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Original paper

An effective time reduction strategy in whole-body SPECT/CT studies using novel acquire during step mode without compromising diagnostic image quality

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ABSTRACT

Purpose: WB-SPECT/CT can provide valuable insight into metastatic disease, assist in diagnosing numerous conditions, and enable volumetric dosimetry. Various approaches have made whole-body (WB) SPECT/CT less feasible in routine practice as it takes impractically long acquisition times. We aim to determine whether acquire during step (ADS) technology can be used for WB SPECT/CT studies to minimise acquisition time without compromising diagnostic quality.
Design: Two different phantom studies were performed using ^{99m}Tc and ^{177}Lu. An initial comparison of step-and-shoot (SSM) and ADS SPECT acquisition mode with full-time, half-time, and quarter-time was carried out. The recovery coefficients were calculated for different spheres and background regions to check the quantitative accuracy of SSM and ADS modes with different acquisition times. The xSPECT quantification tool was used to obtain the SUVs in the VOI.
Result: The SPECT scan time with full-time ADS was 3.5 min quicker for each bed compared to full-time SSD. The ADS mode saved 15%-of acquisition time compared to the SSM mode. For both ^{99m}Tc and ^{177}Lu, no statistical difference in recovery coefficients was noted between different acquisition times in SSM and ADS mode. No significant changes were noted in the background SUV between SSM and ADS for ^{99m}Tc and ^{177}Lu isotopes.
Conclusion: A 15%-time reduction could be achieved using ADS technology in our SPECT/CT scans without any change in quantitative accuracy. We also found that time can be reduced further, and scans can be acquired faster by implementing a half-time or quarter-time ADS in routine practice without compromising quantitative accuracy. The improvements in WB SPECT acquisition time could reduce motion artefact, especially for patients with pain and improve the accuracy of disease diagnosis and personalised dosimetry.

1. Introduction

Over the past few years, several technological advancements have been made in single-photon emission computed tomography (SPECT) [1]. Quantification in SPECT/CT is achievable by incorporating scatter correction, computed tomography (CT)-based attenuation correction and resolution recovery [2]. SPECT-CT acquisitions can be carried out in different ways, including continuous acquisition mode (CM), step and shoot (SSM) and continuous step-and-shoot (CSSM). Data is acquired in the CM of acquisition when the detector moves continuously. In the SSM, data is acquired when the detector is stopped at the projected view during rotation. The CSSM combines CM and SSM, where data are acquired when the detector moves and stops. The concept of CSSM was first introduced by Cao et al. [3], who performed simulation studies to assess the image quality between SSM and CSSM. Previous studies have demonstrated that CSSM has a similar sensitivity to CM but with a resolution similar to SSM [4]. A recent phantom study by Thibault et al. [5] suggested that the Swiftscan solution which works on the CSSM principle improves the volumetric sensitivity compared to SSM mode without deteriorating image quality. Because of this reason, CSSM has also been successfully applied in clinical settings [6–8]. Siemens Healthineers commercialised the acquire during step (ADS) technology, which uses the concept of CSSM [7]. This mode can be used with low-energy, medium-energy, and high-energy collimators. ADS mode with

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Table 1
Detailed acquisition and reconstruction parameters of SPECT used for the 99mTc and 177Lu phantom imaging.

Collimator	LEHR (for 99mTc) and MELP (for 177Lu)
SPECT type	"Advanced"
Window (keV)	140 ± 10 %(99mTc) and 208 ± 10 %(177Lu)
Scatter window (keV)	For 99mTc: 120 ± 5 % For 177Lu: 178 ± 5 % and 240 ± 5 %
Matrix	256 × 256
Pixel size	2.21 × 2.21 mm
Number of views	120
Auto-contour	On
Frame stop conditions	Counts for 99mTc* and Time for 177Lu*
Reconstruction type	xSPECT Best
Iterations	Variable (based on counts): 72, 60 or 48
Subsets	1
Gaussian Filter	0 mm

* Counts and time details are given in Table 3.

Table 2
Comparison of time between different modes of acquisition.

Scan Type	Start Time	Phantom Activity (MBq)	Scan duration (min)*
SSM 500kcounts	13:26	517	29.22
ADS 500Kcounts	14:14	471	25.70

* Scan duration is corrected for decay.

