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Evaluation of PET list data-driven gated motion correction technique applied in lung tumors

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Abstract

Purpose PET/CT is an important tool for tumor staging or evaluation of treatment response, especially for lung tumors. However, due to patients' free-breathing, the static PET image could be blurred, resulting in decreasing in image quality and incorrect quantitative values. The purpose of this study was to evaluate whether the Q.Static scan mode with the novel PET list data-driven gated (DDG) technique decreases the lesion blurring problems in lung cancer patients.

Methods 194 patients with lung tumors were retrospectively reviewed. DDG Q.Static scan mode was set with 3 beds to cover the whole chest and the upper abdomen in their routine PET/CT scans. It was activated automatically when sensed significant respiratory motion. Routine reconstruction algorithm was applied to the data. Only those lesions located in the motion-corrected areas were measured and calculated for statistics.

Results There were 124 out of 194 patients whose acquisition beds at least one bed activated the DDG Q.Static procedure. However, only 49 out of 124 patients showed lesions in their activated beds. Compared to noncorrection data, DDG Q.Static data showed improved accuracy by increasing SUV_{max} and SUV_{mean} by 8.52% (9.20 ± 5.42 to 9.74 ± 5.42) and 8.65% (6.11 ± 3.68 to 6.48 ± 3.68). And, MTV was reduced from 6.54 ± 8.58 to 5.55 ± 7.33 (14.79% reduction). For subjective image quality, DDG Q.Static data was scored higher than noncorrection data.

Conclusions This study demonstrated that both quantitative values and image quality were improved after correction. The DDG Q.Static technique provided an easier way to correct motion artifacts in PET/CT scans.

Keywords Data driven gated (DDG) · Q.Static · Respiratory motion correction · PET/CT

1 Introduction

Positron Emission Tomography/Computed Tomography (PET/CT) with 18F-fluoro-2-deoxyglucose (18F-FDG) offering tumor metabolism image and anatomic image simultaneously is considered as an accurate modality for evaluating lung cancer. It can effectively assess the malignancy of solitary pulmonary nodules and metastatic lesions. The excellent detection abilities make PET/CT scan become an integral part of lung cancer staging in recent years [1-4]. However, due to static PET acquisitions taking a few minutes for each axial field of view, patients' free-breathing cause PET images blurring especially for tumors in the thorax and abdomen. The respiratory motion artifacts degrade PET image quality. The degradation potentially results in decreased lesion detectability, underestimated measured standard uptake value (SUV), overestimated measured metabolic tumor volume (MTV), all of which impact image interpretation [5-8].

In the past, there were many motion correction methods that could mitigate the artifacts by utilizing an external device to detect respiratory information, e.g. elastic chest belt, Real-time Position Management (RPM) system, respiratory temperature sensor, and spirometer [9-12]. However, setting these external gating devices was not only time-consuming and inefficient but increasing technologists radiation exposure.

Nowadays, a device-less data-driven gated (DDG) technique called Motionfree® (GE Healthcare, Waukesha, WI) was launched. Motionfree is an algorithm based upon principal component analysis (PCA), that determines the magnitude of respiratory impact to the data. The method analyzes the coincidence data and converts it to respiratory waveforms without any external devices [13-15]. Q.Static (GE Healthcare, Waukesha, WI) scan mode is a phase-based gating correction method that extracts a fraction of PET data from the end-expiration smoother parts of breathing cycles. Because of acquiring the relatively stable breathing period, the Q.Static reduces respiratory motion artifacts and generates a corrected image. However, executing the Q.Static scan mode needs to use an external device to detect respiratory information.

The vendor combines Q.Static and Motionfree techniques called DDG Q.Static, which provides an easier way to acquire end-expiration phase data in deviceless way. The user only needs to set the coverage for desiring correction areas. DDG Qstatic is activated and corrects the image automatically when the respiratory motion is significant. So, the purpose of this study was to assess that the data driven gated (DDG) Q.Static technique mitigates PET respiratory artifacts and improves PET image quality and quantitation accuracy in lung cancer cases.

2 Materials and methods

2.1 DATA ACQUISITION

The current study was retrospectively studied from October 2019 to February 2020 in our hospital. Patients who were confirmed primary lung cancer and arranged whole-body PET/CT scans by clinical physicians were reviewed. Lung metastatic lesions cases or cases with too many lesions to measure were excluded. A total of 194 patients were eligible for criteria. It consisted of 98 men and 96 women with a mean age of 65 ± 13 years (range: 32-90 years) and a mean BMI of 23.7 ± 3.6 kg/m²(range: 16.9-33.3). All the data collection and analyses performed in this study were approved by the Institutional Review Board.

