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Added Value of Digital Over Analog PET/CT: More Significant as Image Field of View (FOV) and Body Mass Index (BMI) Increases

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Abstract

Background: The digital positron emission tomography/computer tomography (PET/CT) scanner with digital photon counting (DPC) technique promises a shorter scan time, improved small lesion detectability, and reduced radiation dose for the PET and CT portions of the exam, while improving image quality. **Methods:** In this single-institution retrospective review study, 84 participants who had undergone PET/CT exams on both the Philips analog and digital scanners were analyzed. The aim was to evaluate the impact of image field of view (FOV) and body mass index (BMI) on the digital compared to the analog PET/CT scanner. The participants were categorized into different groups based on their BMI. Total scan times, 18F-fluorodeoxyglucose (18F-FDG) doses, and dose length product (DLP) were collected and compared. Image quality was also assessed by certified nuclear medicine physicians and graded on a scale from 1 to 5. **Results:** In the skull-to-mid thigh FOV values, the digital scanner had a shorter scan time by 37% *($p < 0.001$),* lower 18F-FDG dose by 16% *($p < 0.001$),* but only 8% reduction in DLP values *($p = 0.2$)*. In the head-to-toe FOV cases, the digital scanner showed reductions in scan time (33%; *$p<0.001$*), 18F-FDG dose (13%; *$p<0.001$*), and DLP (19%; *$p<0.001$*). When BMI was accounted for, the digital scanner had a shorter scan time by 33% (*$p<0.001$)* as well as reduced DLP (*$p<0.001$)* and 18F-FDG dose *($p<0.001$)* with the most prominent changes in the overweight and obese participants. Image quality was also improved in the digital scanner with a score of 4.5 vs 4.0 in the analog scanner. **Conclusion:** The digital scanner has a shorter scan time, lower DLP, requires lower 18F-FDG dose and provides improved image quality when compared to the analog scanner. The most impactful difference in scan time, DLP, and 18F-FDG dose were observed in the obese and overweight participants.

Keywords:

Scan time, DLP, Weight based dosing, BMI, digital

Introduction

Positron emission tomography/computed tomography (PET/CT) is one of the most accurate molecular imaging modalities which provides elaborate information at the cellular and molecular levels (*1*). Despite the impact of PET/CT on staging, restaging, and post treatment evaluation in oncology, ionizing radiation has always been a concern. Efforts to reduce radiation exposure to both patients and the staff have been ongoing in the imaging community (*2*). The advances in the digital PET scanner detectors from conventional photomultiplier tubes (PMTs) to one-to-one solid detectors and the improvement of image reconstruction are some changes taken towards reduction of radiation dose in the PET/CT imaging systems. (*3*). The PET/CT scan creates high resolution images while integrating the anatomical framework from CT with functional images that come from PET.

Philips digital and analog PET/CT scanners are the intended scanners that are the focus of this study. Components of the analog PET scanner (GEMINI) detectors include crystals that can convert photons to flashes of light, but cannot count all individual photons. These scintillation crystals are coupled with multiple PMTs which convert the flashes of light to electron signals. These electron signals are then sent to a computer for further processing and image production. The digital PET scanner (Vereos) is equipped with digital counting detectors in which solid-state detectors count every individual photon created during a PET scan (*4,5*). Each solid-state detector is composed of multiple scintillator elements. The high count rate ability of solid-state

detectors comes from one-to-one coupling between the scintillator elements with light-sensing elements which leads to improved spatial resolution and faster image acquisition (*4*).

To investigate the radiation dose in the CT part of the exam, dose length product (DLP) is used which is the total amount of radiation a person receives during a CT examination. On the digital scanner, DLP indicates the sum of radiation dose from scout and slices; on the analog scanner, DLP calculates the radiation exposure from slices only. The Philips Vereos digital scanner has promised shorter scan time, lower radiation dose from CT, and reduced 18F-fluorodeoxyglucose (18F-FDG) dose (*6*). Since both the digital and analog systems are used clinically, the possible impact of image field of view (FOV) and body mass index (BMI) in these two systems was considered. The purpose of this study was to compare the scan time and radiation dose associated with the Philips digital Vereos and analog GEMINI PET/CT system. More effectively, the impact of image FOV and BMI on scan time and radiation dose was considered.

Materials and Methods

The study was approved by the University's Institutional Review Board and the requirement to obtain informed consent was waived.

Participant Characteristics

This study was a single-institution retrospective study of 84 PET/CT patients in an oncology cohort over a period of five years. The participants' age ranged between 18-75 years old and their BMI ranged between 15-68.

A total of 110 participants had undergone both the analog and digital PET/CT scans using the same injected 18F-FDG dose of 5.18 MBq (0.14 mCi/kg) which was the factory recommended

dose. A maximum dose of 555 MBq (15 mCi) for the analog scanner and a maximum dose of 370 MBq (10 mCi) for the digital scanner was used which was also factory recommended by Philips. Given the retrospective nature of the study, the 2 scans could not be done on the same day. The time difference between the analog and digital scans was a mean of 11 months.