Table 3
The different stop conditions used in SPECT phantom imaging.

Scan name	Counts
Full time (20 sec)	128 k
Half time (10 sec)	64 k
Quarter time (5 sec)	32 k

Table 4
The total time for multiple bed SPECT-CT acquisition using ADS and SSM mode (20 s per view, 60 views per head).

	1-Bed SPECT-CT		2-Bed SPECT-CT		3-Bed SPECT-CT	
	ADS	SSM	ADS	SSM	ADS	SSM
Bed 1 Time (min)	20	23.5	20	23.5	20	23.5
M	1	1	1	1	1	1
Bed 2 Time (min)	–	–	20	23.5	20	23.5
Movement	–	–	1	1	1	1
Bed 3 Time (min)	–	–	–	–	20	23.5
M	–	–	–	–	1	1
CT	2	2	2	2	2	2
Total Time (min)	23	26.5	44	51	65	75.5

a conjugate gradient reconstruction algorithm provides similar SPECT sensitivity and quantification accuracy as SSM by including resolution recovery and noise reduction strategy.

WB-SPECT/CT involves multiple bed positions to cover a larger field of view (FOV) of the body than a standard single FOV SPECT/CT. Various approaches have made whole-body (WB) SPECT/CT feasible in routine practice [9]. Studies have suggested that WB-SPECT/CT is a valuable tool for metastatic workup compared to planar whole-body scintigraphy (PWB) [10,11]. Also, from the quantification perspective, i.e., in uptake measurements or dosimetry, SPECT/CT provides improved accuracy compared to planar scintigraphy [12]. As a result, WB SPECT/CT may replace PWB entirely [13]. In addition, planar images may be reprojected from SPECT/CT data similarly to conventional planar scans with a higher detectability rate [14]. By utilising a WB SPECT/CT workflow with planar reprojections, clinicians can read planar images, aided by historical familiarity, when transitioning to tomographic data only.

Incorporating standard SPECT/CT protocols into WB-SPECT/CT would result in impractically long acquisition times. Standard SPECT/CT acquisition time, such as those used for SPECT/CT with a single FOV, is usually around 15–20 min [15]. This could significantly increase the total study time in WB-SPECT/CT, where three or more axial FOVs are required. A WB-SPECT/CT acquisition would be impractically long if standard multi-FOV SPECT/CT protocols were applied, directly affecting patient comfort. By reducing the SPECT/CT image time, the translation of WB-SPECT/CT into clinical practice would be more accessible by reducing the probability of patient motion and bringing the overall acquisition time in line with PWB protocols. Besides, this could also be considered for implementation in a busy nuclear medicine department without the requirement for additional imaging time. Recent studies have shown promising results in reducing imaging time with SPECT/CT without compromising diagnostic image quality [16,17].

Here, we assessed the feasibility of incorporating ADS technology in routine WB SPECT/CT studies to reduce acquisition time and improve patient experience.

2. Methodology

2.1. Phantom description and preparing

A Jaszczak phantom with a measured volume of 6143 ml and fillable spheres with volumes ranging from 1.1 ml to 16.8 ml was used. The scanner was calibrated using ^{57}Co and ^{75}Se xSPECT reference sources for the accurate and reproducible quantification of three-dimensional (3D) ^{99m}Tc and ^{177}Lu SPECT images. The phantom filling was performed with a sphere-to-background ratio of 4:1 (^{99m}Tc) and 8:1 (^{177}Lu). The first set of phantom scans and analysis was carried out using ^{99m}Tc (340 MBq), which was later repeated using ^{177}Lu (1224 MBq).

2.2. Phantom imaging and reconstruction

Two different measurements were performed with ^{99m}Tc and ^{177}Lu

Table 5
A comparison of acquisition times between old and new scan protocols for different WB SPECT studies.