The patients were all injected with 3.7 MBq/kg $\pm 10\%$ of 18F-FDG after fasting for at least 4 hours and serum glucose concentrations were less than 200 mg/dl, then PET/CT scans were obtained 60 minutes after injecting radiopharmaceutical. All PET/CT scans were performed with Discovery MI DR (GE Healthcare, Waukesha, WI, USA). A clinical whole body PET/CT protocol was used for each patient to acquire from the top of the skull to the middle of the thigh. A free-breathing CT was acquired first and used the following parameters: tube voltage, 120 kVp; effective tube current, smart mA (range from 30 to 130 mA); pitch of 0.984:1; gantry rotation time 0.5s; and 3.75 mm slice thickness. No intravenous contrast agents were used. After the CT scanning, Static PET was acquired with 2 minutes per bed position and used the list-mode and the time of flight (TOF) technique.

All the patients were requested to breathe steadily and regularly during the whole scan time. The DDG Q.Static technique arranged to detect respiratory motion from bed 3 to bed 5 which were covered the whole thorax and upper abdomen (Fig. 1.a). First, the DDG Q.Static would determine whether it needs to be activated. It analyzed the PET coincidence data and calculated a unitless ratio, R, which presented the strength of the signal being respiratory-like. The R value was calculated in

46 real-time. The manufacturer suggested that the R value sets 15.0 as a threshold to assess whether the respiratory motion is
 47 significant. If the calculated R value exceeded the threshold, the DDG Q.Static acquisition mode was activated. Then, PET
 48 acquired phase of DDG Q.Static was preset 30% offset and 50% width, which was the stable phase of the breathing cycle. A
 49 total acquisition time of the DDG Q.Static activated bed increased to achieve a consistent signal. The settings of phase offset
 50 and phase width were also suggested by the manufacturer (Fig. 1.b). Then we recorded the bed whose R value was over the
 51 threshold for statistics.
 52

Fig. 1 (a) shows the PET scan range from head to thigh, and the DDG Q.Static scan mode sets from the third bed to the fifth bed which is covered the whole lung and upper abdomen. (b) is a regular breathing waveform. It shows the Q.Static respiratory motion software to extract PET data in the end of expiration which is considered as a stable phase in a respiratory cycle (Picture composition was from GE Motionfree®).

53 2.2 IMAGE RECONSTRUCTION AND ANALYSIS

54 There were two series of images that were reconstructed: Using the DDG Q.Static correction image (QSC) and no cor-
 55 rection image (NC). Both of them used the same CT-based attenuation correction and same PET reconstruction algorithm: 3-
 56 D VUE Point FX (ordered-subset expectation maximization algorithm with 2 iterations, 24 subsets, and 5mm Gaussian filter)
 57 and Sharp IR (PSF model). They were reconstructed with a 256 x 256 matrix and 3.27 mm slice thickness. The CT and PET
 58 fusion images were produced and analyzed with AW server 3.2(GE Healthcare, Waukesha, WI).

59 Both QSC and NC were drawn the 3D volume of interest (VOI) in the same size for the lung lesions and measured the
 60 maximum standardized uptake value (SUV_{max}), the mean standardized uptake value (SUV_{mean}), and metabolic tumor volume
 61 (MTV). The VOI was semi-automatically drawn with an iso-contour threshold of 50% SUV_{max} so that reducing artificial mistakes.
 62 The percentage variation of SUV_{max} ($\% \Delta SUV_{max}$) (1), SUV_{mean} ($\% \Delta SUV_{mean}$) (2), and MTV ($\% \Delta MTV$) (3) were calculated. If
 63 the patients had more than one lesion, only the highest SUV_{max} one at the activated bed was included in this study. Further-
 64 more, these lesions were divided into two groups according to their anatomical location. The upper lung group included
 65 bilateral upper lobes (S1-S3) and the lower lung group included bilateral middle and lower lobes (S4-S10).
 66

$$\% \Delta SUV_{max} = \frac{SUV_{max, QSC} - SUV_{max, NC}}{SUV_{max, nc}} \times 100\% \quad (1)$$

$$\% \Delta SUV_{mean} = \frac{SUV_{mean, QSC} - SUV_{mean, NC}}{SUV_{mean, nc}} \times 100\% \quad (2)$$

