Spatio-temporal Constrained Adaptive Sinogram Restoration for Low-dose Dynamic Cerebral Perfusion CT Imaging

Zhaoying Bian[1,2,3], Dong Zeng[2,3], Tianwu Xie[1], Jing Huang[2,3], Qianjin Feng[2,4], Jianhua Ma[2,3], Habib Zaidi[1], *Senior Member, IEEE*

***Abstract*–Dynamic cerebral perfusion computed tomography (PCT) imaging shows its potential in acute stroke diagnosis by visualizing and quantifying hemodynamic information of cerebral tissue and vessels. However, high radiation dose imposed on patients during dynamic PCT scanning has aroused growing concerns. To address this issue, we proposed a spatio-temporal constrained adaptive sinogram restoration (ST-ASR) method to improve the quality of dynamic cerebral perfusion CT imaging with low-dose protocol. The proposed ST-ASR method explores the spatio-temporal correlation in dynamic cerebral PCT projections to develop a new spatio-temporal prior model for sinogram restoration, and conducts an adaptive sinogram weighting according to the noise variance of sinogram data. Experimental results with clinical patient data demonstrate that the proposed ST-ASR method can achieve noticeable improvements over existing adaptive sinogram restoration method in terms of noise reduction and quantitative evaluations for low-dose dynamic cerebral PCT imaging.**

I. INTRODUCTION

DYNAMIC cerebral perfusion computed tomography (PCT) imaging is a promising tool to visualize and quantify hemodynamic information of tissue and vessels throughout the brain, which is typically displayed in perfusion maps, such as cerebral blood flow (CBF), cerebral blood volume (CBV), and mean-transmit time (MTT) maps[1]. However, due to multiple three-dimensional image volume acquisitions protocol, dynamic cerebral PCT scanning imposes high radiation dose on the patients with growing concerns[2]. Minimizing the radiation dose in dynamic cerebral PCT imaging is a useful and interesting topic with ongoing research activities[3-5].

This work was supported in part by the National Natural Science Foundation of China under Grants 61701217, U1708261, 81701690, and 61571214, the Guangdong Natural Science Foundation under Grant 2015A030313271, the Science and Technology Program of Guangdong, China under Grants 2015B020233008 and 2015B010131011, the Science and Technology Program of Guangzhou, China under Grant 201510010039 and Grant 201705030009, and the China Postdoctoral Science Foundation funded project under Grants 2016M602488 and 2016M602489. Corresponding Author: Habib Zaidi (e-mail: Habib.Zaidi@hcuge.ch).

[1] Z. Bian (e-mail: zybian@smu.edu.cn), T. Xie and H. Zaidi are with Division of Nuclear Medicine and Molecular Imaging, Geneva University Hospital, Geneva, Switzerland.

[2] Z. Bian, D. Zeng, J. Huang, Q. Feng and J. Ma are with School of Biomedical Engineering, Southern Medical University, Guangzhou 510515, China.

[3] Z. Bian, D. Zeng, J. Huang and J. Ma are also with Guangzhou Key Laboratory of Medical Radiation Imaging and Detection Technology, Southern Medical University, Guangzhou 510515, China.

[4] Q. Feng is also with Guangdong Province Key Laboratory of Medical Image Processing, Southern Medical University, Guangzhou 510515, China.

To reduce the radiation dose in dynamic cerebral PCT imaging, lowering milliampere-second (mAs) during scanning is a simple way to conduct in clinic. However, the associated dynamic cerebral PCT images reconstructed from the low-mAs projection data by standard filtered back-projection (FBP) reconstruction method would be degraded by unavoidable noise-induced artifacts and would also influence the perfusion maps calculation accuracy. To address this issue, lots of low-dose dynamic cerebral PCT imaging methods have been developed[3-6], including image-based denoising methods[6], image-based deconvolution methods[4,5] and statistical iterative reconstruction (SIR) methods[3]. However, the distribution of noise in dynamic cerebral PCT images reconstructed by FBP method is non-uniform, which makes it a great challenge for image-based methods to fully take the noise properties into account. By modelling the measured projection data statistics properties and imaging geometry, the SIR methods could achieve a good performance for low-dose dynamic cerebral PCT imaging in an iterative scheme with complicated algorithm solving and heavy computational load.

In this work, we focus on an alternative way to improve the quality of dynamic cerebral PCT images via sinogram restoration by considering the measured projection data statistics properties. Similar with image-based methods and SIR methods, the spatio-temporal information within the dynamic cerebral PCT data is useful to improve the image quality. By exploring the spatio-temporal correlation in dynamic cerebral PCT projections, we proposed a spatio-temporal constrained adaptive sinogram restoration (ST-ASR) method for low-dose dynamic cerebral PCT imaging.

