image fusion, SPECT-CT overlay, point-based method

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CT/SPECT IMAGE FUSION IN PATIENTS TREATED WITH IODINE-131

Computer tomography gives visualization of anatomical structures and abnormalities, but it lacks of functional information. On the other hand, single photon emission tomography provides the missing information about the tumour function, but it has relative low resolution and the localization of the visible focus may be difficult, especially when iodine ^{131}I is used. Thus, several methods of image fusion are applied. We present an algorithm of image fusion based on affine transformation. On the base of a phantom study, we showed that the created program can be a useful tool to fuse CT and SPECT images and then applied to patients' datasets. External marker method was used to align patient functional and anatomical data. Image alignment quality depends on appropriate marker placement and acquisition protocol. The program estimates maximal misalignment in a volume between the markers. Created acquisition protocol minimizes misalignment of patient placement on both CT and gamma camera, however misalignment derived from respiratory movements cannot be avoided. The proposed technique is simple, low-cost and can be easily adopted in any hospital or diagnostic centre equipped with gamma camera and CT. Fusion of morphology and function can improve diagnostic accuracy in many clinical circumstances.

1. INTRODUCTION

There are many three-dimensional imaging techniques which enable radiologists to create images of the human body and its internal structures. Depending on the modality, images provide different diagnostic information. Continuous development of image devices keeps quality and resolution of 3D images increase as well as decrease of acquisition time. The available computing power and dedicated software allows merging data from different modalities in order to obtain complementary information. The application performing medical data fusion can by useful for example for treatment planning, non-invasive diagnosis, stereo-tactic radio-surgery. The task of matching two datasets is not simple due to different images resolutions, patient's spatial orientation and misalignments of patient position. The goal of computation process is to find a spatial transformation. Having known this transformation registered datasets can be fused.

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There are three general methods for fusing medical images: point-based, surface-based and volume-based [5]. In the most cases a volume-based method with mutual information registration criterion is used [8]. Mutual information method is frequently applied to fuse brain imaging (CT and MRI modalities) in radiotherapy planning. Robust and completely automatic registration of multimodality images with minimal tuning and without prior segmentation or other pre-processing steps is provided by mutual information registration method.

Due to specificity of examination, in our case, we used point-based method. Having SPECT scintigraphy performed with iodine ^{131}I we often find isolated radiopharmaceutical uptakes without visualization of anatomical structures. Computed tomography provides missing by SPECT morphological information. Fusion of these modalities is not possible using mutual information method because of lack of corresponding structures [2,5,6,10]. The point-based method involves the determination of the corresponding points in the different images. These points can be defined by external markers placed on the patient's skin before acquisition, internal landmarks or stereo-tactic frames. Using the external markers provides better results then the internal landmarks [3]. Minimal number of external markers is four – this is minimal number of markers needed to determine three-dimensional space. By means of these markers, matrix of the affine transformation is computed. The matrix is globally applied to one of the datasets, in order to obtain data fusion.

2. MATHEMATICAL BASICS OF THE DATA TRANSFORMATION

As mentioned above to transform data from one space to another we use affine transformations [1,7,9]. Then we consider three-dimensional space, affine transformation can be written as the matrix equation:

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}, \tag{1}$$

where a_{ij} (i=1,2,3; j=1,…,4) are elements of transformation matrix. Simplifying form of the equation (1) we obtain:

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = M \times \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}. \tag{2}$$

Coordinates of points are homogenous, because of that size of affine matrix grows to 4×4 for 3D space transformation. Homogenous coordinates enable simplification of the form of many equations, especially when we consider operation of translation.

Transformation matrix M from above equation (2) can by decomposed into sequence of other affine transformations, which order is significant:

$$M = T \times R_z \times R_y \times R_x \times S\,. \tag{3}$$

where S represents matrix of scaling operation:

$$S = \begin{bmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{4}$$

R_x, R_y, R_z represents rotation matrixes (around all axes):

$$R_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{5}$$

$$R_y = \begin{bmatrix} \cos\beta & 0 & \sin\beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\beta & 0 & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{6}$$

$$R_z = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 & 0 \\ \sin\gamma & \cos\gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{7}$$

T represents translation matrix:

$$T = \begin{bmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{8}$$

If we want to decompose M matrix of any affine transformation we have to calculate parameters of each transformation: S_x, S_y, S_z, α, β, γ, T_x, T_y, T_z. Following equation show how to calculate matrix transformation M:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 & 0 \\ \sin\gamma & \cos\gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\beta & 0 & \sin\beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\beta & 0 & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (9)$$

equation after multiplying we can write as:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} s_x \cos\beta\cos\gamma & s_y(\sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma) & s_z(\cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma) & T_x \\ s_x \cos\beta\sin\gamma & s_y(\sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma) & s_z(\cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma) & T_y \\ -s_x\sin\beta & s_y\sin\alpha\cos\beta & s_z\cos\alpha\cos\beta & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (10)$$

