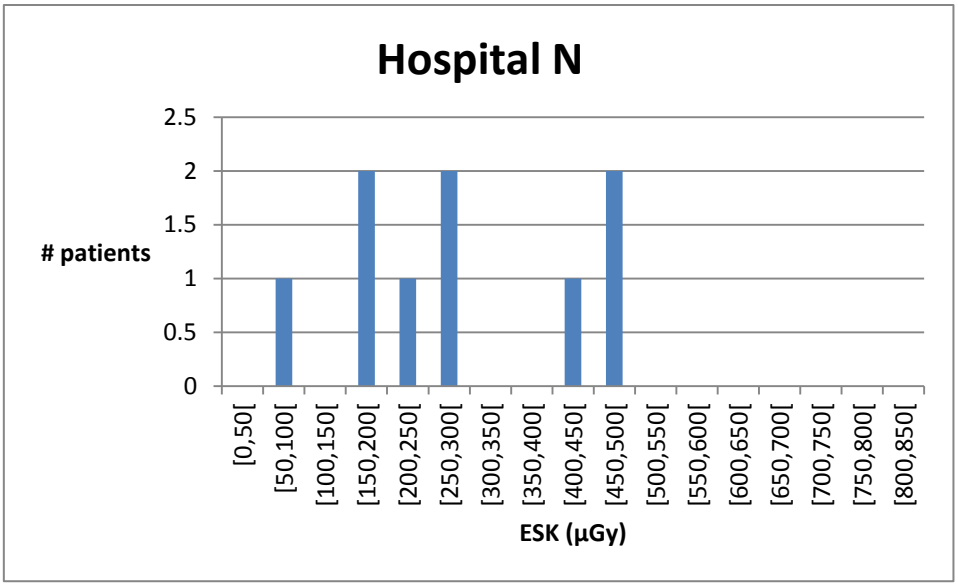
[650,700[
[700,750[
ESK (µGy)

(h)


Hospital N
patients
2.5
2
1.5
1
0.5
0
[0,50[
[50,100[
[100,150[
[150,200[
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[250,300[
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[450,500[
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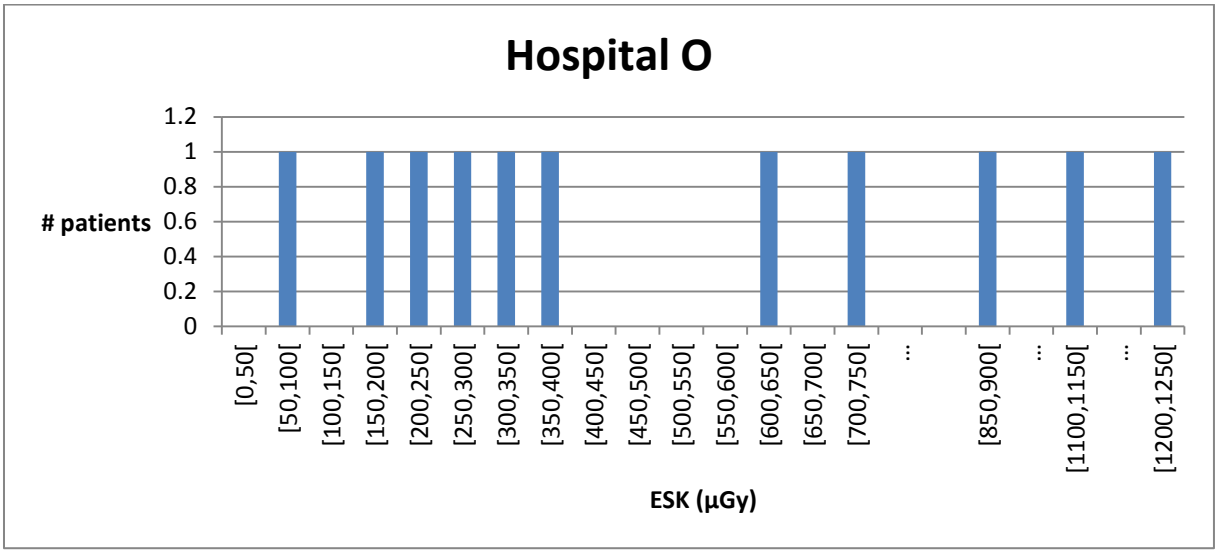
[750,800[
[800,850[
ESK (µGy)

