EFFECTIVE DOSES TO STAFF AND DOSE RATES EMITTED FROM PATIENTS UNDERGOING POSITRON EMISSION TOMOGRAPHY UTILIZING ^{18}F-FLUORODEOXGLUCOSE

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Abstract

Introduction: The purpose of this two--folded quantitative study was to determine the radiation doses received by staff during 2014 at the PET--department at St. Olavs Hospital in Trondheim, Norway. Although studies show that the doses received by staff performing such examinations are far beneath the limits set by regulation, there was a need to determine how much radiation the staff at this clinic actually was exposed to. We investigated in detail both dose rates emitted by ^{18}F from different parts of the body to the surroundings along with effective doses to staff during 2014.

Method: **Part one** - Dose rates from 20 patients undergoing FDG-PET/CT--scans were measured with dosimeter RadEye B20 (Thermo Scientific, USA) from five measuring points at three different stages of a standard whole body PET-scan utilizing ^{18}F-FDG.

Part two - Effective doses to five radiographers and four bioengineers were registered daily during 2014. The effective dose measurements were done daily by the staff with personal dosimeter RadEye EPD MK2+ (Thermo Scientific, USA). The dosimeter was worn at chest level. The automatic injector Medrad Intego (Bayer, Germany) administrate the radioactive doses.

Results: Part one - Dose rates emitted from different parts of patients show significant differences. The highest dose rate was measured from the head and sternum of the patients. The knees emit the least dose rate of all body parts and was considerably lower from one meter distance.

Part two - The average effective doses were far below the recommended limits for occupational radiation. The total average effective dose per member of staff was 0.13 mSv in 2014 and the

daily average dose was 4.91 μSv/day.

Conclusion:

Part one- ^{18}F-FDG showed irregular distribution in the body, the lowest dose rates originated from the lower extremities and reflects the metabolism of glucose in the body at rest.

Part two - We found significant differences between staff working with both CT and the radioisotope injection compared to the staff working solely with one of these tasks. Nevertheless, all effective- doses were safely within the guideline limits for occupational radiation.

Introduction

PET - Positron Emission Tomography

There has been an astonishing advance in PET technology since the concept was conceived in the 1950s [1] until today's modern hybrid and digital systems. Today we combine PET with Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) to produce detailed images of high diagnostic value. The technology is mainly used for cancer and metastasis imaging, but also proves useful for diagnostics in patients with Alzheimer's disease, infections, cardiac diseases, epilepsy and stroke [2].

St. Olav's Hospital in Trondheim was the first hospital in Norway to install PET/MRI and will eventually establish it's own dedicated cyclotron. Currently, the PET department at St. Olavs Hospital run examinations twice a week, with an average of six patients per day [3]. The radioactive tracers are produced in a cyclotron facility located in Oslo and are delivered daily to the department. The examinations are planned and carried out by bioengineers and radiographers. The working tasks include preparation/administration of the radioisotope ^{18}F-FDG - and operating the scanners. Most of the staff work solely with one of these tasks, while some switch between both tasks.

Ionizing radiation

Although the modality has vast diagnostic potential, it causes exposure of ionizing radiation for both patients and technologists. Ionizing radiation can be harmful and is affected by the absorbed dose, measured in gray (Gy). Sievert (Sv) is another measuring unit that describes the effective dose and the equivalent dose. Effective dose is a way of measuring ionizing radiation on behalf of potential harmful damage. Sievert takes into account both the type of radiation and the tissue weighting factor of the organ it is applied to [4]. Calculations have been made which show that with every absorbed unit of Sievert the body absorbs, the risk of developing cancer increases by about 5% [5 p.12]. The recommended annual limit for occupational radiation exposure in Norway is 20 mSv [6]. Although several studies confirm that the effective doses to such staff are far below these limits [7-16], further optimization on lowering exposure is recommended, following the ALARA-principle (As Low As Reasonably Achievable) [17 p.12].