To calculate BMI in this study, participants' weight in kilograms (kg) was divided by the square of their height in meters (BMI=kg/m^2). In order to factor changes in the 18F-FDG dose based on significant weight changes, participants with greater than 10% variation in their BMI during their follow-up period (n= 26) were excluded from further analyses. The remaining 84 cases (16 skull to mid-thigh and 68 head to toe) were categorized into different groups based on BMI: Underweight (<18.9), Normal weight (19-24.9), Overweight (25-29.9), and Obese (>30). All participants were instructed to fast for at least 6 hours before the scan. The participants' blood glucose level was measured before the injection of the 18F-FDG dose with an acceptable level of <200 mg/dL. Participants were positioned in a quiet dimly lit room and kept in a warm unstimulated condition during their standard 60-minute uptake time before imaging.
More recently, we adjusted the 18F-FDG dosing in our center from weight-based to BMI-based dosing and included 20 patients that had a prior scan using the weight-based dosing. Patients we divided into 3 groups: BMI $\leq$ 25, BMI 26-34, BMI $\geq$ 35.

Image quality was reviewed and analyzed by two board certified nuclear medicine physicians blinded to the scanner. Image quality for all scans was graded on a scale of 1 to 5 (1=poor; 5=excellent). Lesion detectability could not be assessed due to the differences in time between the scans.

Image data acquisition

Both Philips PET/CT scanners used in this study are fused with a 64 slice CT scanner (*7*). Philips GEMINI and Philips Vereos were used as the analog and digital PET/CT scanners, respectively. Both scanners were American College of Radiology (ACR) certified to ensure accurate analysis. For the GEMINI analog scanner (installed at this site in 2006), the CT image data were reconstructed using filtered back projection technique, 512x512 matrix size, 600 mm FOV in participants with BMI< 34 and 700 mm FOV in participant with BMI>34.

To provide significant improvements in image quality combined with dose reduction capabilities, Philips Vereos digital PET/CT scanner (installed at this site in 2018) uses iDose reconstruction technique to reconstruct CT images (*7*). iDose is the fourth generation of advanced iterative reconstruction technique and the latest addition to Philips DoseRight tools (*7*). The FOV for the different BMIs and the matrix size in the digital scanner were similar to the analog scanner. The CT scan was performed in a transaxial FOV with similar parameters for all participants, regardless of the BMI: 120 kVp, variable mAs in range between 30-100, average of 15.5 cm axial FOV in skull to mid-thigh and 56.2 cm trans axial FOV in whole body, 4 mm slice thickness, 4 mm increment, a pitch of 0.704, a rotation time of 0.5 seconds, collimation of 64x0.625. The iDose was on in the digital scanner. The CT studies were obtained with an average time of 34.2 seconds in skull to mid-thigh and 54.3 seconds in the whole body.

Ordered-subset expectation maximization (OSEM) was utilized for PET image reconstruction in both digital and analog scanners (3 iterations with 33 subsets in analog and 3 iterations with 15 subsets in digital). The PET parameters included: 10 frames in skull-to-mid thigh and maximum of 18 frames in whole body. In the analog PET exams, photon counting time per frame was variable based on BMIs: -BMI< 25, 60 seconds per frame from skull to mid-thigh (frames 1-10) and 30 seconds per frame for lower extremity (frames 11-18); BMI between 25 to

29.9, 90 seconds per frame from skull to mid-thigh and 30 seconds per frame for lower extremity; BMI between 30 to 35, 120 seconds per frame in skull to mid-thigh and 30 seconds per frame in lower extremity; BMI >35, 180 seconds per frame in skull to mid-thigh and 60 seconds per frame in lower extremity (Table 1).

Two protocols were used in the digital PET exams: the regular body protocol was used for participants with a BMI $\leq$ 34 and a large body protocol was used for participants with a BMI >34. In the regular body protocol, photon counting time was obtained 75 seconds per frame in skull to mid-thigh (frames 1-10) and 37 seconds per frame in lower extremity (frames 11-18). In the large body protocol, the photon counting was obtained 105 seconds per frame in each bed for skull to mid-thigh and 45 seconds in each bed for lower extremity (Table 2).

Data Analysis

The comparisons were limited to participants who had identical FOVs that included either skull to mid-thigh or head-to-toe (whole body). The mean DLP, scan time for both PET and CT exams (both FOVs, skull to mid-thigh and whole body), and 18F-FDG dose were collected and compared. For statistical analyses, paired t-tests were applied. A p-value < 0.05 was considered significant. All analyses were performed in Microsoft Excel (v. 15).

Results

FOV effect on scan time, 18F-FDG dose, and DLP values

The differences between Philips analog (GEMINI) and digital (Veroes) PET/CT scanners regarding scan time, 18F-FDG dose, and DLP were investigated. The scan time, DLP, and administered 18F-FDG of exams that had been performed at our institution between 2012 to 2019 were collected and compared.

The analysis revealed a shorter total scan time (from both CT and PET), a lower 18F-FDG dose, and lower DLP in the digital scanner compared to the analog GEMINI scanner. In terms of skull to mid-thigh FOV values, there was a significant difference in the scan time ($p<0.001$; 37% reduction) and 18F-FDG dose ($p<0.001$; 16% reduction). The difference in DLP values (p=0.2; 8% reduction) in Vereos when compared to GEMINI was not significant (Fig. 1, Table 3). In the head to toe (whole body) FOV cases, Vereos revealed significant differences in scan time ($p<0.001$; 33% reduction), 18F-FDG dose ($p<0.001$; 13% reduction), and DLP ($p<0.001$; 19% reduction) (Fig. 2, Table 3).