(i)


Hospital O
patients
1.2
1
0.8
0.6
0.4
0.2
0
[0,50[
[50,100[
[100,150[
[150,200[
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[600,650[
[650,700[
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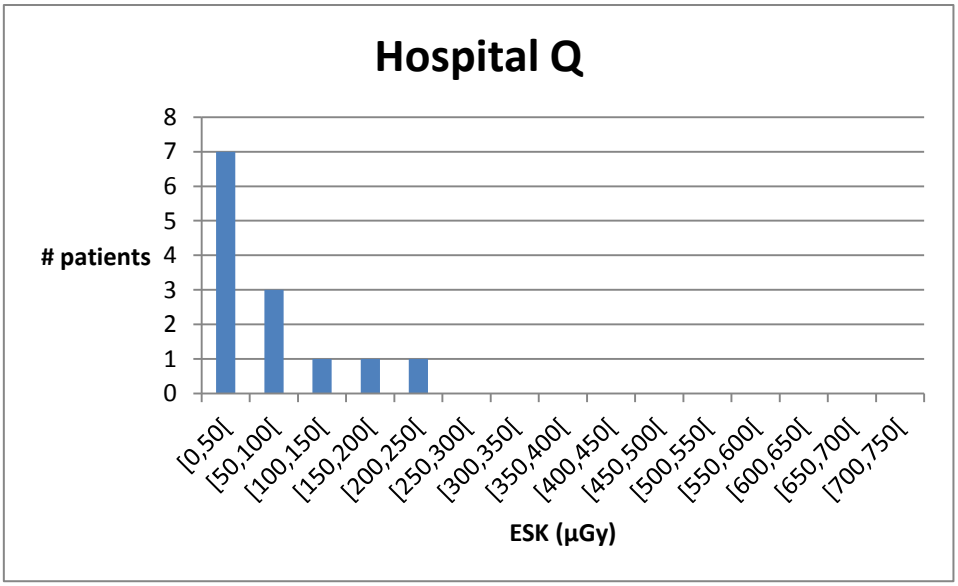
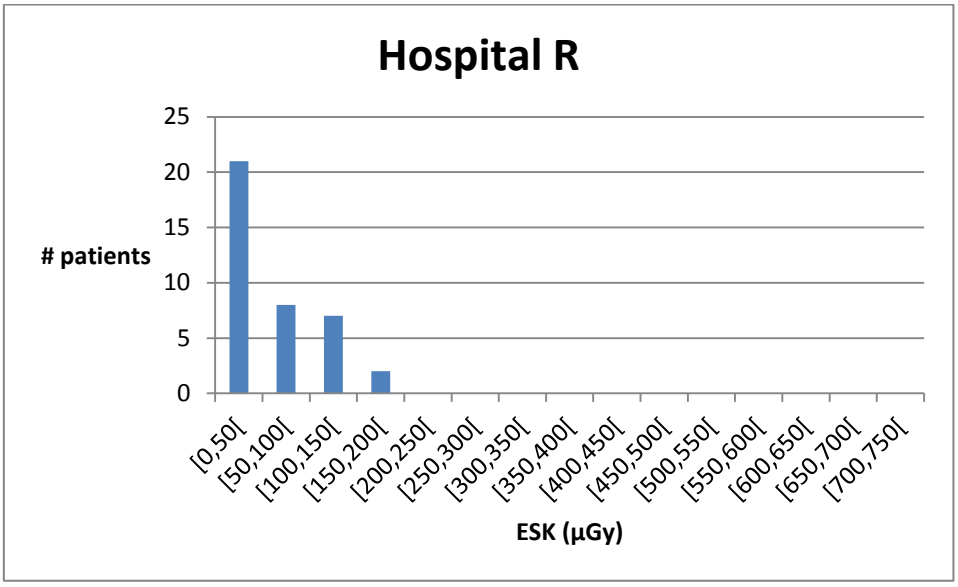
...
[850,900[
...
[1100,1150[
...
[1200,1250[
ESK (µGy)