To simplify equation we have replaced result of multiplying mentioned five matrices by one matrix containing all transformations. Now our transformation we can write as:

$$\begin{bmatrix} x_{NM} \\ y_{NM} \\ z_{NM} \\ 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x_{CT} \\ y_{CT} \\ z_{CT} \\ 1 \end{bmatrix}. \quad (11)$$

To calculate element of the *M* matrix (12 elements) we need 4 points in each space so:

$$\begin{bmatrix} x_{NM1} & x_{NM2} & x_{NM3} & x_{NM4} \\ y_{NM1} & y_{NM2} & y_{NM3} & y_{NM4} \\ z_{NM1} & z_{NM2} & z_{NM3} & z_{NM4} \\ 1 & 1 & 1 & 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x_{CT1} & x_{CT2} & x_{CT3} & x_{CT4} \\ y_{CT1} & y_{CT2} & y_{CT3} & y_{CT4} \\ z_{CT1} & z_{CT2} & z_{CT3} & z_{CT4} \\ 1 & 1 & 1 & 1 \end{bmatrix}, \quad (12)$$

after matrix division:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} x_{NM1} & x_{NM2} & x_{NM3} & x_{NM4} \\ y_{NM1} & y_{NM2} & y_{NM3} & y_{NM4} \\ z_{NM1} & z_{NM2} & z_{NM3} & z_{NM4} \\ 1 & 1 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} x_{CT1} & x_{CT2} & x_{CT3} & x_{CT4} \\ y_{CT1} & y_{CT2} & y_{CT3} & y_{CT4} \\ z_{CT1} & z_{CT2} & z_{CT3} & z_{CT4} \\ 1 & 1 & 1 & 1 \end{bmatrix}^{-1}. \quad (13)$$

However there is one condition, inverse matrix of CT markers must exist, so we can formulate it in other way:

$$\det \begin{bmatrix} x_{CT1} & x_{CT2} & x_{CT3} & x_{CT4} \\ y_{CT1} & y_{CT2} & y_{CT3} & y_{CT4} \\ z_{CT1} & z_{CT2} & z_{CT3} & z_{CT4} \\ 1 & 1 & 1 & 1 \end{bmatrix} \neq 0. \quad (14)$$

In practise if we want to translate it – we have to avoid placing markers on the same surface (in this case we are loosing information about third dimension).

Summarising, when we possess *M* matrix, which is our transformation matrix, we have to multiply all points from CT-space to find them corresponding points in NM-space, this is the basis to fuse data.

3. CONTROL OF MATCH QUALITY

Created computer program includes datasets alignment control. Applied fusion method is based on the points' location so quality of the fusion strongly depends on quality of precise location of the external markers. On the basis of information about markers coordinates and information loaded from DICOM (Digital Imaging and Communication in Medicine) files such as: pixel spacing and slice thickness, real distances between markers from different studies are computed [3]. Comparing distances between corresponding pairs of markers we estimate errors of markers location. This measure is useful for example to qualify which external marker is not correctly marked in program or not correctly placed on skin of the patient before one of the acquisition.

4. PROGRAM DESCRIPTION

Created program "Image-Fusion", realizes calculations mentioned above. As input data we use Microsoft Access database containing information about studies available on the local hard disc. Main input data are images saved in DICOM standard [4]. First step in program is to choose two studies of one patient but came from two different modalities (for example CT and NM). The most important stage in program processing is choosing markers location in two image sets.

This action impacts the most fusion errors, that is why it has to be made very carefully. Precision is needed as well in X, Y directions as in Z direction. Experienced operator chooses markers in pairs, for example one in CT slice and corresponding on SPECT slice.

As we have coordinates of four pairs of points, program is ready to make the computations and to transform one image space (smaller) to the other (bigger). Result of image fusion depends on earlier defined method of overlay. There are available: and, or, xor, minimal value, maximal value, sum, difference.

5. EXPERIMENTAL RESULTS

Image datasets were acquired with *SIEMENS E.CAM DUET* gamma camera and *SIEMENS SOMATOM 16* CT. During first phase of experiment we acquired several phantom studies. Cylindrical phantom with capillaries filled with technetium ^{99m}Tc was made. We placed four point markers on the surface of phantom. Markers were made of plexi-glass filled with cobalt ^{57}Co.

For testing purposes we acquired SPECT (matrix from 64x64 to 256x256, energy window was set for 122[keV] plus 140 [keV]) and CT (matrix 512x512, slice thickness form 1 to 5 [mm]). Quality of each fusion was calculated from distances between markers, as described above.

Figure 1 shows image fusion of phantom. Black and white layer represents data obtained with CT. It's a phantom and glass capillaries. Colour layer represents SPECT data and shows location of radioisotope inside capillaries.