Impact of BMI on scan time, 18F-FDG, and DLP

The standard procedure for the administration of an 18F-FDG dose for a PET scan has been based on the weight of the participants (*8*). In a weight-based dosing system, body habitus is not considered and hence this system could be prone to over- or under-estimation of the radiation dose that the participants may receive (*9*). By means of BMI, however, weight and height both are considered and the role of body habitus becomes more prominent. Therefore, it is considered that BMI could be an effective factor in minimizing scan time, DLP, and 18F-FDG dose.

To address this, the participant data were evaluated from two scanners (digital verses analog) and a significant difference was found in total scan time between Vereos and GEMINI ($P<0.001$; 33% reduction; Fig. 3, Table 4). Among the BMI groups, scan time differences were the most prominent in the obese cases and the least in the normal cases. The lower scan times (in the digital when compared to analog scanner) included 16% in underweight group (P<0.004), 8% in normal weight (P=0.0014), 26% in overweight ($P<0.001$), and 47% in obese ($P<0.001$) group (Fig. 3, Table 4)

Similarly, a significant difference was observed in the total DLP of all cases between the digital and analog system (*P<0.001*). However, when the cases were split into four BMI groups, the decrease of DLP in digital was significant in the overweight (*P<0.001*) and obese (*P<0.001*) group, but not in the underweight (*P=0.8)* group. In the normal weight group this trend was the opposite: the DLP was higher on the digital system than the analog system (*P=0.08)* (Fig. 4, Table 4). Consistently, a significant lower value for digital (in comparison to analog) was observed in the total 18F-FDG dose for all cases (*P<0.001*) and again significant lower values were found in normal weight participants (*P*=0.012), overweight (*P*<0.001), and obese participants (*P<0.001)*, but not in underweight (*P*=0.5). Of note, because the 18F-FDG dose had been administrated per kg of body weight, the major difference between the analog and digital scans was observed in participants with higher BMI (overweight and obese), most notably in participants with a BMI of >30. This suggests that these two groups of participants might benefit the most (lower 18F-FDG doses; Fig. 5, Table 4).

These encouraging findings merit further investigation regarding the effect of BMI on administered 18F-FDG dose. Therefore, we changed the administered 18F-FDG dose from weight-based to BMI-based. In this new BMI based administration dose system (20 participants), the administered 18F-FDG dose is 222 MBq (6 mCi) for participant with BMI< 25, 296 MBq (8 mCi) for participants with BMI between 26-34, and 370 MBq (10 mCi) for participants with BMI>35 in the digital Vereos PET/CT system. The data of the administered 18F-FDG dose from GEMINI, Vereos weight-based dose, and Veroes BMI-based dose were collected and compared to each other. The results shows a significant difference in GEMINI weight-based to Vereos weight-based dose system (*P* <0.001), 34% reduction), and Vereos weight-based dose to Vereos

BMI-based dose system (P <0.001, 22% reduction) (Figure 6, Table 5). However, the new dosing system is an ongoing research project to reduce radiation dose to participants.

Image quality

Review of the image quality demonstrated a mean score of 4.0 for the analog scanner and 4.5 for the digital scanner. Overall, the images on the digital scanner appeared less noisy than the analog scanner.

Discussion

Historically, the early idea of PET was developed in 1950 and the first scanner was innovated in 1970 at Washington University in Saint Louis, MO, USA (*3*). From the early single-slice detector design to the commercial scanners of today, the benefits of PET/CT in oncological studies cannot be denied but there have always been aspirations of reducing the 18F-FDG dose and scan time. The single pair of detectors for planar imaging has evolved into the current one-to-one solid detectors in PET, which has led to advanced acquisition electronics, data processing, and image analysis over the past 50 years (*3*). The latest improvement in PET/CT scanners has been the digital technology with DPC technique, which promises shorter scan time and lower radiation dose, while improving image quality and small lesion detectability.

Multiple studies (*10,11*) have reported the superiority of digital PET/CT syatems over analog scanners respecting the improved small lesion detectability and image quality (*10,11*). However, to our knowledge, no study has addressed the differences between digital and analog PET/CT scanners with respect to scan time, radiation dose from administered dose and radiation dose from the CT portion of the scan. In this study, scan time, 18F-FDG dose, and DLP were evaluated in digital and analog PET/CT scanners and significant differences between digital and

analog in these factors were observed. In line with expectations, scan time and radiation dose were lower in digital than analog PET/CT scanners (*12*). With a few exceptions (underweight cases), results from all cases indicated a significantly shorter scan time and reduced radiation dose in the digital scanner compared to the analog scanner (Fig. 3, Table 4).

The DLP value in the skull to mid-thigh FOV showed no significant difference that could be raised from the different calculation methods in digital and analog scanners. The digital DLP is calculated using the sum of the radiation dose from both the scout and the slices. However, for the analog scanner the DLP could only use the sum of the radiation from the slices only since the scout was not available. This in theory should give the digital scanner a higher DLP, however the new iDose iterative reconstruction technique is able to maintain image quality with lower radiation dose. Our evaluation is likely underestimating the radiation savings since the scout is not included in the analog DLP calculation. In terms of different BMI groups, the DLP and 18F-FDG dose values were not beneficial for underweight participants that could be due to two potential reasons; First, the mentioned reason in variation DLP calculation in digital and analog. The second reason comes from under sampling in underweight groups due to exclusion criteria (most of the cases in these groups were excluded from further analyses due to more than 10% variation in their BMIs).