(j)



(k)



(l)

Figure 30: Cumulative ESK distribution per hospital

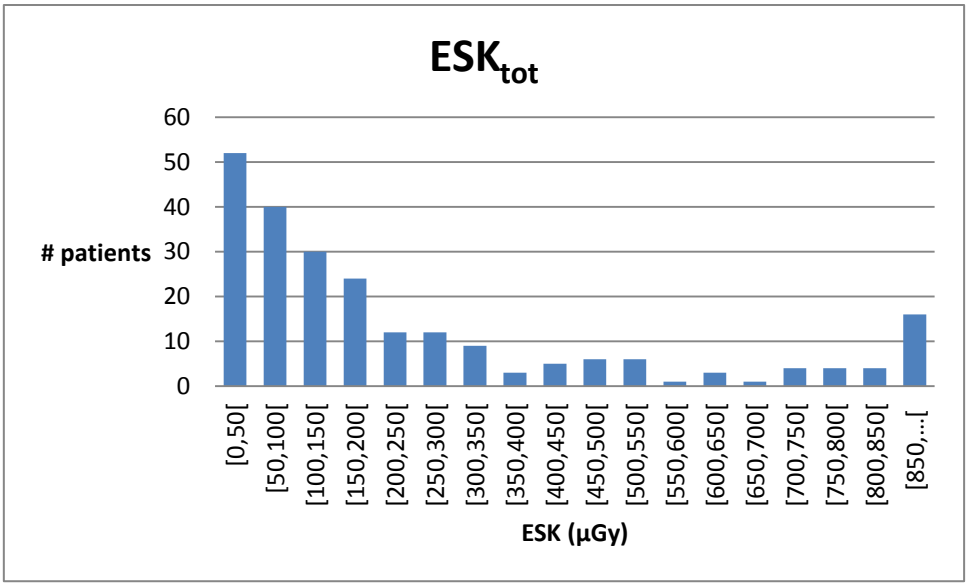


Figure 31: Cumulative ESK distribution at the Belgian level

Cumulative organ doses

Figure 32 gives the distribution of the cumulative doses for some organs of interest for the whole of Belgium. This distribution consists of the data of 109 patients from 6 centres (A, E, J, K, M and N).

The percentage of patients that received a dose to the thyroid superior or equal to 50 µGy amounts to 19%; while, for the red bone marrow, the colon and the lungs, this percentage increases to 32, 70 and 83% respectively. Nearly all the patients (97%) received a dose to the breast superior to 50 µGy.