$$\% \Delta MTV = \frac{MTV - MTV_{nc}}{MTV_{nc}} \times 100\% \quad (3)$$

67

68 2.3 IMAGE QUALITY ASSESSMENT

69 One physician who has over 10 years of experiences in the nuclear medicine field reviewed and scored the image quality
70 of two reconstructions (QSC and NC) subjectively. A 5-point Likert grading was applied to assess image sharpness and lesion
71 distortion to judge the effects of artifacts. For image sharpness, the reader reviewed QSC and NC at the same time and rated
72 the lesions as follows: 5 is an excellent image and lesion is shown clear; 4 is a good image with minimal blurring lesion; 3 is
73 an acceptable image; 2 is a poor image which affects diagnosis; 1 is a non-diagnostic image with severe blurring lesion. For
74 lesion distortion, the reader compared the lesion in PET and CT images and assessed that PET lesion distorted in external
75 morphology: 5 is excellent lesion external morphology and almost looks like CT one; 4 is >75% of lesion external morphology
76 similar to CT; 3 is moderate distortion image, 50%-75% of lesion external morphology similar to CT; 2 is 25%-50% of lesion
77 external morphology similar to CT; 1 is severe distortion image, <25% lesion of lesion external morphology similar to CT. The
78 images were not scored if the CT image could not be diagnosed or the external morphology could not be defined like atelec-
79 tasis and tumor necrosis.

80 2.4 STATISTICAL ANALYSIS

81 The VOI measured data were presented with mean $\pm$ standard deviation. Patients' characteristics and DDG Q.Static ac-
82 tivation were assessed by the Chi-square test. The Paired Sample t-test was used to assess the differences of the SUV_{max} ,
83 SUV_{mean} , and MTV for QSC and NC. The differences of SUV_{max} , SUV_{mean} , MTV, $\% \Delta SUV_{max}$, $\% \Delta SUV_{mean}$, and $\% \Delta MTV$ between
84 two groups (the upper lung and lower lung groups) were evaluated by the Mann-Whitney U test. The correlation between
85 $\% \Delta SUV$ and MTV was evaluated by simple linear regression analysis. A P value of < 0.05 was considered to be statistically
86 significant.

87 3 Results

88 In all 194 recruited patients, there were 124 (63.9%) patients whose R values were over the threshold and activated the
89 DDG Q.Static acquisition procedure for at least one bed. Most of the activated beds were bed 4 (80/124) and bed 5 (91/124)
90 in statistics, which completely covered the lower lung and diaphragm areas. On the contrary, Bed 3(3/124) covering the upper
91 lung was seldom activated in this study and was simulated with other beds (Table 1). No significant relationship was observed
92 in the DDG Q.Static activation and between the sex or BMI ($P > 0.05$).

Table 1 The activated bed(s) in 194 patients.

Activated bed(s)	Case	percentage
Bed 3 only	0	0%
Bed 4 only	33	17%
Bed 5 only	44	22.7%
Bed 3+4	0	0%
Bed 3+5	0	0%
Bed 4+5	44	22.7%
Bed 3+4+5	3	1.5%
NA	70	36.1%
Total	194	100%

Among 124 patients mentioned above, there were only 49 patients' lesions located at activated beds and the other 75 patients were excluded because they could not assess the correction ability of the DDG Q.Static. Only these 49 lesions were evaluated for quantitation accuracy and subjective image quality assessment.

For quantitation accuracy, Table 2 showed the quantitative value of QSC and NC. In most lesions, both of SUV_{max} and SUV_{mean} were significantly higher and MTV was less in QSC than in NC. The mean of SUV_{max} , SUV_{mean} , and MTV in QSC were 9.72 ± 5.42 , 6.48 ± 3.68 , and 5.55 ± 7.33 and those in NC were 9.20 ± 5.42 , 6.11 ± 3.68 , and 6.54 ± 8.58 , respectively ($P < 0.05$). Additionally, the $\% \Delta SUV_{max}$, $\% \Delta SUV_{mean}$, and $\% \Delta MTV$ were $8.54 \pm 11.62\%$, $8.65 \pm 11.49\%$, and $-14.79 \pm 20.70\%$. For subjective image quality assessment, each of the lesions got 4 scores after the reader reviewed. However, there were two cases that were not scored the lesion distortion because their CT images could not define external morphology. The average scores were 3.71 ± 0.61 and 3.14 ± 0.65 with QSC, 3.08 ± 0.75 and 2.98 ± 0.76 with NC in image sharpness and lesion distortion respectively. Overall, the image quality of QSC was scored higher than NC in image sharpness, but not obviously higher in lesion distortion. It improved 1.18 and 1.03 times in QSC compared with NC in image sharpness and lesion distortion respectively (Fig. 2).