Since the administered 18F-FDG dose was weight-based, the results illustrate that reducing 18F-FDG dose would not be beneficial to underweight participants, while it is beneficial to the normal weight, overweight and obese participants. Per our findings, the dosing system is currently changed to a BMI-based system instead of weight-based at our center. In this new BMI-based administration dose system (20 participants), the administered 18F-FDG dose is 222 MBq (6 mCi) for participant with BMI< 25, 296 MBq (8 mCi) for participants with BMI

between 26-34, and 370 MBq (10 mCi) for participants with BMI>35 for the digital Vereos PET/CT system (Fig. 6, Table 5).

Some limitations should be considered regarding the interpretation and generalization of our findings. First, this was a single institution study. Second, it is important to remember that in digital, DLP is not calculated the same way as analog but DLP has been utilized for evaluation of radiation in CT, and as it was a retrospective study, this parameter could not be edited. Third, since this was a retrospective study, our findings need to be reevaluated prospectively comparing different analog and digital scanners from other vendors. In addition, lesion detectability could not be assessed due to the different time points in the scans of each patient. However, this has been assessed in a recent study where patients had both scans after a single 18F-FDG injection and confirmed the digital scanner demonstrated superior small lesion detection (*13*). Fourth, we have compared the digital and analog PET/CT scanners from the same manufacturer. Future research could compare data acquired from digital PET/CT scanner from multiple manufacturers, again comparing the scan time, 18F-FDG dose, and DLP. Finally, we did not find beneficial effects for the underweight cases and it worth noticing that two potential intrinsic factors could be involved here: i) in this short period of time between the first scan and the follow-up scans for each case, it would be unlikely to occur big shift in the weight of each case; and ii) yet these little changes would significantly affect the "percentage of weight change" in the underweight cases, but not in the overweight or obese cases. Therefore, under-sampling for the underweight cases might be a caveat of our study. Expanding this analysis to a bigger population of underweight cases might help clarify this conundrum.

Conclusion

Compared to the Philips GEMINI analog PET/CT system, the Philips Vereos digital PET/CT scanner provides improved image quality with the benefits of shorter scan time, lower radiation exposure dose, and lower administered 18F-FDG dose which leads to a lower radiation dose to the technologist and public. Based on this study, the digital PET/CT scanner is a beneficial molecular imaging modalities regarding less radiation dose and shorter scan time.

Disclosure

The authors have no conflicts of interest relating to the work described in this manuscript.

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Table 1. Variable photon counting time per frame in analog PET scanner for different BMIs.

BMI	< 20	20- 24.9	25-29.9	30-35	>35
Time/frame (frames 1-10)	60 Sec.	60 Sec.	90 Sec.	120 Sec.	180 Sec.
Time/frame (frames 11-18)	30 Sec.	30 Sec.	30 Sec.	30 Sec.	60 Sec.

Table 2. Photon counting time per frame in digital PET scanner based on BMIs.

FOV	Time/frame in regular protocol (BMI $\leq$ 34)	Time/frame in large protocol (BMI > 34)
Skull to mid-thigh (frame 1-10)	75 Sec.	105 Sec.
Lower extremity frame (11-18)	37 Sec.	45 Sec.

Table 3. The mean value, SD, and *P*-value of 18F-FDG dose, scan time, and DLP in GEMINI verses Vereos PET/CT scanner regarding different FOVs.

FOV	Mean (SD) 18F-FDG dose (MBq)			Mean (SD) Scan Time (mins)			Mean (SD) DLP (mGy/cm)		
	GEMINI	Vereos	*p*-value*	GEMINI	Vereos	*p*-value*	GEMINI	Vereos	*p*-value*
Skull-to-midthigh	443.26 (91.95)	370.00 (46.46)	<0.001	22.37 (8.50)	13.94 (2.32)	<0.001	463.33 (162.14)	424.38 (115)	NS
Whole body	412.18 (95.30)	355.94 (62.24)	<0.001	27.00 (9.93)	18.05 (3.01)	<0.001	702.22 (261.36)	567.46 (144.28)	<0.001

NS=not significant

*Determined by t-test

Table 4. Mean value, SD, and *p*-value of 18F-FDG dose, scan time, and DLP in GEMINI verses Vereos PET/CT scanner among different BMI groups.