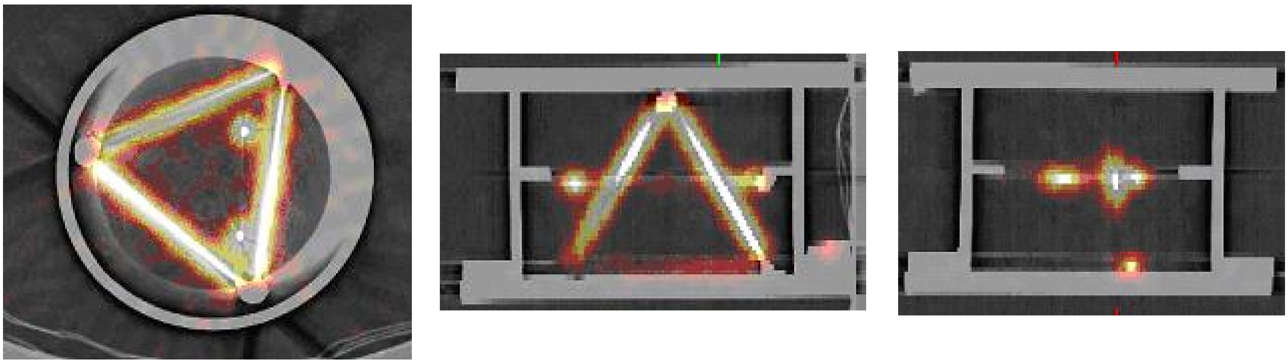

Fig. 1. Example of SPECT-CT fusion in a phantom study.

In second phase we fused image data of 15 diagnosed patients. For image fusion we choose patients with unknown localization of uptake in SPECT.

Figure 2 shows images fusion of patient (50 y.o.) with thyroid cancer and metastases to the cervical spine. In ^{131}I scintigraphy an uptake placed in neck area is showed, but it is equivocal whether it is uptake in local recurrence or uptake in metastases to spine. Image fusion shows uptake in spine.

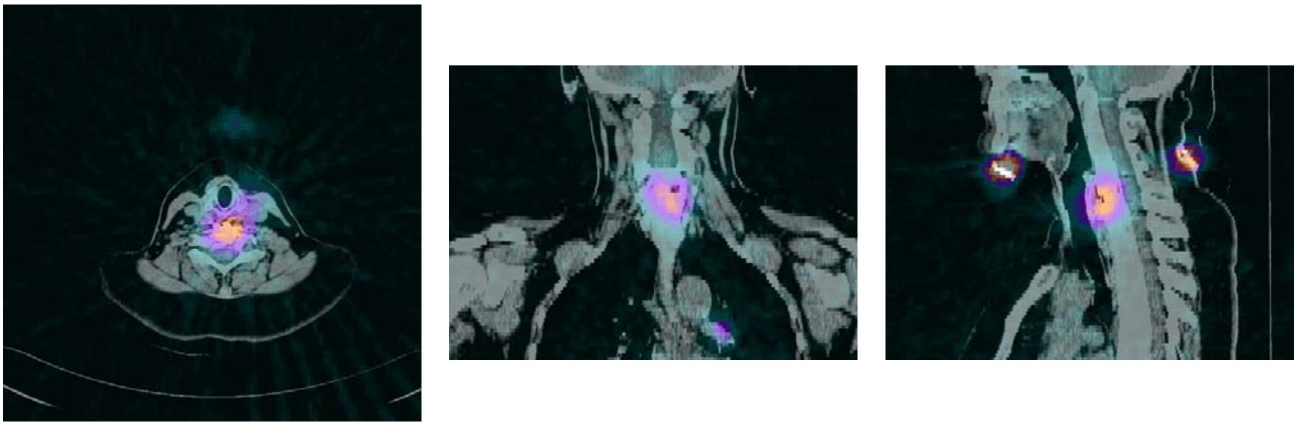

Fig. 2. SPECT-CT fusion in patient with thyroid cancer and metastases to spine.

6. CONCLUSIONS

Lack of anatomical information in iodine ^{131}I studies is a main problem of uptake localisation. Image fusion algorithm provides missing anatomical information. To solve affine transformation matrix four pairs of references points are needed. Quality control shows that proper acquisition protocol gives misalignment error less than 5 [mm] in neck and lung studies. In case of liver and abdomen studies, because of respiratory movements misalignment is bigger. These movements provides additional errors, witch cannot be calculated. This problem is also present in hybrid SPECT-CT or PET-CT systems, where hardware image fusion is available.

Software image fusion is very effective and low-cost method where SPECT-CT or PET-CT systems are not available.

In most of examined cases image fusion provides additional information that helps to make proper diagnose.

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