Study name	Old Protocol (Step and Shoot)		New Protocol (ADS)			
	Scan Parameters	Scan Duration (SPECT only)	Scan Parameters	Clinical justifications	Scan Duration (SPECT only)	Time-Saving
99mTc Tektrotyd	SSM, 20 s per view	2 × 23.5 = **47 min**	ADS, 20 s per view	Maintain low noise	2 × 20 = **40 min**	15 %
177Lu PRRT	SSM, 20 s per view	2 × 23.5 = **47 min**	ADS, 20 s per view	Maintain low noise	2 × 20 = **40 min**	15 %
177Lu PSMA	SSM, 20 s per view	3 × 23.5 = **70.5 min**	ADS, 10 s per view	Accept increased noise and maintain quantitative accuracy	3 × 10 = **30 min**	57 %

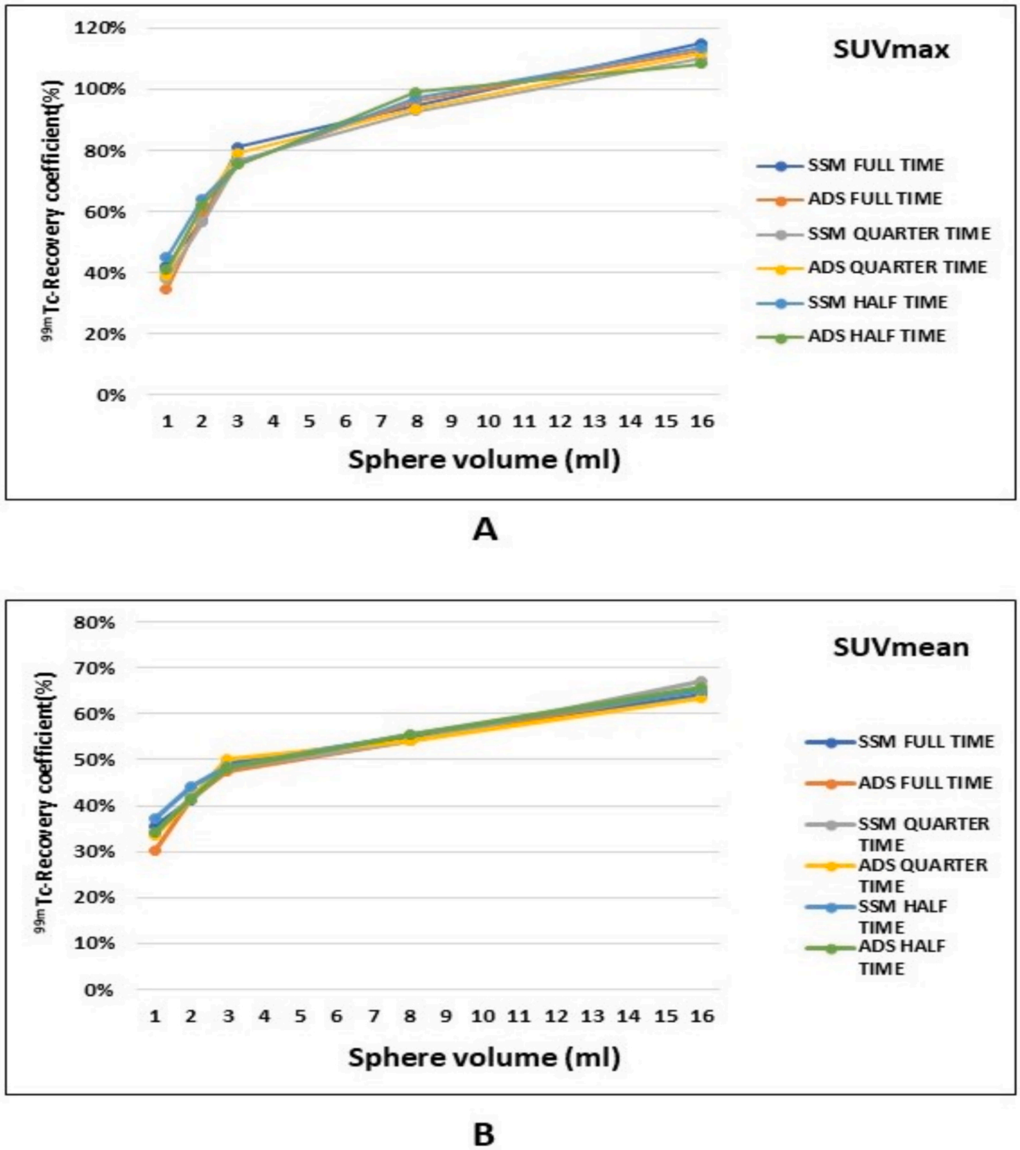


Fig. 1. Recovery curves are generated using SUVmax (A) and SUVmean (B) for SSM and ADS modes for different sphere volumes filled with ^{99m}Tc activity.