^{18}F-Fluodeoxyglucose

^{18}F is the most commonly used radioisotope at PET examinations [2]. The isotope decays with a mean energy of 0.63 MeV which in turn produces photons with an energy of 511 keV. The half-life of the isoptope is 109.8 minutes and the HVL (Half Value Layer) is 4.1 mm lead [18]. These attributes requires a different approach when planning for radiation protection, compared to other radiographic examinations like CT scans or X-rays.

Prior Research

Effective doses to staff have declined during the last two decades. The values have descended from 5.5 µSv/examination to 2.43 µSv/examination [7-10, 13-16]. The implementation of injection robots have contributed to these improvements. The automatic injectors give several benefits including less hazards when handling the material, lowered staff dose and a more precise dose administration. Another main factor contributing to the variation in effective dose is the amount of radioisotope injected into the patient [7-16]. The total injection dose on examinations have declined due to the fact that injection dose are currently calculated according to the patient´s weight instead of the former fixed dose. The procedure at St. Olavs Hospital currently recommends 4 MBq/kg for a full body examination. Other reasons for lower injection doses are mainly due to better PET-systems with better PET detectors with higher sensitivity and better overall performance characteristics.

Aim

The aim of this study was to determine the radiation dose rates emitted from patients undergoing whole body FDG-PET examinations and the effective doses to staff working at the PET-department at St. Olavs Hospital during the facility's first year of operation. We looked at how the staff may optimize working routines to lower radiation doses in the future by assessing how ^{18}F-FDG was distributed in the body during examination.

Methods

Design

In order to address the aforementioned concerns we have split this descriptive quantitative study into two separate parts.
Part one consists of measurements of dose rate emitted from patients to the surroundings during different stages of a standard whole body PET-scan.
Part two consists of measurements of effective doses to the staff utilizing an injection robot.

Sample selection

Part one - Twenty patients undergoing whole body PET-scans volunteered to participate in the study. ^{18}F-FDG was prescribed as the radioactive tracer for all patients.

Part two - Five radiographers and four bioengineers working at the facility volunteered to enter the study. Values registered before and after 2014 and examinations done manually with the radiotracer 18F-FACBC were excluded from the study.

Approach

Part one - The participants were measured from five different points at three different stages. The measurements were conducted using RadEye B20 (Thermo Scientific, USA). All measurements showed mean dose rates and were measured at least 15 seconds. The following data were registered in an Excel spreadsheet: i) participant number, ii) height, iii) weight, iv) injection dose and v) mean dose rates from the following points; i) forehead, ii) sternum, iii) urinary bladder, iv) the knees and v) 1 meter vertically from the sternum in a supine position. All measurements were done directly onto the respective body parts, apart from the last measuring point. The following stages of the examination were measured: i) immediately after administration of radioisotope, ii) one hour after and iii) post-scan (directly after the PET/CT-scan was completed).

Part two - Daily radiation exposures to staff were continuously registered since the opening of the facility during the autumn of 2013. Effective doses were measured using personal dosimeter RadEye EPD MK2+ (Thermo Scientific, USA). The dosimeters were worn at chest level. The injections were administered by Medrad Intego injection robot (Bayer, Germany).

We also investigated the possible differences between professions and working tasks. The following data from staff were registered: i) profession, ii) working task, iii) date of measurement, iv) the frequency of measurements and v) the effective dose as measured. The descriptive analysis included i) total mean effective dose, ii) individual mean effective dose iii) differences between the two professions and iv) differences between working tasks