BMI category (kg/m^2)	Mean(SD) 18F-FDG dose (MBq)			Mean (SD) Scan Time (mins)			Mean (SD) DLP (mGy/cm)		
	GEMINI	Vereos	*p*-value*	GEMINI	Vereos	*p*-value*	GEMINI	Vereos	*p*-value*
Total	422.3 (91.3)	358.53 (59.55)	<0.001	26.12 (9.80)	17.26 (3.31)	<0.001	656.72 (262.30)	540.2 (149.63)	<0.001
Underweight (<18.9)	209.05 (83.99)	205.81 (76.71)	NS	16.35 (2.18)	13.65 (2.08)	NS	289.37 (132.22)	294.5(102.16)	NS
Normalweight (19-24.9)	345.21 (76.09)	326.10 (63.63)	0.012	17.62 (2.6)	16.04 (3.1)	0.0014	412.99 (102.51)	455.69 (154.3)	NS
Overweight (25-29.9)	438.45 (48.96)	373.90 (42.69)	<0.001	22.27 (2.46)	16.34 (2.32)	<0.001	597.85 (148.1)	545.74(132.4)	<0.001
Obese (>30)	484.33 (52.57)	384.90 (0.45)	<0.001	37.8 (8.08)	19.66 (3.2)	<0.001	932.04 (170.1)	623.35 (99.2)	<0.001

NS=not significant

*Determined by t-test

Table 5. Difference in GEMINI weight-based to Vereos weight-based dose system ($p<0.001$), and Vereos weight-based dose to Vereos BMI-based dose system ($p<0.001$).

Mean (SD) 18F-FDG Dose in MBq					
GEMINI Weight-Based	*p*-value	Vereos Weight-Based	*p*-value	Vereos BMI-Based	*p*-value
445 (72.57)	<0.001	374.07 (27.43)	<0.001	296 (56.75)	<0.001

Figures

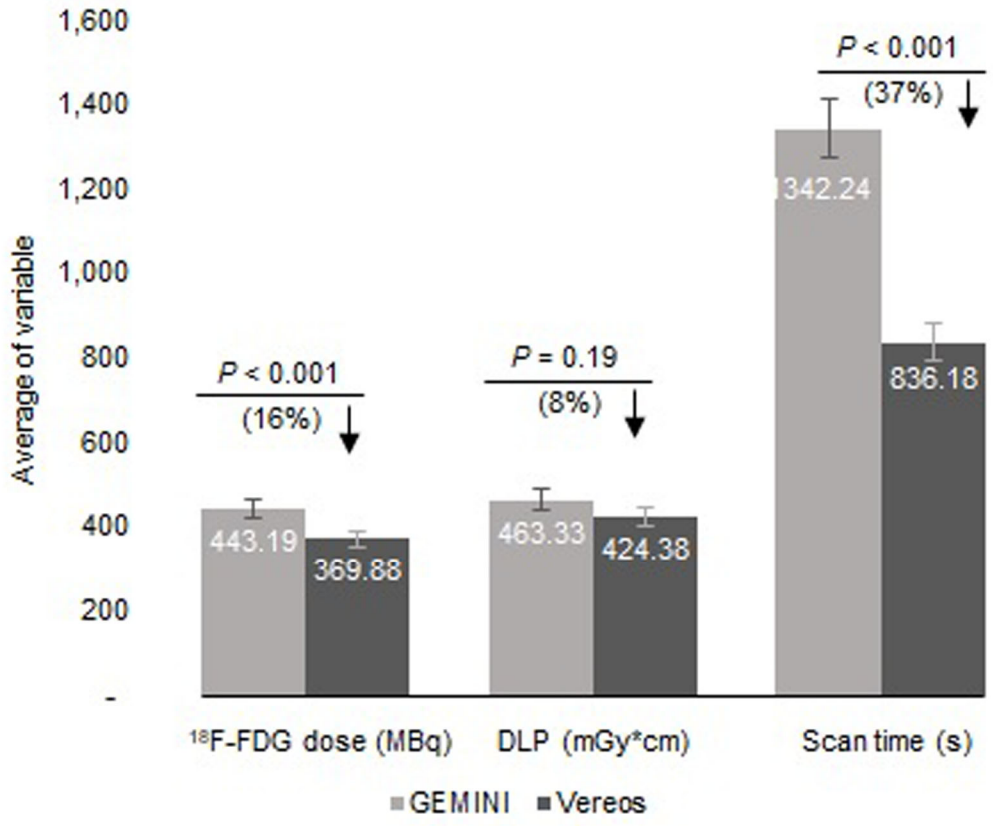

Figure 1. The skull-to-midthigh FOV, indicates a significant difference in scan time and in 18F-FDG dose in Vereos compared to GEMINI. No significant difference in DLP was observed. *P* values, percentage of changes (differences), and increase (_) or decrease (↓) in the corresponding values are indicated. 18F-FDG: 18F-fluorodeoxyglucose, MBq: megabecquerel, DLP: Dose length product. Error bars indicated as 5% percentage.