Table 6
A comparison of SUV between SSM and ADS in the phantom background filled with ^{99m}Tc activity.

	SUVmax	SUVmean
SSM Full time	1.17	1.01
ADS Full time	1.26	0.99
SSM Half time	1.36	0.97
ADS Half time	1.38	0.97

filled phantoms on a Symbia Intevo Bold SPECT/CT scanner with low-energy high-resolution (LEHR) collimators and medium-energy general purpose (MEGP) collimators, respectively. Table 1 provides detailed acquisition and reconstruction parameters. All the reconstructed images were corrected for scatter, attenuation, and resolution recovery. To ensure comparable counts between different acquisitions, the acquisition protocol used the stop-on count setting. When scanning with stop on counts, the first two projections are used to acquire the desired number of counts, while all subsequent projections acquire for the time that the first projection took so that all projections have the same acquisition length. We use low-dose CT for anatomical co-registration and attenuation correction of SPECT images. The xSPECT reconstruction algorithm was used for image reconstruction, while xSPECT Quant software was used to quantify scans, using inbuilt sensitivity factors for different isotopes.

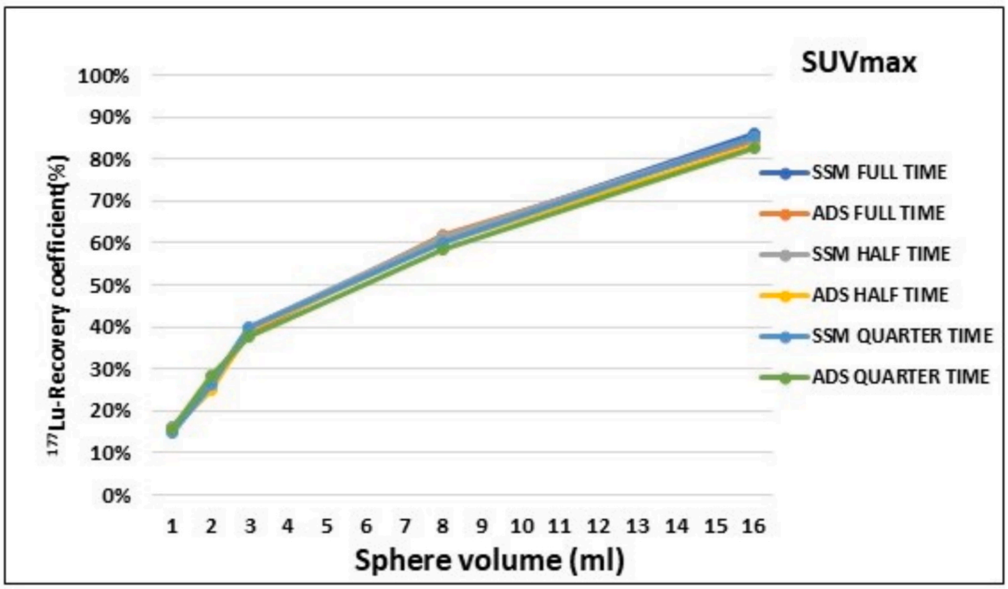
2.3. Comparison of scanning modes using ^{99m}Tc Jaszczak phantom

An initial comparison of scanning modes (SSM and ADS) was carried out using a ^{99m}Tc phantom. Table 2 compares times when the scanner is set to use different modes. A comparison was made to ensure that all scanning modes resulted in a similar (±1%) number of counts per second of scan time per becquerel activity.