II. METHODS

A. Dynamic cerebral PCT sinogram restoration

Based on the noise model of low-dose CT sinogram developed in our previous work[7,8], the penalized weighted least-square (PWLS) cost function for low-dose dynamic cerebral PCT sinogram restoration can be expressed as:

$$\Phi(P) = (Y-P)^T \Sigma^{-1}(Y-P) + \beta R(P)\,, \tag{1}$$

where $Y = \{y_t,\ t = 1,2,\cdots,M\}$ and $P = \{p_t,\ t = 1,2,\cdots,M\}$ denote the measured and to-be-estimated dynamic PCT sinogram data wherein t is the index of time frame and M is the total number of dynamic frames, $R(P)$ is the regularization term, β is a smoothing parameter, and Σ is diagonal weight matrix with the elements of the sinogram variance $\sigma_{i,t}^2$ determined by the following mean-variance relationship:

$$\sigma_{i,t}^2 = \frac{1}{I_{i0}} \exp(\bar{p}_{i,t}) \left(1 + \frac{1}{I_{i0}} \exp(\bar{p}_{i,t})(\sigma_e^2 - 1.25) \right), \quad (2)$$

where I_{i0} denotes the incident x-ray intensity along ith projection path, $\bar{p}_{i,t}$ is the sample mean of sinogram data $y_{i,t}$ along ith projection path at time frame t, and σ_e^2 is the background electronic noise variance. In this work, the sample mean $\bar{p}_{i,t}$ is calculated by neighborhood averaging with a 3× 3 window, and the parameters I_{i0} and σ_e^2 can be measured through the standard routine calibration operation in modern CT systems[7].

B. Spatio-temporal constrained adaptive sinogram restoration (ST-ASR)

Considering the spatio-temporal correlation in dynamic cerebral PCT projections, we developed a spatio-temporal prior model for PWLS-based sinogram restoration to constrain the solution of the PWLS cost function. The spatio-temporal prior model is expressed as follow:

$$R(P) = \sum_t \sum_i \sum_{j \in N_i} w(i,j)(p_{i,t} - p_{j,t})^2 \quad (3)$$

where N_i is the neighborhood centered with pixel position i, and $w(i,j)$ is the weight describing the interaction degree between the sinogram data $p_{i,t}$ and $p_{j,t}$, which is calculated as:

$$w(i,j) = \frac{1}{Z(i)} \exp\left\{ -\frac{(i-j)}{2\sigma_s^2} \right\} \exp\left\{ -\frac{\|T(i) - T(j)\|^2}{2\sigma_t^2} \right\} \quad (4)$$

wherein parameters σ_s^2 and σ_t^2 control the spatial neighborhood and temporal dynamic correlation, respectively, $T(i) = \{y_{i,t}, t = 1, 2, \cdots, M\}$ represents the dynamic time intensity curve of PCT sinogram data at pixel position i, the normalizing factor $Z(i)$ is calculated as:

$$Z(i) = \sum_{j \in N_i} \exp\left\{ -\frac{(i-j)^2}{2\sigma_s^2} \right\} \exp\left\{ -\frac{\|T(i) - T(j)\|^2}{2\sigma_t^2} \right\} \quad (5)$$

Thus, the cost function of the proposed spatio-temporal constrained sinogram restoration is written as follow:

$$\Phi(P) = (Y-P)^T \Sigma^{-1} (Y-P) + \beta \sum_t \sum_i \sum_{j \in N_i} w(i,j)(p_{i,t} - p_{j,t})^2 \quad (6)$$

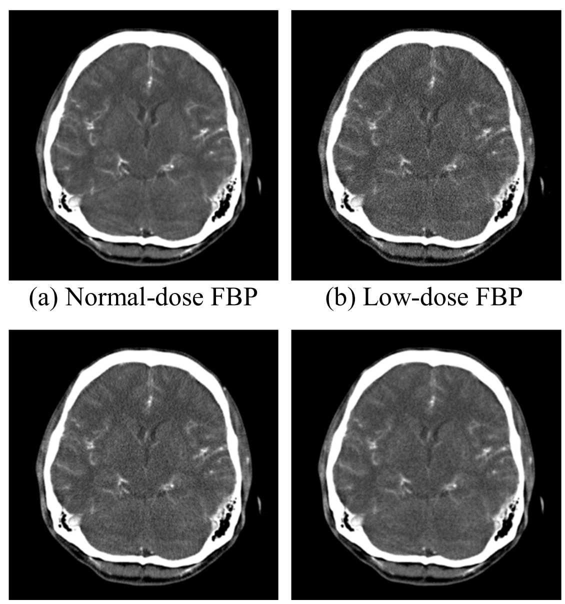
After sinogram restoration, an adaptive sinogram weighting is conducted same as the work[8] to avoid possible resolution loss, which is written as:

$$\hat{y}_{i,t} = w_{i,t} \cdot y_{i,t} + (1 - w_{i,t}) \cdot p_{i,t}, \quad \text{wherein} \quad w_{i,t} = \begin{cases} 1, & \sigma_{i,t}^2 \le \delta \\ 0, & \sigma_{i,t}^2 > \delta \end{cases} \quad (7)$$

where $\hat{y}_{i,t}$ is final weighted sinogram data for the following FBP reconstruction, and the threshold value δ is determined by the noise level.

III. Results and Discussions

To validate and evaluate the performance of the proposed ST-ASR method in dynamic cerebral PCT imaging, a set of clinical cerebral PCT data was used. The patient PCT data were acquired by normal-dose scan with the protocol as follow: 200 mA, 80 kVp, slice thickness of 5.0 mm, 1 s per rotation for duration of 40 s. To obtain the low-dose PCT data, we simulated the low-dose cerebral PCT sinogram data using the simulation method[9]. The CTDIvol for the simulated low-dose PCT data is about one-fifth of that for normal-dose PCT scan. To validate and evaluate the performance of ST-ASR method, ASR method using in the work[8] was also conducted for comparison.



(a) Normal-dose FBP (b) Low-dose FBP

(c) Low-dose ASR (d) Low-dose ST-ASR

Fig.1 The dynamic cerebral PCT images at 15th frame reconstructed by different methods

Figure 1 shows the reconstructed dynamic cerebral PCT image at 15th frame. Comparing with the FBP reconstructed image from normal-dose sinogram data, the FBP reconstructed image from low-dose sinogram data without sinogram restoration is corrupted by serious noise and artifacts, while the reconstructed images by ASR and ST-ASR methods show noticeable gains in the suppression of noise and artifacts. Comparing the results of two sinogram restoration method, ST-ASR method achieves better performance in noise reduction than ASR method.