Table 2 Compare results with and without DDG Q.Static correction quantitative values.

	SUV_{max}	SUV_{mean}	MTV
NC	9.20 ± 5.42	6.11 ± 3.68	6.54 ± 8.58
QSC	9.72 ± 5.42	6.48 ± 3.68	5.55 ± 7.33
Mean difference	0.52 ± 0.70	0.37 ± 0.49	-0.99 ± 2.21
Mean percentage difference (%)	8.54 ± 11.62	8.65 ± 11.49	-14.79 ± 20.70
Significance	$P < 0.01$	$P < 0.01$	$P < 0.01$

Data are displayed in mean $\pm$ SD
Mean difference = QSC - NC
Mean percentage difference = (QSC - NC)/NC $\times$ 100%

Fig. 2 Mean subjective image quality scores for QSC and NC. Error bars represent 1 SD.

Furthermore, of the 49 lesions, 25 were in the upper lung group, and the other 24 were in the lower lung group. In the group of the upper lung, the mean of SUV_{max} , SUV_{mean} , and MTV in QSC were 11.22 ± 5.56 , 7.48 ± 3.89 , and 5.14 ± 7.22 and those in NC were 10.92 ± 5.68 , 7.26 ± 3.92 , and 5.59 ± 7.28 , respectively. The $\% \Delta SUV_{max}$, $\% \Delta SUV_{mean}$, and $\% \Delta MTV$ were $4.29 \pm 9.20\%$,

3.99±9.33%, and -9.75±22.47%. In the group of the lower lung, the mean of SUV_{max}, SUV_{mean}, and MTV in QSC were 8.29±4.88, 5.53±3.27, and 5.95±7.55 and those in NC were 7.55±4.67, 5.01±3.12, and 7.46±9.73, respectively. The %Δ SUV_{max}, %Δ SUV_{mean}, and %Δ MTV were 13.43±12.28%, 13.85±11.90%, and -20.03±18.07%. The differences of %Δ SUV_{max}, %Δ SUV_{mean}, and %Δ MTV for the lower lung were significantly higher than those for the upper lung (P<0.05)(Table 3). However, the variation of SUV_{max} and SUV_{mean} (%Δ SUV_{max}, %Δ SUV_{mean}) were not significantly related to MTV (R²= 0.0034, R²= 0.007).

Table 3 Comparison results between the upper lung and the lower lung groups.

	Upper lung(n=25)	Lower lung(n=24)	Significance
SUV _{max,NC}	10.92±5.68	7.55±4.67	P=0.027
SUV _{max,QSC}	11.22±5.56	8.29±4.88	P=0.043
%ΔSUV _{max}	4.29±9.20	13.43±12.28	P=0.0011*
SUV _{mean,NC}	7.26±3.92	5.01±3.12	P=0.035
SUV _{mean,QSC}	7.48±3.89	5.53±3.27	P=0.071
%ΔSUV _{mean}	3.99±9.33	13.85±11.90	P=0.0003*
MTV _{NC}	5.59±7.28	7.46±9.73	P=0.38
MTV _{QSC}	5.14±7.22	5.95±7.55	P=0.624
%ΔMTV	-9.75±22.47	-20.03±18.07	P=0.03*

Data are displayed in mean ± SD.

*P-value < 0.05

4 Discussion

In this study, Table 2 showed that the quantitative values in QSC were significantly higher than those in NC (P<0.05). And the image scores in QSC were also higher than those in NC (Fig. 2). In other words, most of the lesions were significantly increasing SUV (increasing 8.54±11.62% in SUV_{max} and 8.65±11.49% in SUV_{mean}) and decreasing MTV (decreasing 14.79±20.70%) after the DDG Q.Static correction. By decreasing the influence of respiratory motion artifacts, the DDG Q.Static technique effectively upgraded the image quality and quantitation accuracy. This is an example shown in Fig. 3. A 68-year-old male with a right lower lobe lesion underwent PET/CT scan. NC presented not only blurred and unconcentrated lesion but distorted lesion's boundary that expanded to the liver causing a diagnostic mistake and quantitation underestimation. In contrast, the lesion in QSC was presented clear and concentrated on the lung accurately. Furthermore, this case's quantitative values were improved: SUV_{max} increased from 6.62 to 7.50 (13.29%), SUV_{mean} increased from 4.12 to 4.84 (17.48%), and MTV reduced from 4.23 cm³ to 1.59 cm³(-62.41%). The DDG Q.Static technique could provide better image quality and more accurate quantitative value undoubtedly.