The difference between groups were compared using student t-test and ANOVA-analysis. The significance level was set to 0.05. The data material was analyzed descriptively and prepared graphically using Microsoft Excel 2011 (version 14.4.9, Microsoft Inc., USA) and IBM SPSS 22.0 (International Business Machines Corporation, USA).
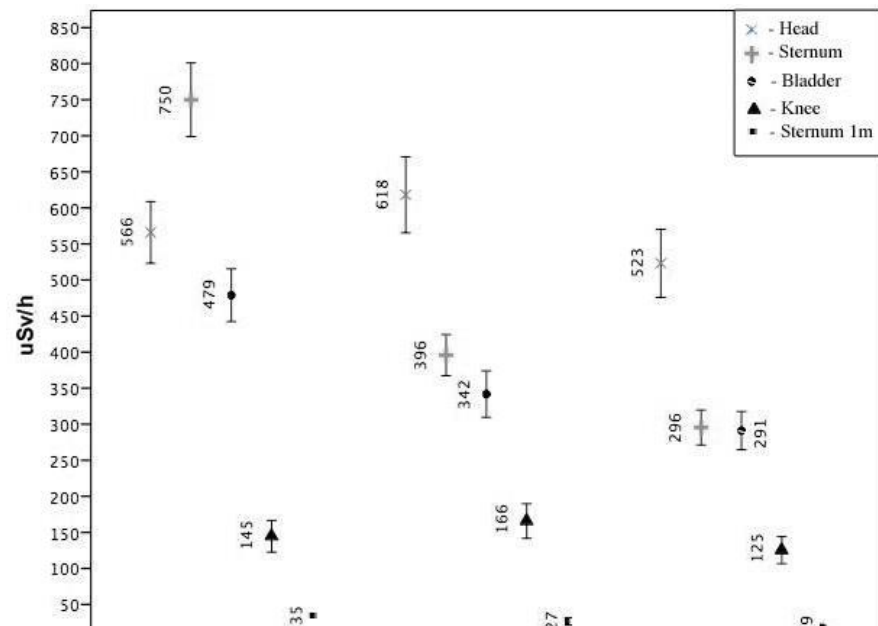
The study's ethical grounds were considered upon commencement. An application for these ethical considerations were evaluated and approved by the Regional Committees for Medical and Health Research Ethics. All participants received necessary information about the study through an informative letter along with a short presentation of the approach. The participants were informed that no disadvantages would follow after participating in our study. No sensitive personal details were registered that could identify the respective individuals. The participants could resign from the study at any given point without giving a specific reason for this.

Results

Part one

The dose rate was substantially higher from the head and sternum and considerably lower from the knee (figure 1, table 1). At one meter distance the dose rate was drastically lower. The dose rate varies from sternum and head during distribution of ^{18}F-FDG (has a high standard deviation), as the sternum is closer to a larger blood volume containing radioactivity.

Figure 1: Dose rate (µSv/h) from head, sternum, bladder, knee and one meter from the sternum in supine position in selected stages i) Administration, ii) one hour after administration of the radioisotope and iii) post-scan. Error flags represent the 95 % confidence interval (n=20).

Head and sternum also showed the largest dose variation during the different stages, falling to a much lower lever after administration, indicating radioactive decay. Table 2 demonstrates the difference between measuring points. We found significant differences between all points apart from between the sternum and bladder after 60 min.

Measuring point	Stage	Mean dose rate (µSv/h) ±
Head	Administration	565.90 ± 91.47
	60 min	618.15 ± 112.60
	Post scanning	523.15 ± 100.90
Sternum	Administration	749.95 ± 109.00
	60 min	395.85 ± 60.98
	Post scanning	295.55 ± 51.76
Bladder	Administration	478.90 ± 77.93
	60 min	341.85 ±68.86

	Post scanning	291.15 ± 56.71
Knee	Administration	144.67 ± 46.89
	60 min	165.75 ± 51.24
	Post scanning	125.35 ± 39.82
1m from sternum	Administration	34.76 ± 4.52
	60 min	26.55 ± 10.67
	Post scanning	19.27 ± 2.83

Table 1: *Dose rate (µSv/h) from measuring points at different stages*

Administration	Head (µSv/h)	Sternum (µSv/h)	Bladder (µSv/h)
Sternum	-184 $p > 0.001$		
Bladder	87 $p = 0.0025$	271 $p > 0.001$	
Knee	421.2 $p > 0.001$	605.3 $p > 0.001$	334.2 $p > 0.001$
60 min	Head	Sternum	Bladder
Sternum	222.3 $p > 0.001$		
Bladder	276.3 $p > 0.001$	54 $p = 0.013$	
Knee	452.4 $p > 0.001$	230.1 $p > 0.001$	176.1 $p > 0.001$
Post-scan	Head	Sternum	Bladder
Sternum	227.6 $p > 0.001$		

| Bladder | 232 p > 0.001 | 4.4 p = 0.8 | |
| Knee | 397.8 p > 0.001 | 170.2 p > 0.001 | 165.8 p > 0.001 |

Table 2: Differences in dose rate between measuring points at different stages (µSv/h) (n=9).