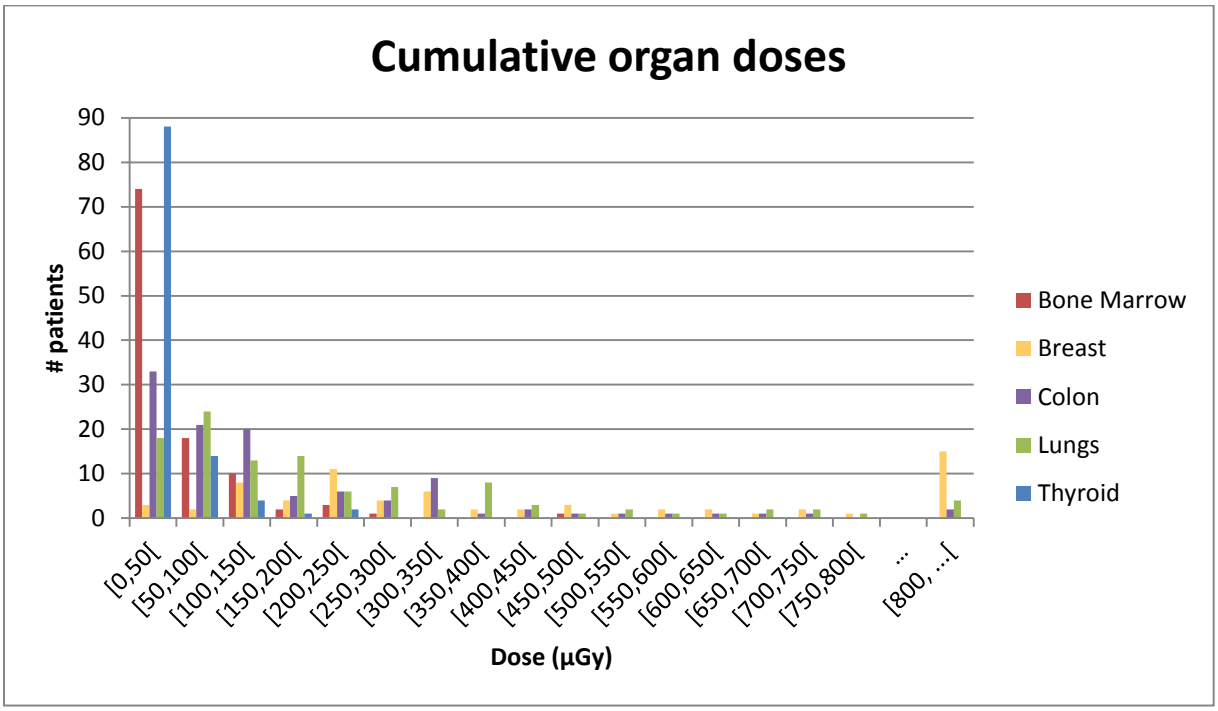
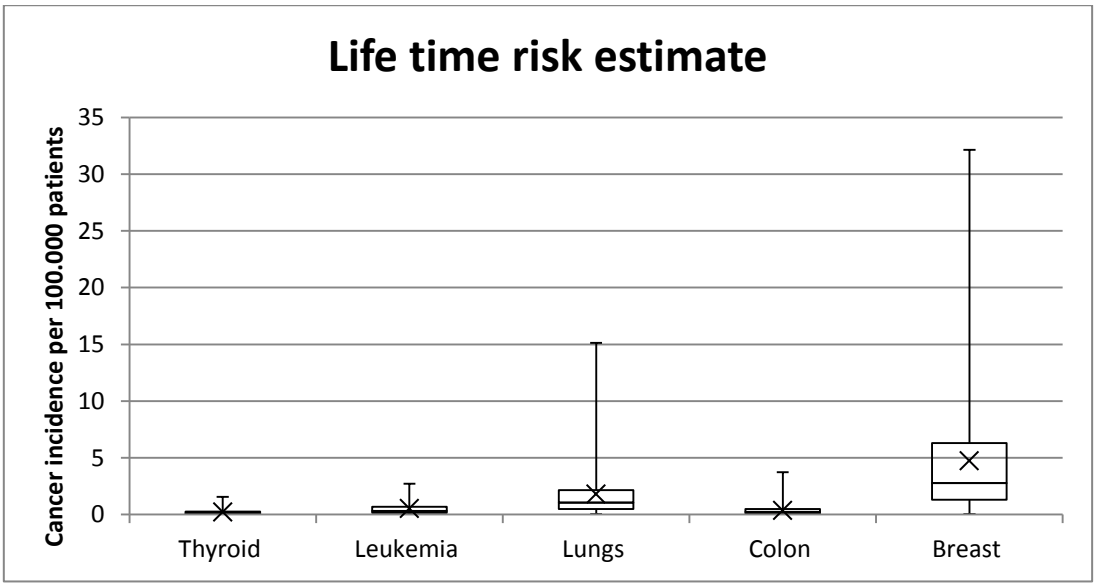