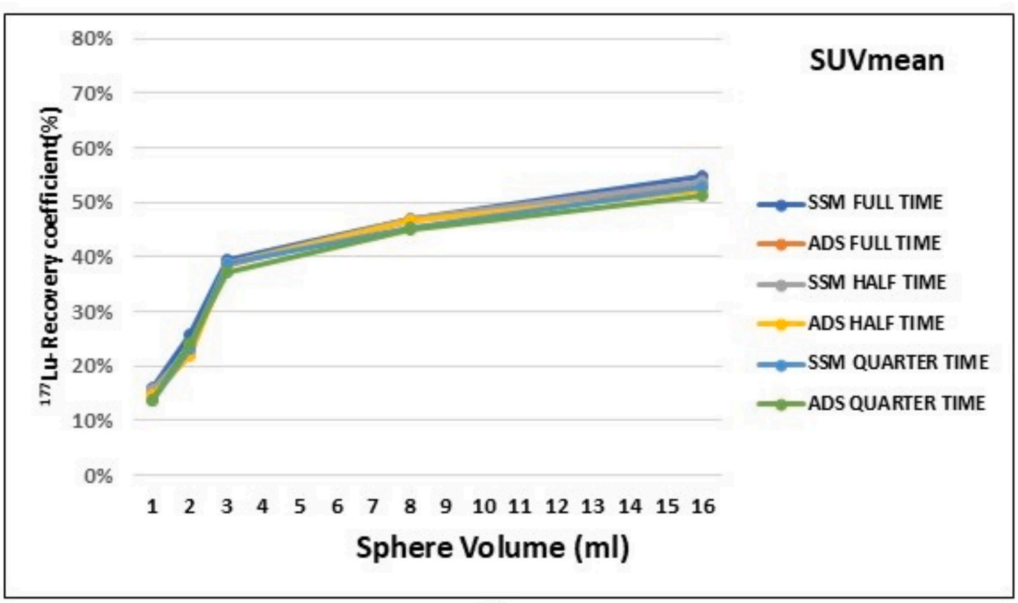
To select the acquisition length, the scanning was performed using a clinical WB ^{99m}Tc Tektrotyd and ^{177}Lu PRRT SPECT/CT workflow, respectively, for phantoms filled with ^{99m}Tc and ^{177}Lu activity (20 s per view, 60 views per head and SSM). The average count from both imaging sessions was 128 k. These counts matched patient WB ^{99m}Tc Tektrotyd SPECT scans (average 123 k counts). All subsequent scans were set to end on counts instead of time to account for decay in the activity of the phantom. The details of different acquisition stop

Table 7
The percentage change in ^{99m}Tc SUV results with different acquisition types from absolute SUV (standard full-time SSM).

	Sphere volume (ml)									
	1.07		2.1		3.65		8.58		16.84	
Type	max	*mean*	max	*mean*	max	*mean*	max	*mean*	max	*mean*
ADS Full time	−19 %	−17 %	4 %	2 %	−7%	−2%	1 %	−2%	−2%	2 %
SSM Half time	−10 %	−6%	−2%	2 %	−5%	−2%	−2%	−2%	−4%	5 %
ADS Half time	−7%	−8%	9 %	2 %	−2%	2 %	−1%	−2%	−3%	0 %
SSM Quarter time	7 %	3 %	12 %	7 %	−6%	−2%	2 %	0 %	−2%	2 %
ADS Quarter time	−2%	−6%	9 %	2 %	−7%	−2%	4 %	0 %	−6%	3 %



A



B

Fig. 2. Recovery curves are generated using SUVmax (A) and SUVmean (B) for SSM and ADS modes for different sphere volumes filled with ^{177}Lu activity.

Table 8
A comparison of SUV between SSM and ADS in the phantom background filled with ^{177}Lu activity.

	SUVmax	SUVmean
SSM Full time	1.11	1
ADS Full time	1.07	0.96
SSM Half time	1.14	0.96
ADS Half time	1.08	0.92
SSM Quarter time	1.24	1.03
ADS Quarter time	1.22	0.95

conditions per frame used for ^{99m}Tc and ^{177}Lu SPECT are mentioned in Table 3.