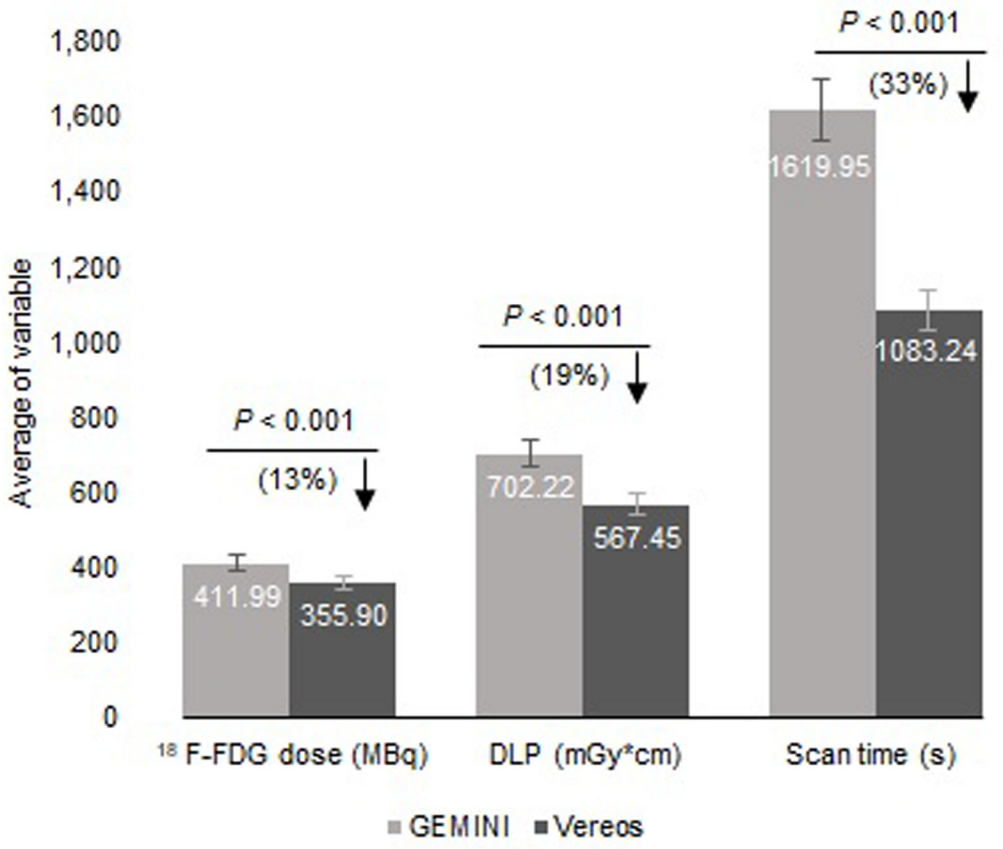

Figure 2. The head-to-toe (whole body) FOV in Vereos indicates a significant difference in scan time compared to GEMINI. *P* values, percentage of changes (differences), and increase (_) or decrease (↓) in the corresponding values are indicated. 18F-FDG: 18F-fluorodeoxyglucose, MBq: megabecquerel, DLP: Dose length product. Error bars indicated as 5% percentage.

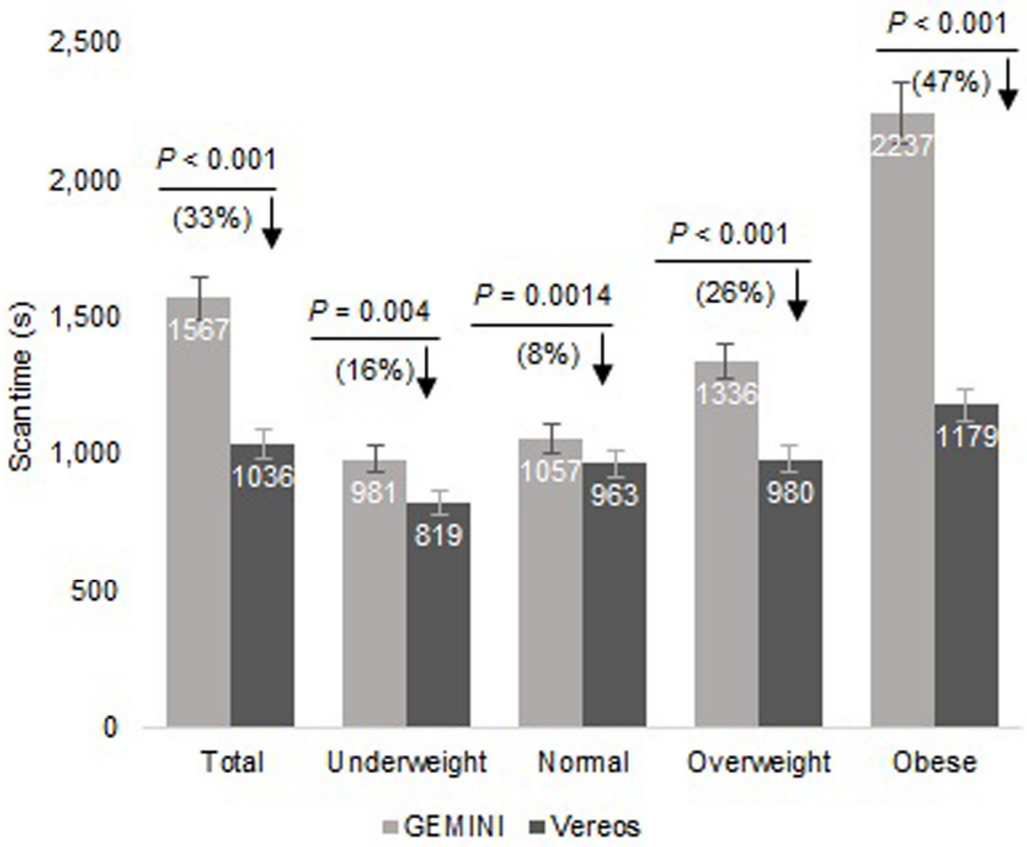

Figure 3. Scan time for digital and analog PET/CT system according to BMI group. Total scan time shows a significant difference between the two scanners (P<0.001; 33% reduction). The largest difference was observed among obese cases and the least in the normal cases. *P* values, percentage of changes (differences), and increase (_) or decrease (↓) in the corresponding values are indicated. S: seconds. Error bars indicated as 5% percentage.