Figure 32: Cumulative organ doses distribution at the Belgian level

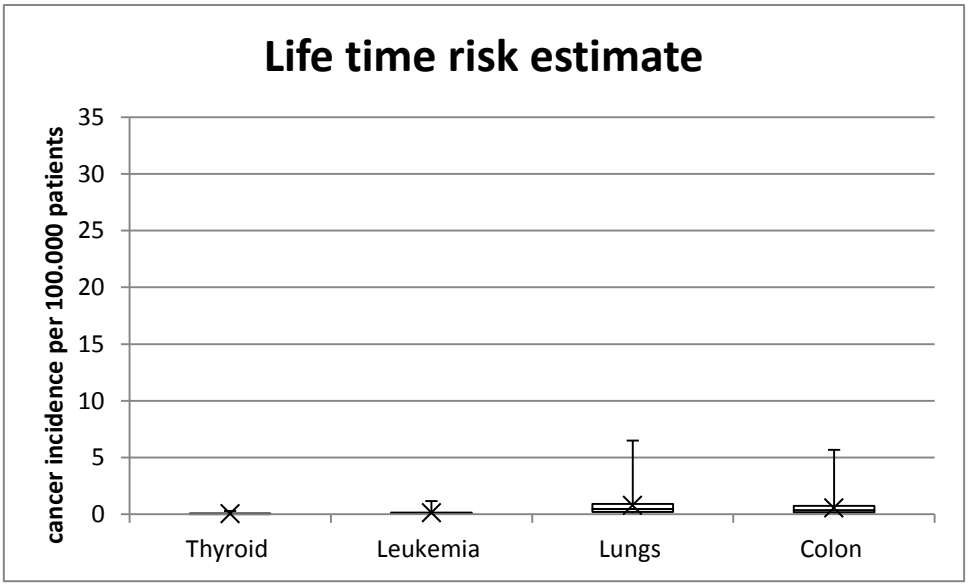
Risk assessment

The lifetime risk estimate for cancer incidence per patient's stay in the NICU was calculated for various cancers (leukaemia, breast - for female patients only - , colon, lungs and thyroid cancer). The estimates were performed for the cumulative organ doses per individual patient's stay. These were calculated for 109 patients, from 6 centres (A, E, J, K, M and N). As the sex of the patients had not been registered, the risk estimates were evaluated twice: all 109 patients were successively considered to be female (*Figure 33 (a)*) and then male *(Figure 33 (b)).*

For a specific cancer type, a large variation of cancer incidence is observed, owing to the broad distribution of the cumulative organ doses per patient's stay. Median values of cancer incidence per 100.000 patients equal 0.08, 0.34, 0.45 and 0.02 for leukaemia, colon, lung and thyroid cancers for male patients, respectively; median values equal 0.31, 2.76, 0.22, 1.04 and 0.13 for leukaemia, breast, colon, lung and thyroid cancers for female patients, respectively. For male patients, the largest risks are clearly the colon and lung cancers, while for female patients the largest risks are the lung and the breast cancers. Indeed, the lungs and breast are totally within the radiation field when chest or combined chest-abdomen examinations are performed (which represent 90% of all collected examinations); the colon is totally within the radiation field when combined chest-abdomen or abdomen examinations are performed (40% of all collected examinations). In addition, lungs and colon, and lungs and breast are the most sensitive organs for male and female (15), respectively.



(a)



(b)

Figure 33: Life time risk estimate for incidence of various cancers per 100.000 patients: leukaemia and breast, colon, lung and thyroid cancer for female patients (a); leukaemia and colon, lung and thyroid cancers for male patients (b).

To gain an insight into global radio-induced cancer risks resulting from all radiographs performed during an individual patient's stay in the NICU, the life time risk estimates of the aforementioned cancers are summed and presented in *Figure 34*. As described earlier, all neonates were successively considered to be female and then male. On average, female patients have 5 times more chances to develop one of the cancers specifically considered in the study as a result of the examinations performed in the NICU. One explanation is that breast cancer, incidence is particularly high for female patients and it is considered to be negligible for male patients.