2.4. Image analysis

SUVmean and SUVmax recovery were calculated for different spheres to check the quantitative accuracy of SSM and ADS modes with different acquisition times. Here, CT images were used to draw the volume of interest (VOIs) for six spheres. 16 cm^3 VOIs were also drawn in a background region, away from hot spheres. The xSPECT quantification tool was used to obtain the SUVs in the VOI. An SUV was calculated by dividing the activity concentration by the total activity administered within the phantom and normalising it to the phantom weight. The recovery curve (RC) was generated from recovery coefficients for different sphere volumes with SSM and ADS modes. Recovery coefficients were calculated using the SPECT acquisition mode based and true activity concentration in the sphere as mentioned in Equation 1:

$$\text{Recovery coefficient} = \frac{\textit{Measured activity concentration in VOI}}{\textit{True activity concentration in sphere}} \tag{1}$$

2.5. Statistical analysis

All the statistical and data analyses were performed using Microsoft Excel. The absolute difference between measured SUV was expressed by percentage difference.

3. Results

The scan duration was timed with ADS and was found to be, on average, 3.5 min quicker each time compared to SSM as mentioned in Table 2 and 4. Based on ^{99m}Tc phantom work, in our clinic we switched WB ^{99m}Tc-Tektrotyd scans to ADS mode. After the ^{177}Lu work, we switched WB ^{177}Lu-PSMA and ^{177}Lu-PRRT post-therapy and dosimetry scans to ADS mode. The scan duration for full-time multiple-bed SPECT acquisitions in ADS and SSM mode is demonstrated in Table 4. A comparison of old and new scan times for different WB SPECT scans with ADS mode is given in Table 5.

3.1. Quantitative and qualitative assessment with ^{99m}Tc

Fig. 1 shows the RC generated from percentage recovery coefficients for different sphere volumes with SSM and ADS modes. The recovery coefficient using SUVmean with full time SSM and ADS mode for 16 ml, 8 ml, 4 ml, 2 ml and 1 ml was 0.62 & 0.61; 0.54 & 0.54; 0.48 & 0.48; 0.40 & 0.40 and 0.30 & 0.30, respectively. No systematic difference in recovery was noted between SSM and ADS acquisition modes for different sphere sizes. Smaller spheres had lower recovery coefficients and were likely affected by the partial volume effect (PVE). The SUV results with ADS mode were stable in the phantom background region compared to SSM (Table 6). The details of the percentage change in SUVs from full-time SSM are mentioned in Table 7.

3.2. Quantitative and qualitative assessment with ^{177}Lu

Fig. 2 shows the RC generated from percentage recovery coefficients for different sphere volumes with SSM and ADS modes. The recovery coefficient using SUVmean with full time SSM and ADS mode for 16 ml, 8 ml, 4 ml, 2 ml and 1 ml was 0.53 & 0.53; 0.46 & 0.47; 0.38 & 0.38; 0.22 & 0.23 and 0.15 & 0.15, respectively. No systematic difference in recovery was noted between SSM and ADS acquisition modes for different sphere sizes. The details of ^{177}Lu SUV results for SSM and ADS in the phantom background region are mentioned under Table 8. The details of the percentage change in SUVs from full-time SSM are mentioned in Table 9.

4. Discussion

Clinical utilisation of SPECT/CT has increased significantly over the last decade. However, SPECT/CT is more time-consuming than standard planar scans. WB SPECT/CT study improves the diagnostic accuracy of various diseases and clinical management of the patients and improves the accuracy of radionuclide therapy dosimetry compared to planar WB scans [10,11,18,19]. However, longer acquisition time and reduced patient comfort are major limitations for establishing WB SPECT/CT in routine practice [15].

4.1. ADS mode in diagnostic imaging using ^{99m}Tc

In our study, ^{99m}Tc phantom results with ADS mode were comparable to standard SSM with a 15 % reduction in acquisition time, saving 3.5 min per SPECT FOV. In clinical implementation, in the WB ^{99m}Tc-Tektrotyd SPECT/CT procedure, where the time per projection is the same and ADS is applied instead of SSM, the total scan time reduction is 7 min for a typical SPECT/CT scan spanning two fields of view. For the same scan duration as SSM, the image quality of ADS would be better than SSM, whereas time reduction is possible with ADS to get the same number of counts as SSM. Many strategies have been evolved in order to improve patient comfort and make WB SPECT/CT feasible for dosimetry and other nuclear medicine procedures [9–11]. An algorithm based on xSPECT and CT zonal mapping and a custom-designed phantom were used by Ichikawa et al. [20] in a study to perform a SPECT scan in 9 min without compromising image quality. The images acquired for 30 min duration were used as a standard. A study using a large field of view (FOV) Cadmium-Zinc-Telluride (CZT) SPECT/CT demonstrated a two-fold scan time reduction with single-bed SPECT/CT [21]. Another

Table 9
The percentage change in ^{177}Lu SUV results with different acquisition types from absolute SUV (standard full-time SSM).