Part two

Table 3 shows that the total daily dose averaged 4.91 µSv/day. Among the nine participants the total average annual dose was 0.13 mSv. This resides far beneath the annual limit of 20 mSv set by Norwegian regulatory authorities [6].

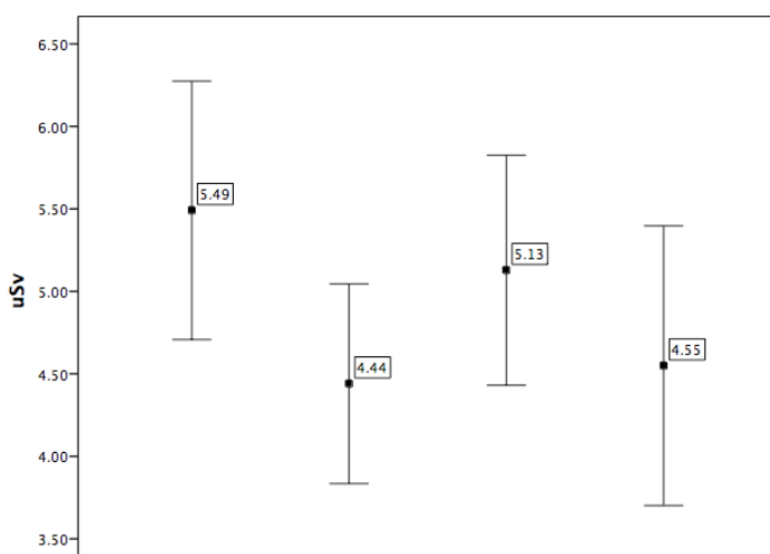| Quarter	Total effective dose (µSv)	Mean effective dose (µSv)	SD
Q1	313	5.5	± 3.0
Q2	222	4.4	± 2.1
Q3	400	5.1	± 3.1
Q4	323	4.6	± 3.6
Sum	**1258**	**4.9**	**± 3.0**

Table 3: Annual effective in 2014 (n=9)

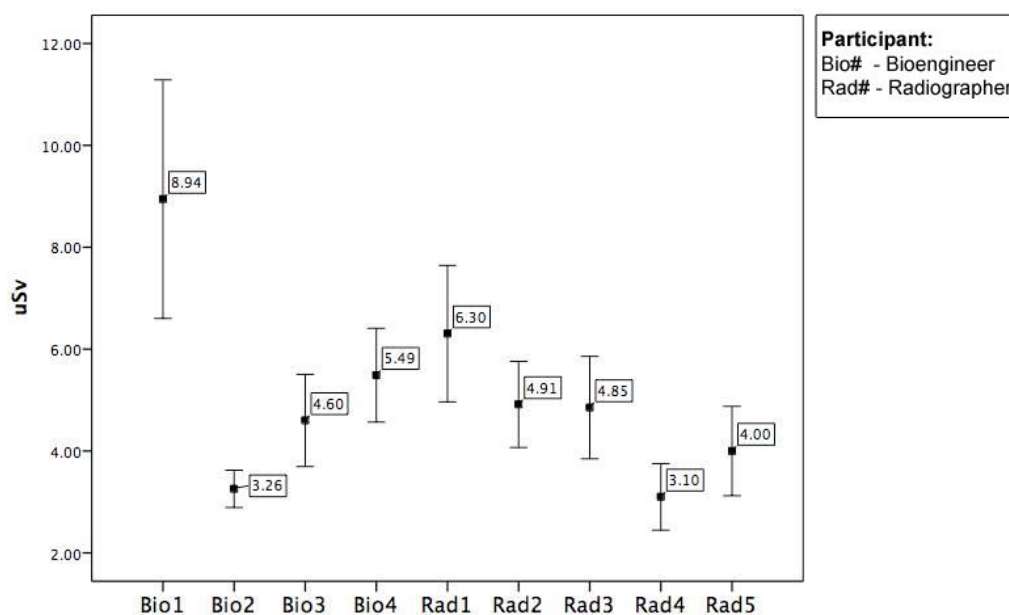*Figure 2: Mean daily effective dose for each quarter of 2014 (µSv/day). Error flags represent the 95% confidence interval (n =9).*