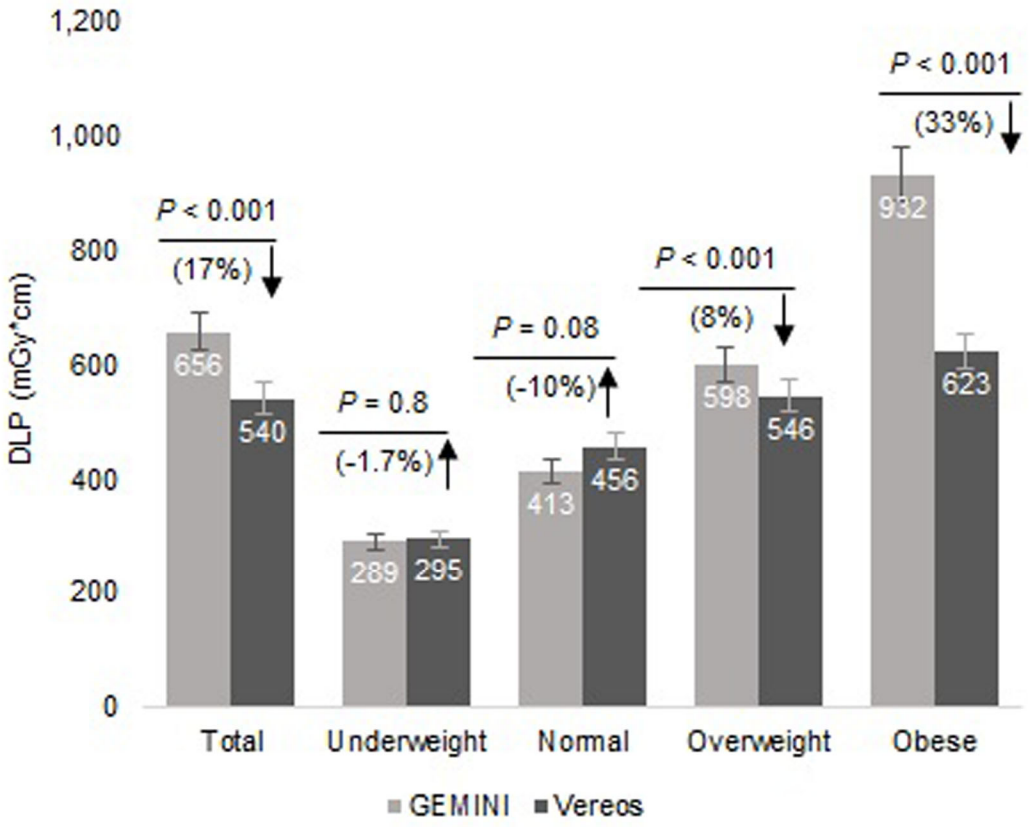

Figure 4. DLP for difital and analog PET/CT systems according to BMI group. A significant difference was obsereved in the overweight and obese groups, but not in the underweight and normal weight groups. *P*-values, percentage of changes (differences), and increase (_) or decrease (↓) in the corresponding values are indicated. mGy/cm: milligray per centimeter (which is the unit of DLP). Error bars indicated as 5% percentage.