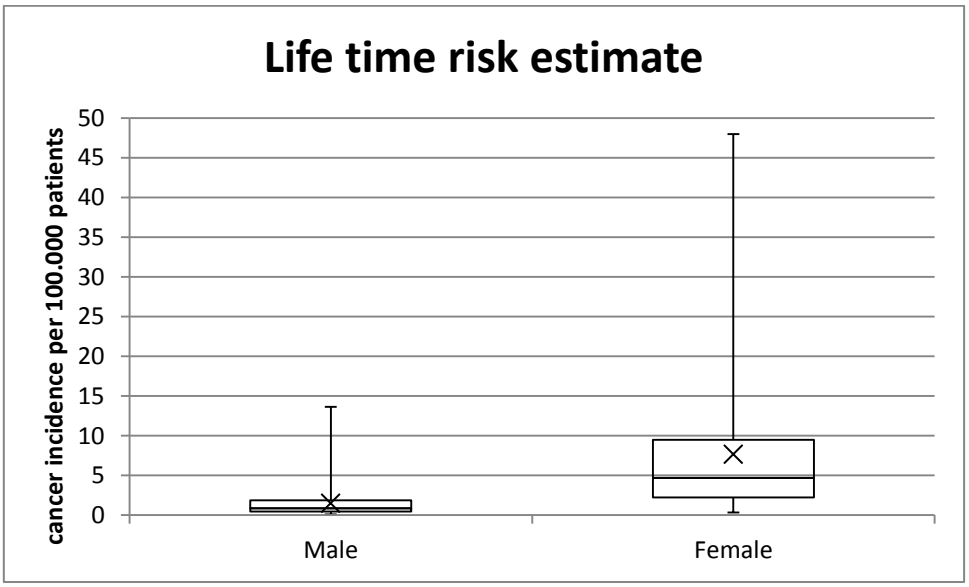


Figure 34: Sum of the life time risk estimates for various cancers per 100.000 patients: leukaemia and colon, lung and thyroid cancers for male patients; leukaemia and breast, colon, lung and thyroid cancer for female patients.

Conclusion

Between the centres, a wide variation of estimated doses is observed. This is caused by a large variation in examination settings, both in the protocols and in daily practice. The distance between focus and detector also varied significantly. Moreover, a large variation was observed in tube output for the different X-ray systems. This indicates that there are ample opportunities for optimisation of the practices. By establishing and using DRLs, the average dose of all centres was compared. Centres that exceeded the respective DRLs have a possibility to change the working procedures to lower the doses. Having a DRL both in terms of ESK and KAP gives us extra information. A lack of collimation of the radiation field can also be detected. A lack of collimation is common practice and is unacceptable in paediatrics.
The DRL in terms of KAP can only be used in practice for X-ray systems with well calibrated KAP-meters, with calibration factors within the range of [0.80, 1.20]. All KAP-meters should be calibrated - at least - annually.

The large variation in the number of examinations performed on a patient during its stay in the NICU was also important, resulting in a large variation in cumulative ESK and organ doses. Further investigation is needed on how the number of examinations is related to the underlying pathology. Cumulative entrance surface kerma could amount up to 540 µGy. The highest doses are delivered to the breasts (up to 95 µGy) for chest and combined chest-abdomen examinations and to stomach (up to 57 µGy) for the abdomen examinations. The dose to the thyroid is of the order of a few micro grays for the chest and combined chest-abdomen examinations. The red bone marrow also received a few micro grays for chest and abdomen examinations. For the combined chest-abdomen examination, the red bone marrow dose could reach up to 12 µGy. An important variation of the risk estimates for various cancer types was also found owing to the variation in the examination frequency and ESK. The principal organs at risk of radio-induced cancers are colon and lungs for male patients and, breast and lung for female patients. On average, female patients are about 5 times more likely to develop one of the cancers specifically considered in the study (leukaemia, breast, colon, lungs and thyroid cancer) than male patients.

One of the limitations of the study is the lack of image quality evaluation. If any optimisation of technical parameters is performed, image quality is an important factor to take into account, aside from the patient dose.

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