Figure 3: Individual mean effective dose (µSv/day). Error flags represent 95 % confidence interval (n= 9).

Table 4 shows the daily mean effective dose on an individual basis. There were few missing values and the data material is considered complete. The reason for blank cells in some of the sections below is due to the time the individual started working at the facility.

Participant	Q1 (µSv/day)	Q2 (µSv/day)	Q3 (µSv/day)	Q4 (µSv/day)
Bioengineer 1		7.0 ± 4.2	9.7 ± 3.0	8.8 ± 6.0
Bioengineer 2	3.3 ± 1.0	4.0 ± 1.1	3.3 ± 1.0	2.5 ± 0.9
Bioengineer 3			5.2 ± 1.5	4.0 ±0.7
Bioengineer 4	5.5 ± 3.5	4.3 ± 1.8	5.6 ± 3.4	6.2 ± 2.7
Radiographer 1	4.3 ± 0.6	5.0 ±1.4	7.1 ± 3.0	8.7 ± 6.0
Radiographer 2	6.4 ± 3.0	5.0 ± 2.5	5.1 ± 4.2	3.3 ± 1.1
Radiographer 3	7.8 ± 2.3	5.1 ± 2.4	4.6 ± 2.0	3.4 ± 3.0
Radiographer 4	4.6 ± 1.6	2.3 ± 1.3	2.8 ± 1.9	2.8 ± 1.3
Radiographer 5		4.0 ± 0.0	4.2 ± 1.6	3.5 ± 1.7

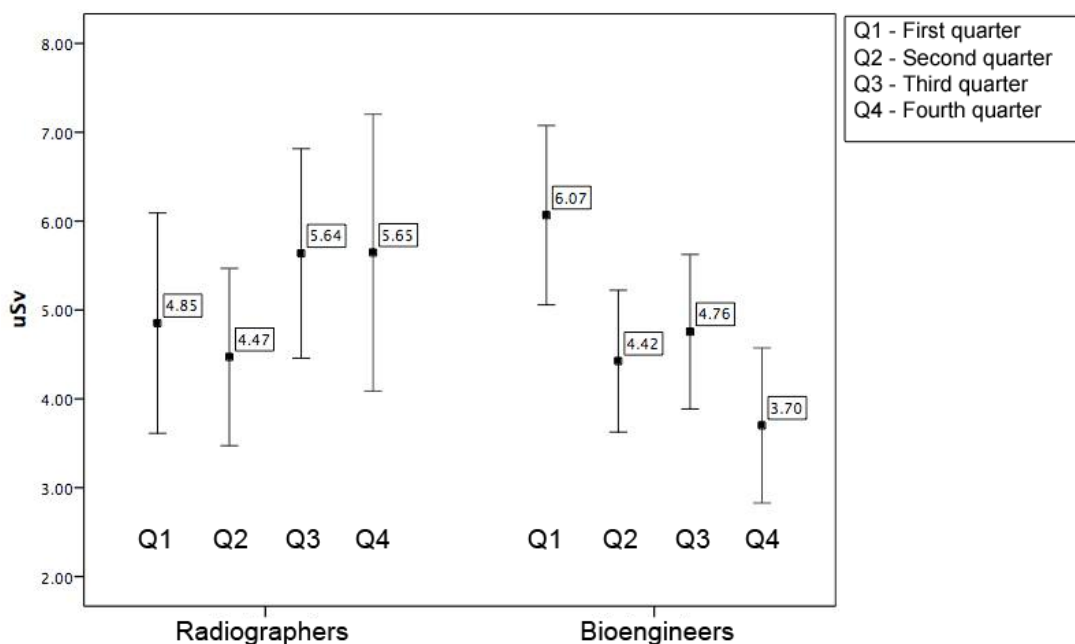**Table 4:** *Individual daily mean effective dose for each quarter (n=9)*