	Sphere volume (ml)									
	1.07		2.1		3.65		8.58		16.84	
SUV:	max	*mean*	max	*mean*	max	*mean*	max	*mean*	max	*mean*
ADS 20 s (Full time)	0 %	0 %	4 %	−8%	0 %	0 %	2 %	0 %	−1%	−2%
SSM 10 s (Half time)	0 %	−6%	−4%	−15 %	−3%	0 %	−2%	0 %	−3%	−5%
ADS 10 s (Half time)	−6%	−13 %	0 %	−12 %	0 %	0 %	−2%	−4%	−1%	−4%
SSM 5 s (1/4 time)	−6%	−13 %	−15 %	−23 %	−5%	−5%	−2%	−2%	2 %	−5%
ADS 5 s (1/4 time)	0 %	−13 %	8 %	−8%	−5%	−5%	−5%	−4%	−3%	−7%

study using CZT SPECT showed the feasibility of WB bone scans with a shorter acquisition time [22]. However, CZT cameras are expensive and not yet widely available.

4.2. ADS mode combined with acquisition time optimisation in quantitative imaging for dosimetry using ^{177}Lu

Using a ^{177}Lu filled phantom with hot lesions we demonstrated that the combination of ADS mode with faster acquisition times in dosimetry studies where quantification accuracy is more important than image visualisation, such as post-therapy ^{177}Lu-PSMA scans, could result in time savings of 57 % by simultaneously applying ADS and reducing the time per projection. Furthermore, the results of our study showed that reducing acquisition time with ADS with conjugate gradient (xSPECT) algorithm did not significantly impact visual image quality and quantification accuracy. To the best of our knowledge, this is the first study to see the feasibility of incorporating ADS mode technology for fast whole-body SPECT/CT.

This technology could be an alternative to large FOV CZT SPECT/CT to reduce time. A study by Alqahtani et al. [16] optimised the acquisition time for WB bone SPECT/CT by optimising reconstruction parameters. It revealed a 50 %-time reduction with a total acquisition time of 8 min per bed; nevertheless, most of these results are based on phantom analysis. Salkica et al. [17] performed a SPECT study with a full acquisition time (15 s per frame) and reduced acquisition time for 75 % and 50 % and found a resolution recovery algorithm useful in order to compensate for noise generated with the shortening of SPECT acquisition time. Another study by Picone et al. [7] and Bailly et al. [8] demonstrated that CSSM can reduce acquisition time by 25 % without compromising qualitative and quantitative analysis. Our findings are in agreement with the above-reported ones, where we demonstrated the possibility of half acquisition time with ADS mode in WB ^{177}Lu-PSMA SPECT/CT for use in dosimetry without compromising the accuracy of lesion quantification. In a phantom study, we also tried using quarter-time acquisition. However, it was not used in patient examinations as images were noisy despite no significant difference in the recovery coefficient values.