Among all patients in our study, there were 124 (63.9%) patients who underwent DDG Q. Static procedure, of whose activated location included at least the fourth or fifth axial field of view (bed 4,5). This result could be interpreted that the respiratory motion seemed to be evident at the location of bed 4 or bed 5 that almost covered the lower lung and diaphragm areas. And for the quantitative value between the upper and lower lung groups, the result showed that the variation percentage of quantitative values in the lower lung group was significantly higher than those in the upper lung group. Combining the above two results, it could be inferred that the lower lung and diaphragm areas were moved violently by free-breathing, producing severe respiratory motion artifacts to degrade PET accuracy. Many past studies have shown similar results [16, 17]. Therefore, we thought that it is important to correct these artifacts, especially if the lesions are located in the lower lung area.

36 But not all the patients presented similar results in our study, a small number of patients showed SUV decreasing or
 37 MTV increasing after the DDG Q.Static correction. We thought there were two possible reasons that impacted the correction
 38 effect. The first reason was that the location of lesions was crossing two acquisition beds or located at the overlapped area.
 39 When one of the acquisition beds activated the DDG Q.Static technique and the other didn't, it would occur that the lesion
 40 was corrected partially, its quantitative values might be affected and cause this result. The second reason was that patients
 41 breathed irregularly and unstably. Since the DDG Q.Static set fixed parameters with 30% phase offset and 50% phase width
 42 to acquire the stable end-expiration phase, the irregular breathing method might affect the DDG Q.Static calculation to ex-
 43 tract the stable phase. In other words, the end-expiration phase data might not be acquired with unstable breathing patterns.
 44 Then, the corrected result might be varied. A previous study set the parameter with different phase offset and phase width
 45 to compare with the default one. They demonstrated that using variable phase offset and phase width which was optimized
 46 to each patient individual breathing cycles was superior to using fixed phase offset and phase width [18]. We considered that
 47 although the default parameters were not optimal for all patients, they were suitable for most people's breathing styles to
 48 extract the stable end-expiration phase. If patients need individual parameters to fit their breathing styles, the DDG Q.Static
 49 provides a retrospective modified option to extract the stable phase with suitable parameters for the patients in need.

50 In the subjective image quality assessment, we evaluated the lesions themselves rather than the overall image quality,
 51 because we would focus on assessing the DDG Q.Static technique decreases the level of lesion blur. For image sharpness, the
 52 result showed that most of the lesions in QSC were scored higher than those in NC because the DDG Q.Static decreased the
 53 effect of respiratory motion artifacts and made them more concentrated and clearer. For lesion distortion, the result showed
 54 there was no significant difference between QSC and NC. We thought that most of the lesions' edges in NC could be presented
 55 clear, so there was no significant different after the DDG Q.Static correction. However, there were still some lesions located
 56 in the vigorous motion area (such as lower lobe or close to diaphragm), that usually presented blurred and distorted edges

Fig. 3 A 68 y/o male has a lesion in the right lower lobe close to the liver. Comparison of the images of the QSC (upper row) and NC (lower row) in PET and fusion images. There was a severe lesion distortion in the NC PET image and it affected the interpretation.

57 before correction. In this condition, the scores of QSC would be much higher than NC. In summary, Our subjective image
58 quality scores confirmed the DDG Q.Static technique can reduce blur and improve the lesion conspicuity.

59 **5 Conclusion**

60 The data-driven gated (DDG) Q.Static technique is a convenient and powerful tool for respiratory motion-associated blur
61 elimination/correction. Without external devices, the DDG Q.Static can get respiratory information easily and calculate gated
62 images from PET list data, so that technologists can shorten the time of positioning patients to reduce radiation exposure.
63 Moreover, the DDG Q.Static technique is a useful method to decrease the effect of respiratory motion artifacts by extracting
64 the end-expiration phases in breathing cycles.

65 Our study demonstrates that the DDG Q.Static technique can eliminate motion artifacts and improve the quantitative
66 values (higher SUV and lower metabolic tumor volume) and image quality to upgrade the accuracy of PET. Especially, those
67 lesions are located at the lower lung or close to the diaphragm areas which are recognized as violent motion areas, they are
68 necessary to be corrected. In summary, the DDG Q.Static is a valuable and clinically helpful technique in PET/CT scans.

69 **Declarations**

70 **Conflict of Interest** There are no conflict of interest.

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