DIRECT ANEURYSM VOLUME ESTIMATION BY MULTI-VIEW SEMI-SUPERVISED MANIFOLD LEARNING

Liansheng Wang[⋆], *Shusheng Li*[⋆], *Yiping Chen*[⋆], *Jiankun Lin*[†], *Changhua Liu*[†], *Xiantong Zeng*[‡], *Shuo Li*[‡]

[⋆]School of Information Science and Engineering, Xiamen University, Xiamen, China.
[†]Department of Medical Imaging, The 174th Hospital of PLA, Xiamen, China.
[‡]Dept. of Medical Imaging, Schulich School of Medicine and Dentistry, University of Western Ontario

ABSTRACT

Accurate volume estimation of left atrial aneurysm plays an essential role in the early diagnosis and therapy planning. However, it is a challenging task due to huge shape variabilities of aneurysms and great appearance variations of images, which tends to be intractable for segmentation methods. In this paper, we propose a novel estimation method for direct estimation of atrial aneurysm volumes without segmentation. To handle the high variabilities and variations, we propose a new multi-view semi-supervised manifold learning (MSML) algorithm, which fuses multiple complementary features to generate compact, informative and discriminative aneurysm image representation by leveraging both labeled and unlabeled data. Based on the obtained image representation, we adopt random regression forests to conduct direct volume estimation. Our method for the first time achieves a fully automatic estimation of left atrial aneurysm volumes. Experiments on a clinical dataset of 67 subjects with a total of 1220 images show that our method achieves a high correlation coefficient of 0.91 with ground truth manually labelled by clinical experts and largely outperforms other methods, which demonstrates the effectiveness for aneurysm volume estimation and indicates its potential use in clinical practise.

***Index Terms*—** Volume estimation, Manifold learning, Left atrial aneurysm

Introduction

The left atrial aneurysm is a severe heart disease, which can produce compression symptoms with diverticulum oppressing neighboring atrium and ventricle leading to arrhythmias, embolic manifestations and heart failure [1]. Clinically, the volume of left atrial aneurysm is widely used to assess the severity of the aneurysm and track its progression. Currently, the volume is estimated and approximated using the diameters of the aneurysm manually obtained by clinical doctors, which, however, is subjective, inaccurate, non-reproducible and heavily labor-intensive. It is therefore highly desired to automatically estimate the left atrial aneurysm, which unwontedly has long been neglected due to the particular challenges caused by the complexity of the aneurysm.

Existing segmentation methods are not directly applicable due their shortcomings coupled with the particular challenges of the left atrial aneurysm. Recently, the direct estimation method [2, 3] without segmentation has emerged as an effective tool for clinical volume estimation of cardiac ventricles, showing great advantages over segmentation based methods [4] in terms of both efficiency and accuracy. Nevertheless, existing direct methods focus on volume estimation of ventricle and atrium whose boundaries are relatively distinct, and location, size, and shape have little change in different people. As a result, those direct methods can not be straightforwardly applicable for volume estimation of the left atrial aneurysm, which, unlike cardiac ventricles, demonstrates complex image appearance and huge shape variabilities.

In this paper, we propose a new direct method for volume estimation of the left atrial aneurysm. To handle the great image appearance variations and the huge shape variabilities of the aneurysm, we propose a multi-view semi-supervised manifold learning (MSML) algorithm, which enables effective fusion of multiple complementary features to generate informative and discriminative aneurysm image representation. We contribute in three major aspects: **(1)** propose the first direct method for automatic aneurysm volume estimation, which enables more accurate and efficient assessment of aneurysm; **(2)** propose a new multi-view semi-supervised manifold learning algorithm (MSML) for aneurysm image representation, which provides a general multi-view feature learning framework and can be extensively applied to other applications; **(3)** open a new direction on automatic analysis of the left atrial aneurysm by providing a large annotated dataset.

Aneurysm Image Representation

Multiple Low-Level Feature Extraction

We extract multiple low-level features, which are regarded as multi-view features, from aneurysm images to capture complementary information for aneurysm image representations.