SPECT can technically be performed over a shorter time, but the image quality should not be compromised. In the phantom study, we evaluated the effects of fast SPECT acquisition on the performance of WB studies. There was no substantial difference in quantitative phantom results for ADS compared to standard SSM acquisition mode without modulation of administered activity. In clinical practice, a difference in measurement is considered significant if the SUV variation is more than 30 % between the two acquisitions in PET [23]. In a study by Picone et al. [7], found no difference in their CSSM SPECT study compared to standard SSM [7]. We also found that no systematic difference between SSM and ADS, indicating no clinical impact of measurement variability. In another experiment, using ^{177}Lu we further tried to reduce imaging time to half with a phantom SPECT study in ADS mode. The recovery curve (RC) indicates how well the reconstructed image recovers the anticipated contrast between the sphere and the background activity. The recovery was not perfect for SUVmeans with smaller sphere sizes, due to the partial volume effect. The overall RC was stable between quarter-time, half-time, and full-time phantom images due to the convergence of the ordered subset conjugate gradient maximisation algorithm. The half-time scan is ideal for dosimetry in patients who are old, unstable or have a history of pain and are unable to tolerate the scans for extended period of time. Furthermore, the quarter-time SPECT is suitable for individualised patient dosimetry, where multiple time point imaging is required to cover the biokinetics of radiopharmaceuticals to tailor the dose. Quarter time also means quarter counts with ADS, so for multiple time point dosimetry, when we are scanning at 96 h, we don't have to increase scan duration much in order to get accurate quantification still as clinicians would typically visually report on the 24 h scan with 96 h being primarily used for dosimetry where higher levels of noise would be acceptable as long as quantitative accuracy is maintained. Ali et al. [24], examined half-time and full-time myocardial SPECT images with resolution recovery reconstruction and reported no difference in qualitative and quantitative results.

Noise is the most significant parameter, and it increases with the reduced SPECT time [17]. Our study used CT-based segmentation as noise in SPECT images could be a problem for threshold-based segmentation. The number of counts per projection largely determines an image's quality. Increasing the number of counts reduces noise and improves the quality of the image. We use the concept of CSSM in ADS mode. A CSSM acquisition provides more counts than SSM acquisitions since more data is collected as the detector moves between views [3]. Therefore, for the same scan time, the quality of CSSM would be better than SSM. Many studies highlighted the use of post-reconstruction Gaussian filters for the reduction of noise and improvement to signal the noise ratio of half-time images [16,17,22]. However, our protocol did not use a post-reconstruction filter as the scans were performed for dosimetry and the filter affects the quantification by degrading spatial resolution and amplifying partial volume effects [25].

4.3. Study outcomes, limitations and future work

Based on our phantom work, we switched our routine WB ^{99m}Tc-Tektrotyd and ^{177}Lu-PRRT scans to ADS mode. Moving to WB, SPECT/CT was implemented with a low-dose CT scan for anatomical localisation and attenuation correction to reduce the radiation exposure compared to diagnostic CT. The effective dose for an eyes to thighs CT for localisation and attenuation correction (non-diagnostic) is ~ 6.5 mSv [26,27]. The effective CT dose for a single FOV depends on the location, for example an abdominal CT for localisation and attenuation correction (non-diagnostic) is ~ 2.85 mSv.

A limitation of our study is that we didn't perform the qualitative and quantitative analysis on patient images. Also the Jaszczak phantom is not ideal for mimicking the torso and the IEC phantom could be a better option. Furthermore, future work needs to be done to use phantoms to provide realistic body organs and shapes to validate quantitative results. We didn't perform the measurement uncertainties due to the unavailability of the scanner for multiple acquisitions. When counts are relatively low, such as WB dosimetry scans acquired after day five, we did not analyse the performance of ADS acquisitions with conjugate gradient algorithms. Future work should be performed to evaluate qualitative and quantitative results with ADS modes with lower counts and conjugate gradient algorithms (e.g. Poisson resampling patient data) to reduce the scan time further. It would be worth checking the clinical utility of ADS mode in list mode in terms of lesion detectability and quantification accuracy as list mode was not available on this scanner. We are also working towards implementing quarter-time ADS phantom results in routine WB SPECT studies acquired for dosimetry.

5. Conclusion

We demonstrated that using ADS technology, a 15 %-time reduction could be achieved in our WB SPECT/CT scans (20 sec projections) without any change in quantitative analysis, resulting in faster scans in cancer patients. We also found that the examination time could be reduced further by implementing a half-time or quarter-time ADS mode in routine practice without compromising quantitative accuracy. The improvements in WB SPECT will induce less motion artefact, especially for patients with pain and improve the accuracy of disease diagnosis and personalised dosimetry.

6. Contributions

TM and SM substantially contributed to the study's concept, acquisition and interpretation of data. AN substantially contributed to the data acquisition, manuscript drafting and data analysis. All authors critically reviewed and revised the manuscript draft before the final version was approved.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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