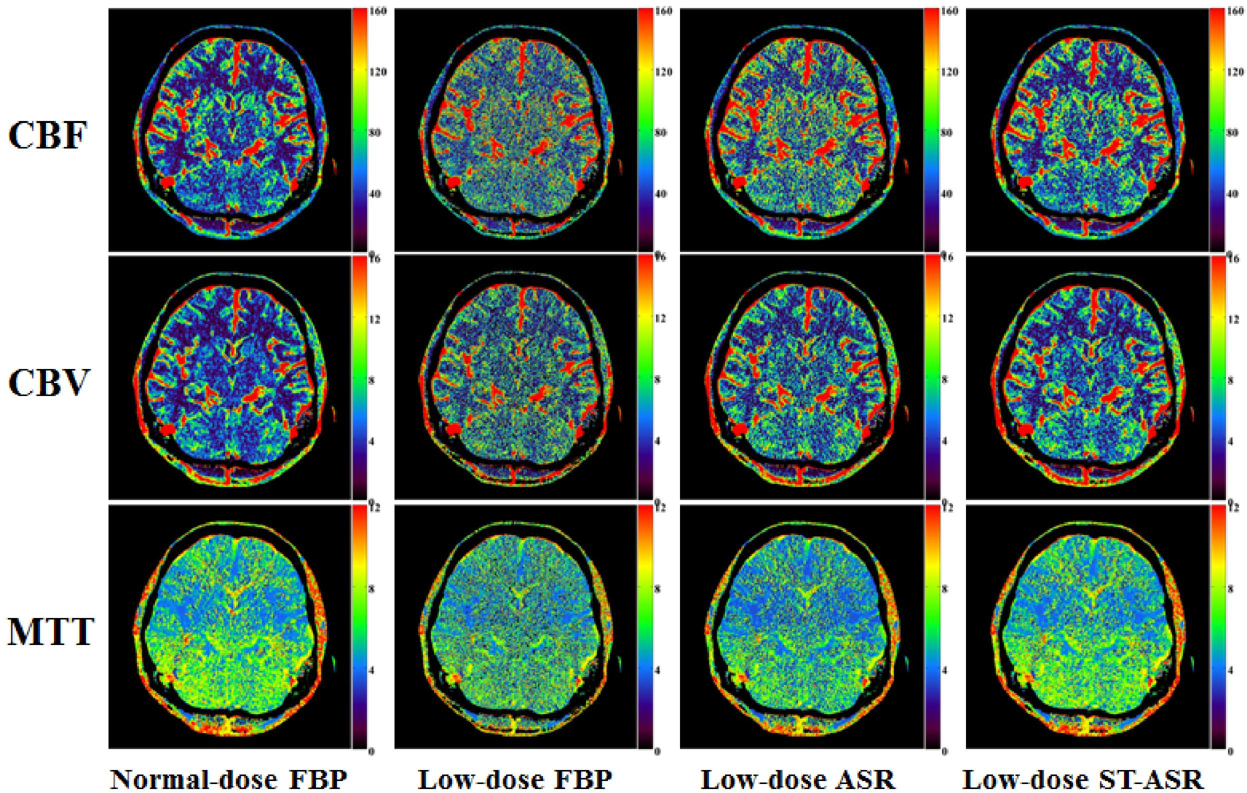


Fig.2 The CBF, CBV and MTT maps calculated from dynamic cerebral PCT images reconstructed by different methods.

To further evaluate the quantitative accuracy of hemodynamic parameter maps, figure 2 illustrates the CBF, CBV and MTT maps calculated from cerebral PCT images reconstructed by different methods. It also can be observed that the hemodynamic maps calculated from ST-ASR match better with normal-dose ones than those from FBP and ASR.

IV. CONCLUSION

In this work, we proposed a spatio-temporal constrained adaptive sinogram restoration method for low-dose dynamic cerebral PCT imaging by exploring the spatio-temporal correlation within dynamic cerebral PCT projections. The preliminary results show that the present ST-ASR method can achieve better hemodynamic maps than other existing methods in comparison with normal-dose ones.

REFERENCES

[1] E. G. Hoeffner, I. Case, R. Jain, S. K. Gujar, G. V. Shah, J. P. Deveikis, R. C. Carlos, B. G. Thompson, M. R. Harrigan, and S. K. Mukherji, "Cerebral perfusion CT: technique and clinical applications." Radiology, vol. 231, pp. 632-644, 2004.

[2] A. E. Othman, S. Afat, M. A. Brockmann, O. Nikoubashman, C. Brockmann, K. Nikolaou, and M. Wiesmann, "Radiation dose reduction in perfusion CT imaging of the brain: A review of the literature." Journal of Neuroradiology, vol. 43, pp. 1-5, 2015.

[3] D. Zeng, Q. Xie, W. Cao, J. Lin, H. Zhang, S. Zhang, J. Huang, Z. Bian, D. Meng, Z. Xu, Z. Liang, W. Chen, and J. Ma, "Low-Dose Dynamic Cerebral Perfusion Computed Tomography Reconstruction via Kronecker-Basis-Representation Tensor Sparsity Regularization," IEEE Transactions on Medical Imaging, vol. 36, pp. 2546-2556, 2017.

[4] R. Fang, A. Gupta, J. Huang, J, and P. Sanelli, "TENDER: Tensor non-local deconvolution enabled radiation reduction in CT perfusion, " Neurocomputing, vol. 229, pp. 13-22, 2017.

[5] D. Zeng, X. Zhang, Z. Bian, J. Huang, H. Zhang, L. Lu, W. Lyu, J. Zhang, Q. Feng, W. Chen, and J. Ma, "Cerebral perfusion computed tomography deconvolution via structure tensor total variation regularization," Medical Physics, vol. 43, pp. 2091-2107, 2016.

[6] J. Ma, J. Huang, Q. Feng, H. Zhang, H. Lu, Z. Liang, and W. Chen, "Low-dose computed tomography image restoration using previous normal-dose scan," Medical Physics, vol. 38, pp. 5713-5731, 2011.

[7] J. Ma, Z. Liang, Y. Fan, Y. Liu, J. Huang, W. Chen, and H. Lu, "Variance analysis of x-ray CT sinograms in the presence of electronic noise background," Medical Physics, vol. 39, pp. 4051-4065, 2012.

[8] Y. Gao, Z. Bian, J. Huang, Y. Zhang, S. Niu, Q. Feng, W. Chen, Z. Liang, and J. Ma, "Low-dose X-ray computed tomography image reconstruction with a combined low-mAs and sparse-view protocol," Optics Express, vol. 22, p. 15190-15210, 2014.

[9] D. Zeng, J. Huang, Z. Bian, S. Niu, H. Zhang, Q. Feng, Z. Liang, and J. Ma, "A Simple Low-Dose X-Ray CT Simulation From High-Dose Scan," Ieee Transactions on Nuclear Science, vol. 62, pp. 2226-2233, 2015.