Figure 4: *Distribution of effective doses based on profession (n= 9). The bioengineers received on average 0.6 µSv/day more than the radiographers (p = 0.123).*
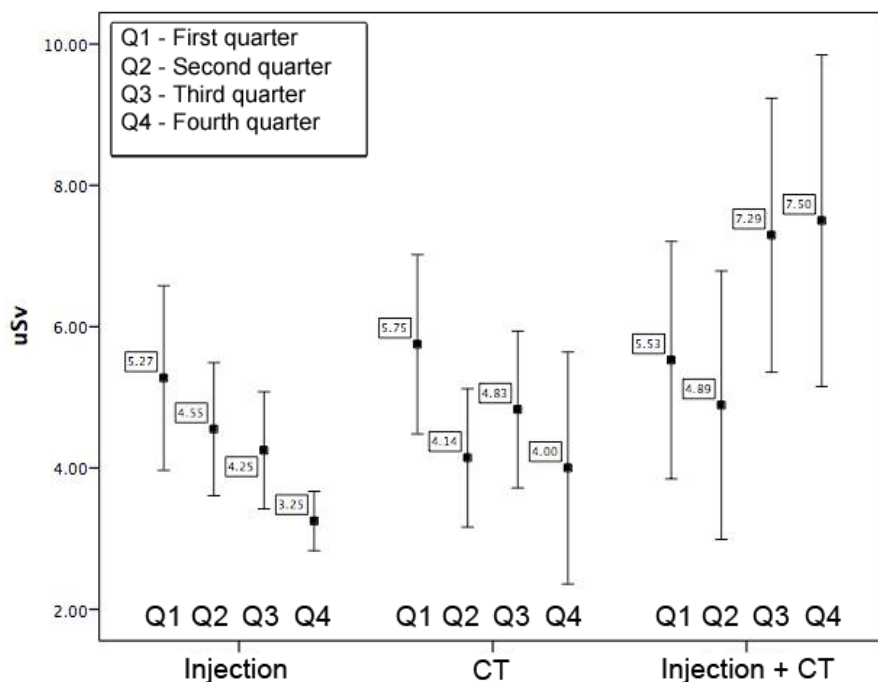

Figure 5: *Distribution of effective doses based on working task (n= 9). There is a significant difference between those solely running injections or operating the CT and those rotating between these tasks (p = 0.001).*

Discussion

Part one

Dose rates from the patients varied in a large extent (figure 1 and table 1). The measurements showed significant differences between all measuring points apart from between the sternum and bladder after 60 minutes (table 2). The dose rate from the head and sternum showed the highest doses, and the knee proved to have the lowest dose rate. The reason for this is that the feet generally have a low uptake of ^{18}F-FDG at rest, keeping in mind that ^{18}F-FDG accumulates where the cells have a high metabolism of glucose. The staff therefore ought to position themselves in respect to this fact. It would also be optimal to place the peripheral venous catheter in one of the lower extremities. This praxis is not performed due to practical reasons and because of the increased discomfort the patient might experience. The results confirmed that the dose rate diminishes with time and decreases substantially as distance from the source is increased, as the inverse-square law suggests. The works of both Chiesa et al [10] and Benetar et al [8] also concluded that the dose rate varies and was much lower from the lower extremities compared to the rest of the body. This study confirms this finding and recommends facilitating working routines in this manner.

Until recently the radiation lowering strategies at the department have included the following actions; to include an injection robot, have mobile stationary shields and maximizing patient shielding from the environment in a dedicated preparing room. The staff is encouraged to work as effectively as possible while keeping the longest possible distance from the radiation source. Video surveillance of the dedicated preparing rooms are also utilized to avoid unnecessary patient contact. Protective garments are not applied as these only seem to attenuate about 9 % of the ^{18}F radiation [19].