978-1-5090-1172-8/17/$31.00 ©2017 IEEE

Authorized licensed use limited to: Northeastern University. Downloaded on October 06,2025 at 19:06:03 UTC from IEEE Xplore. Restrictions apply.

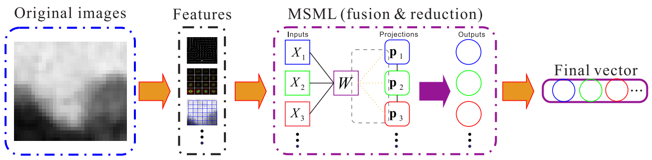


Fig. 1. A graphical interpretation of multi-view semi-supervised manifold learning.

Histogram of Oriented Gradients (HOG) [5] describes the main shapes of atrial aneurysm by counting distribution of local intensity edge based on oriented gradients, which is invariant to geometric and photometric transformations by operating on localized cells.

GIST [6] is to develop a low dimensional representation of a scene which is called the Spatial Envelope, without any form of segmentation. GIST provides a holistic representation of the atrial aneurysm image by capturing the global layout information of aneurysm.

Pyramid SIFT (P-SIFT) [7] builds local feature to capture local information by a multi-resolution set of descriptors. P-SIFT describes the patches of the atrial aneurysm image at different levels utilizing the advantage of both spatial pyramids and multi-scale local descriptor sampling.

Multi-view Semi-supervised Manifold Learning (MSML)

Instead of directly concatenating multiple features [4], we propose multi-view semi-supervised manifold learning (MSML) to effectively fuse multiple features to achieve informative and discriminative aneurysm image representation.

Multi-view Manifold Learning. Given training samples with low-level features from the v-th of V views: $X_v = [\mathbf{x}_1, \dots, \mathbf{x}_i, \dots, \mathbf{x}_N] \in \mathbb{R}^{D_v \times N}$, where D_v is the feature dimensionality of the v-th view, $\mathbf{x}_i$ is the i-th sample and its associated volume is y_i. We would like to seek for linear projections $\{\mathbf{p}_v\}_{v=1}^V$ to map features of each view into lower but discriminative feature spaces, where $\mathbf{p}_v \in \mathbb{R}^{D_v}$. Instead of learning one single projection for the features obtained by directly concatenating multi-view features, we propose learning optimal projections for features of each view in a general manifold learning framework.

$$\min_{\{\mathbf{p}_v\}_{v=1}^V} \sum_{v=1}^{V} \alpha_v {\mathbf{p}_v}^\top X_v L {X_v}^\top \mathbf{p}_v, \quad s.t.\ \mathbf{p}_v^\top \mathbf{p}_v = 1 \text{ and } \sum_v \alpha_v = 1 \tag{1}$$

where L is the Laplacian matrix [8] shared by different views and α_v is the weight associated with the v-th view. L is obtained by $L = D - W$, where W is the similarity matrix defined as $W_{ij} = \exp\left(\frac{-\|y_i - y_j\|^2}{2\sigma^2}\right)$, where $i, j = 1, \dots, N$ and $\sigma > 0$. The diagonal elements of W are set to be zeros, *i.e.*, $W(i,i) = 0$, and D is a diagonal matrix obtained by $D_{ii} = \sum_j W_{ij}$.

Since L is calculated using the volumes of samples, the supervision is incorporated into feature learning, obtaining a supervised manifold learning. As a result, the obtained low-dimensional features are highly discriminative. Multi-view features share the same Laplacian matrix, which enables to extract complementary while highly related features in the lower-dimensional spaces.