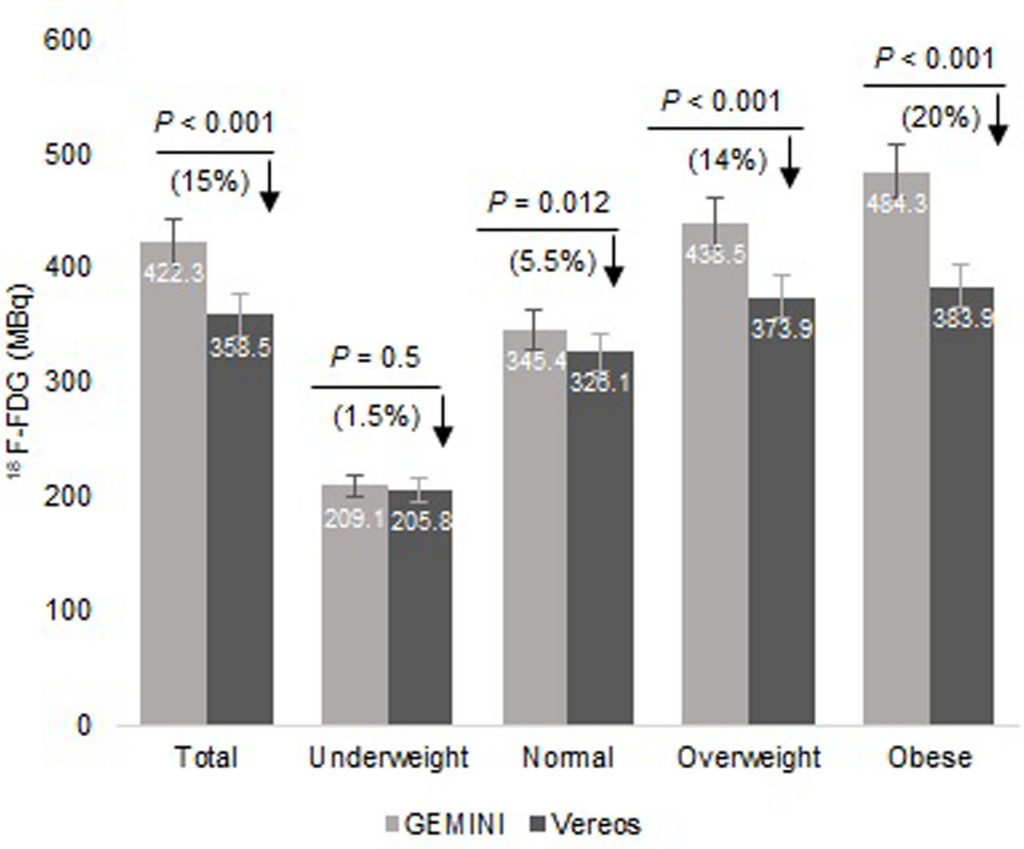

Figure 5. 18F-FDG dose for digital and analog PET/CT systems according to BMI group. Significantly lower doses in normal weight, overweight, and obese participants, but not in underweight cases. *P*-values, percentage of changes (differences), and increase (_) or decrease (↓) in the corresponding values are indicated. 18F-FDG: 18F-fluorodeoxyglucose, MBq: megabecquerel. Error bars indicated as 5% percentage.

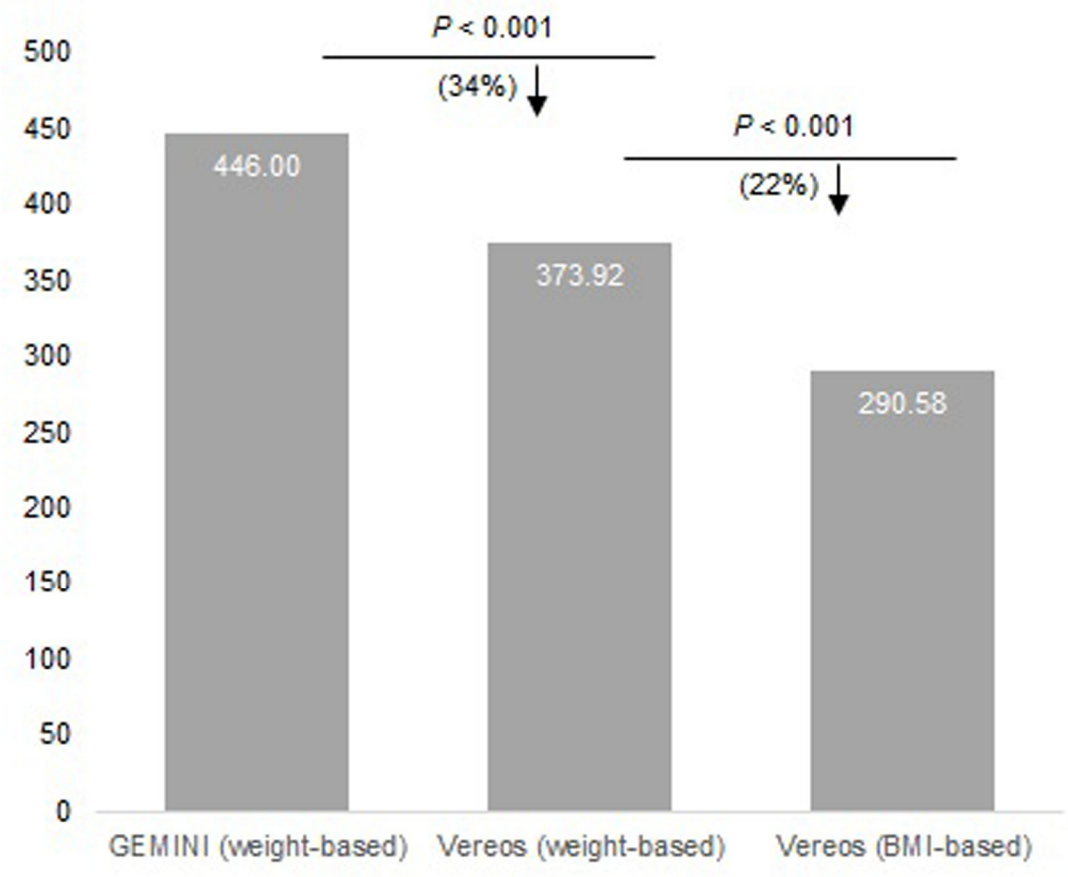

Figure 6. Comparisons between GEMINI weight-based dosing, Vereos weight-based dosing, and Vereos BMI-based dosing approaches. The figure shows a significant difference in between analog and digital weight-based dosing syatem. The figure also illustrates a significant difference in digital weight-based and digital BMI-based dosing system. *P* values, percentage of changes (differences), and increase (_) or decrease (↓) in the corresponding values are indicated. BMI: body mass index, 18F-FDG: 18F-Fluorodeoxyglucose, MBq: megabecquerel. Error bars indicated as 5% percentage.