Part two

With the dose limiting measures applied at the department in 2014 we calculated the daily mean effective dose to be **4.91 ± 3.06 µSV/day/employee** (table 3). For comparison; an aerial flight at 35,000 feet lasting 7 hours will give an expected effective dose of 34 µSv/flight [20].

The results reside 6-7 times lower compared with the similar study from Oslo in 2006, in which the staff received 36 µSv/day [7]. It is a good comparison, because the study was also conducted during the first year of operation. The difference between the studies was that neither an injection robot nor lead syringe shields were utilized in the study from 2006 [7]. This implies that making use of an injection robot is recommended. The effective dose also depends on the amount of injected radioactive isotope [7-16]. It is currently recommended to inject 4.0 MBq/kg. An important measure to reduce the effective dose to staff in the future could be to further lower the injected dose. The problem with lower injection dose is increased examination time with the machines currently in operation. This has consequences for the patient and increased workload of the department.

The stochastic effect of ionizing radiation suggests that the probability of developing radiation induced mortal cancer is increased by 5 % for each Sv the cells absorbs [5]. Our results show an annual mean effective dose of **0.14 mSv/employee.** This corresponds to an individual annual increase of 0.007 ‰ to develop mortal cancer. It should be taken into consideration that the capacity at the department should have a fourfold increase once the department becomes fully operational [3] and the effective dose to staff will then naturally increase. Nevertheless, these values will reside far beneath the recommended annual limit for ionizing radiation.

Working tasks have also shown to be a factor for received effective dose (figure 5). It was expected that staff working with CT would receive an increased amount of radiation because the aforementioned individuals are in close contact with the radiation source during administration of the contrast agent and table alignment. Our study found a significant difference when comparing radiation doses to those working solely with injection or CT-scanning and those combining these tasks (p = 0.001) (table 5). Our results do not show significant differences between professions. The bioengineers had only 0.6 µSv higher daily radiation dose than the radiographers (p = 0.123) (figure 4). This could indicate that the level of knowledge on radiation hygiene between the occupations is equal.

Method

In Part one we have used measuring device RadEye B20 (Thermo Scientific, USA). The instrument has a linearity error margin of 30 % on energy spectra surpassing 150 keV. This affects the reliability of the study. However, the manual of the unit suggests that the margin of error decreases with higher levels of energy. The instrument was calibrated towards the radioisotope 137Cs with an energy level of 662 keV. The aforementioned linearity error margin further decreases when an appropriate filter is not applied [21]. Because this was not utilized in our study, we regard this margin of error as lower than 30 %.

In Part two we have utilized effective dose values registered with the personal dosimeter Radeye EPD MK2+ (Thermo Scientific, USA). This device has a margin of error of 20 % and displays personal doses in µSv without decimals [22]. The limited number of participants also affects our result, taken into consideration that only nine volunteers participated in the study. A strength of the study is that such experiments have been conducted prior to our study. Information regarding their selected method is however limited in some of the other studies. We can highlight that the registration of the effective doses were carried out daily during the whole year with few missing values. This makes our data material in part one complete. Nevertheless, our results do not take into account in case some of the staff forgot to register daily effective dose or if the staff forgot to wear their personal dosimeter. Another strength with this approach is that it may be continued in the future. In such a way it is possible to draw connections between our conclusions and apply these to further decrease future effective doses.

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Conclusion

Part one

Dose rates from different parts of the body show significant differences. Values were highest from the head and sternum and lowest from the knees. The staff ought to position themselves from the patient's lower extremities to optimize radiation hygiene.

Part two

Effective doses to staff were individually spread. This could probably be explained by different working methods. The cumulative annual effective doses were far below the limit set for occupationally exposed workers and the calculated increased risk for cancer was minimal. A significant difference in effective doses between the different professions was not found. Concerning working tasks we found that those combining both CT and injection received the highest dose.

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