Unsupervised Learning. In order to leverage the abundant unlabeled data, which is largely and inexpensively available, we further introduce semi-supervised manifold learning. Assume that there are u unlabeled samples, and we have $\widetilde{X}_v = [\mathbf{x}_1, \mathbf{x}_2, ..., \mathbf{x}_N, \mathbf{x}_{N+1} ..., \mathbf{x}_{N+u}]$ of each view v. We would like to simultaneously maximize the covariance of multi-view features in the new lower dimensional space obtained by $\mathbf{p}_v$, which can further remove the redundant information from the original features to achieve compact representations.

$$\max_{\{\mathbf{p}_v\}_{v=1}^V} \sum_{v=1}^{V} \alpha_v {\mathbf{p}_v}^\top \widetilde{X}_v \widetilde{X}_v^\top \mathbf{p}_v, \quad s.t.\ \mathbf{p}_v^\top \mathbf{p}_v = 1 \text{ and } \sum_v \alpha_v = 1 \tag{2}$$

where α is shared with the objective in (1).

Objective Function. By integrating (1) into (2), we achieve semi-supervised learning by leveraging both labeled and unlabeled data and obtain the final objective function of the multi-view semi-supervised manifold learning (MSML) as follows:

$$\begin{gathered} \arg\min_{\{\mathbf{p}_v\}_{v=1}^V} \sum_{v=1}^{V} \alpha_v \mathbf{p}_v^\top (X_v L X_v^\top - \beta \widetilde{X}_v \widetilde{X}_v^\top) \mathbf{p}_v, \\ s.t.\ \mathbf{p}_v^\top \mathbf{p}_v = 1 \text{ and } \sum_v \alpha_v = 1 \end{gathered} \tag{3}$$

where $\beta \in (0, \infty)$ is a tuning parameter and α_v can be empirically obtained by cross validation. The projections $\mathbf{p}$ can be obtained by respectively solving an eigen-decomposition problem with respect to each view.

The object function of the MSML in (3) is able to jointly extract the complementary, discriminative features from high-dimensional raw multi-view features by supervised learning (1) and removes redundant, irrelevant information by globally maximizing the covariance of features in the lower-dimensional spaces (2). By leveraging both labeled and unlabeled data, the MSML provides a general semi-supervised manifold learning framework to effectively fuse multi-view features for informative and discriminative image representation.

Authorized licensed use limited to: Northeastern University. Downloaded on October 06,2025 at 19:06:03 UTC from IEEE Xplore. Restrictions apply.

Direct Aneurysm Volume Estimation by Random Forests

Regression forests have recently shown great power in predicting continuous data and become a primary regressor in medical image analysis. We adopt random forests for atrial aneurysm volume estimation due to that it can **1)** effectively disentangle the non-linear relationship between the multi-view feature of atrial aneurysm image and the volumes; **2)** generate highly precise predicted volumes without overfitting; and **3)** effectively handle heterogeneous multi-view features for efficient atrial aneurysm volume prediction.

Given a set of images for a test aneurysm, we pass them the proposed MSML to generate compact and discriminative image representations $\mathbf{x}_t$, following which the atrial aneurysm areas y_t are predicted using the trained regressor.

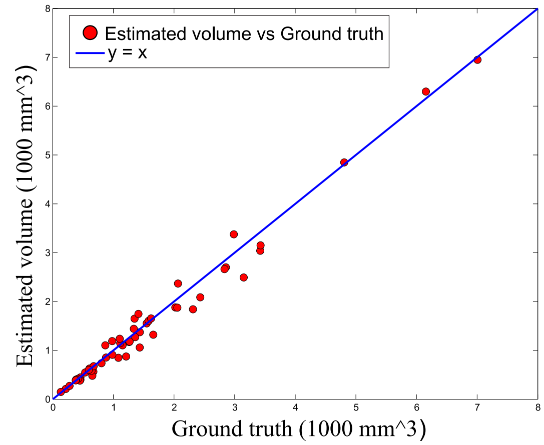
$$p(y_t|\mathbf{x}_t) = \frac{1}{T}\sum_{i=1}^{T} p_i(y_t|\mathbf{x}_t) \tag{4}$$

where T is the number of trees in the forest and p_i is the prediction from the i-th tree. The volume of the left atrial aneurysm is finally calculated by integrating the predicted areas in the sagittal direction.

Experiments and Results

Datasets and Implementation Details

The datasets were collected from the Department of Medical Imaging in the cooperation hospital, which contains 67 clinical subjects (1220 images in total) and some patients have two or three atrial aneurysms. In the datasets, there are 844 labeled images and 336 unlabeled images. In order to reduce the computational cost and improve the precision, the Region of Interest (ROI) is extracted from the original 2D images to avoid processing the whole images. The multiple low-level features are extracted from ROIs using HOG, GIST, and P-SIFT because of their effectiveness and complementarity. Through the proposed MSML, the dimensions of HOG, GIST and P-SIFT are reduced to 721, 512 and 721, respectively. The final feature vector as the image representation is of 1079 dimensions, which is then fed into random forests for atrial aneurysm volume estimation. For regression forests, 500 trees are used to learn the regression model, which can obtain satisfactory performance [4]. For volume estimation, we employ a leave-one subject-out cross-validation approach. The performance is evaluated by comparing to ground truth volumes using correlation coefficients, absolute estimation errors, and estimation accuracy. The correlation coefficient ($r \in [0, 1]$) measures the correlation between estimated and ground truth volumes, where a larger r indicates better performance. For more comprehensive evaluation of the performance, we further adopt two statistics, i.e. the mean (m_{vol}) and standard



(a)

Fig. 2. Comparison of the volumes obtained by the proposed method and manual segmentation (ground truth) for atrial aneurysm.

deviation (σ_{vol}) of estimated volume error for the left atrial aneurysm, which are defined as, $m_{vol} = \frac{1}{N}\sum_{i=1}^{N}\widehat{\xi_i}$ and $\sigma_{vol} = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(\widehat{\xi_i} - m_{vol}\right)^2}$ where N is number of subjects, and $\widehat{\xi_i}$ stands for the absolute difference between estimated volumes and those of ground truth.

Experimental Results and Quantitative Analysis

The proposed method for the first time achieves a fully automatic estimation of atrial aneurysm volumes and produces high estimation accuracy with a high correlation coefficient of around 0.91 by overcoming the great challenges including huge shape variabilities and great image appearance variations.

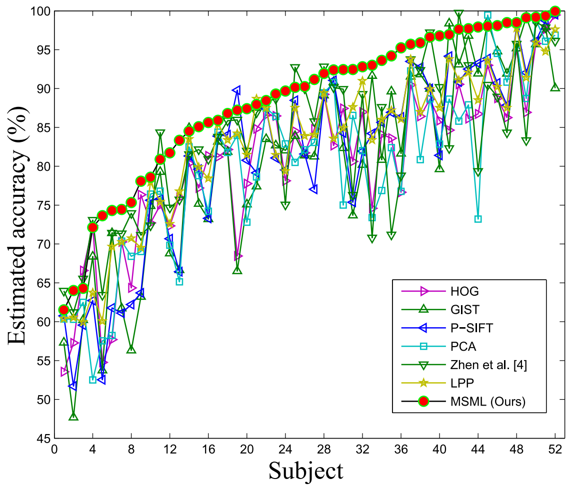
Fig. 2 shows the correlations between estimated and manually obtained volumes of atrial aneurysm, which indicates that the proposed method can produce volumes very close to those of ground truth. It is demonstrated that our method provides very close proximal estimated volumes to those of ground truth and the high estimate accuracy is clinical significant for assessment of the left atrial aneurysm in piratical use.

The advantage and effectiveness of the proposed MSML algorithm for the aneurysm image representation can also be demonstrated by comparing features obtained by other algorithms and existing direct estimation method. Table 1 shows that the MSML substantially and consistently outperforms the state-of-the-art features, i.e., HOG, GIST, and P-SIFT without any fusion and two representative dimensionality reduction methods, i.e., principal component analysis (PCA) and locality preserving projections (LPP) and the existing repre-

Authorized licensed use limited to: Northeastern University. Downloaded on October 06,2025 at 19:06:03 UTC from IEEE Xplore. Restrictions apply.

Table 1. The quantitative comparison in term of three metrics.

Feature	MSML	HOG	GIST	P-SIFT	PCA	LPP	Zhen *et al.* [4]
r	**0.910**	0.853	0.833	0.849	0.866	0.874	0.884
m_{vol}	**158.172**	280.908	300.937	272.721	295.591	249.369	234.044
σ_{vol}	**24.448**	38.4389	49.499	41.926	44.110	30.106	30.138



(a)

Fig. 3. The comparison of estimation accuracy with respect to subjects.

sentative direct estimation method (Zhen *et al.* [4]) in terms of mean and standard deviation.

Due to the discriminative and informative image representations obtained by the MSML which effectively fuses multi-view complementary features, our method can achieve more stable estimation than other volume estimation methods for all subjects as shown in Fig. 3. In general, our proposed method is able to generate a strong and reciprocal feature representation which can overcome the great variability and complex surroundings of the left atrial aneurysm.

Conclusion

In this paper, we have presented a new direct method for automatic estimation of the left atrial aneurysm volumes without segmentation. Specifically, we proposed a general multi-view semi-supervised manifold learning (MSML) algorithm to fuse multiple complementary features, which is able to generate compact, informative and discriminative image representations of the left atrial aneurysm. Regression forests is adopted for direct and efficient volume estimation. Our proposed method for the first time enables automatic volume estimation of left atrial aneurysm without segmentation and experimental results demonstrate our method achieves high estimation accuracy, which is clinically significant, indicating its potential use in the clinical diagnosis.

Acknowledgement.

This work was supported by National Natural Science Foundation of China (Grant No. 61671399, 61601392) and by the Fundamental Research Funds for the Central Universities (Grant No. 20720150110).

1. REFERENCES

[1] Sravan Reddy, AJ Ashwal, R Padmakumar, Rohith Reddy, and Sudhakar Rao, "An interesting and rare case of dextrocardia: Asymptomatic left atrial aneurysm in an adult," *EJCM*, vol. 3, no. 1, pp. 464–465, 2015.

[2] Mariam Afshin, Ismail Ben Ayed, Ali Islam, Aashish Goela, Terry M Peters, and Shuo Li, "Global assessment of cardiac function using image statistics in MRI," in *MICCAI*. 2012, vol. 7511, pp. 535–543, Springer.

[3] Zhijie Wang, Mohamed Ben Salah, Bin Gu, Ali Islam, Aashish Goela, and Shuo Li, "Direct estimation of cardiac biventricular volumes with an adapted bayesian formulation," *Biomedical Engineering, IEEE Transactions on*, vol. 61, no. 4, pp. 1251–1260, 2014.

[4] Xiantong Zhen, Zhijie Wang, Ali Islam, Mousumi Bhaduri, Ian Chan, and Shuo Li, "Direct estimation of cardiac bi-ventricular volumes with regression forests," in *MICCAI 2014*, pp. 586–593. Springer, 2014.

[5] Navneet Dalal and Bill Triggs, "Histograms of oriented gradients for human detection," in *CVPR*, 2005, vol. 1, pp. 886–893.

[6] Aude Oliva and Antonio Torralba, "Modeling the shape of the scene: A holistic representation of the spatial envelope," *IJCV*, vol. 42, no. 3, pp. 145–175, 2001.

[7] Lorenzo Seidenari, Giovanni Serra, Andrew D Bagdanov, and Alberto Del Bimbo, "Local pyramidal descriptors for image recognition," *IEEE TPAMI*, vol. 36, no. 5, pp. 1033–1040, 2014.

[8] X He and X Niyogi, "Locality preserving projections," in *Neural information processing systems*, vol. 16, pp. 153–160. 2004.

Authorized licensed use limited to: Northeastern University. Downloaded on October 06,2025 at 19:06:03 UTC from IEEE Xplore. Restrictions apply.