Physica Medica 53 (2018) 62–71

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

Original paper

Segmentation improvement through denoising of PET images with 3D-context modelling in wavelet domain

Carlos Huerga[a,*], Luis Glaría[b], Pablo Castro[c], Luis Alejo[a], José Bayón[a], Eduardo Guibelalde[d]

[a] Medical Physics and Radiation Protection Service, Hospital Universitario La Paz, Paseo de la Castellana 261, 28046 Madrid, Spain
[b] Radiation Oncology Service, Hospital Universitario La Paz, Paseo de la Castellana 261, 28046 Madrid, Spain
[c] Medical Physics Department, Hospital Universitario de La Princesa, C/Diego de León 62, 28006 Madrid, Spain
[d] Department of Radiology, Faculty of Medicine, Complutense University, Avenida Complutense, s/n, 28040 Madrid, Spain

ARTICLE INFO

Keywords:
Positron emission tomography
3D wavelet transform
Denoising
Segmentation

ABSTRACT

Positron emission tomography (PET) images have been incorporated into the radiotherapy process as a powerful tool to assist in the contouring of lesions, leading to the emergence of a broad spectrum of automatic segmentation schemes for PET images (PET-AS). However, not all proposed PET-AS algorithms take into consideration the previous steps of image preparation. PET image noise has been shown to be one of the most relevant affecting factors in segmentation tasks. This study demonstrates a nonlinear filtering method based on spatially adaptive wavelet shrinkage using three-dimensional context modelling that considers the correlation of each voxel with its neighbours. Using this noise reduction method, excellent edge conservation properties are obtained. To evaluate the influence in the segmentation schemes of this filter, it was compared with a set of Gaussian filters (the most conventional) and with two previously optimised edge-preserving filters. Five segmentation schemes were used (most commonly implemented in commercial software): fixed thresholding, adaptive thresholding, watershed, adaptive region growing and affinity propagation clustering. Segmentation results were evaluated using the Dice similarity coefficient and classification error. A simple metric was also included to improve the characterisation of the filters used for induced blurring evaluation, based on the measurement of the average edge width. The proposed noise reduction procedure improves the results of segmentation throughout the performed settings and was shown to be more stable in low-contrast and high-noise conditions. Thus, the capacity of the segmentation method is reinforced by the denoising plan used.

1. Introduction

Radiotherapeutic process is highly dependent on digital image in many stages of its process. From the prescription to the follow-up of the treatment [1].

Thus, new procedures appear to help in the interpretation and analysis. In general, image segmentation performs an important function in medical image processing and analysis [2]. In radiotherapy, these tasks have an essential role.

The positron emission tomography (PET) image has become a powerful tool, providing functional information on radiotracer localisation and extension in pathological regions [3], making it fundamental in the radiotherapeutic process, which needs to precisely contour regions of pathological uptakes for helping to define target volumes. The PET image is characterised by a low signal-to-noise ratio (SNR) and blurred edges in comparison with other modalities (CT or MRI). Small volumes are affected by the partial volume effect (PVE) [4], a limiting characteristic of PET images; thus, image preparation is necessary prior to segmentation. In many cases, this stage includes the application of noise reduction procedures.

Noise is one of the most relevant affecting factors in segmentation [5], and the noise reduction method is one of the keys to its application. The effectiveness of maintaining the uptake magnitude is one of the challenges facing denoising algorithms for PET images. The algorithm used must also preserve the edges to prevent contour modification of the objects and as well as prevent changes in the volumes of interest.

However, the recent Report of American Association of Physicists in Medicine (AAPM) Task Group No. 211 [6] shows that few authors provide information on presegmentation processing. The study by Geets et al. [7] is one of the few that explicitly includes this stage of preprocessing in the segmentation framework. In this study, the denoising process is performed within the segmentation framework, as a previous

* Corresponding author.
E-mail address: carlos.huerga@salud.madrid.org (C. Huerga).

https://doi.org/10.1016/j.ejmp.2018.08.008
Received 23 March 2018; Received in revised form 22 May 2018; Accepted 12 August 2018

step, by applying a bilateral filter (bf) and using a deblurring process to compensate for the effect of the system's point spread function (psf). Other authors [8,9] have used anisotropic diffusion filtering (adf) during the preparation stage of the image. The use of adf prevents blurring of the object's edges and preserves the average activity within a region. A combined approach of noise reduction and the process of segmentation by means of wavelets is shown in a study by Hanzouli et al. [10], using the anatomical information of the CT. The sensitivity of the segmentation process with the choice of the postreconstruction filter has been demonstrated by McGurk et al. [11], showing that the choice of the filter can produce wide variations in segmentation accuracy depending on the method used. Taking into account the previous Report of the AAPM [6], relatively few authors focus on the filtering process as a necessary step prior to segmentation; those who do, however, agree to use filtering procedures with favourable edge preservation properties.

We have proposed a wavelet-based noise reduction technique [12] with the ability to maintain uptake values while preserving the edges in "significant" regions (determining the local variance through the correlation of pixels and adapting the denoising process to the context). In this study, the extension to 3D was estimated by averaging the various directions of each voxel. We are proposing in the following paper an improvement when obtaining the relation of each voxel with its context directly in 3D (full 3D). This algorithm has two important features that make it especially interesting in segmentation tasks.

The first feature is significant noise reduction in the background regions, which had been outlined in the previous study, with an increase in contrast between various tissues (liver, lung, mediastinum) being considered as reference [13]. The second essential feature is edge preservation, which is crucial in segmentation tasks. This property is improved when the relationship of each voxel with its 3D surroundings is evaluated.

In this study, the capabilities of the improved noise reduction algorithm under various automatic PET segmentation schemes (PET-AS) are shown. In order to accomplish this demonstration, the denoising method we proposed has been compared with other methods of noise reduction frequently used in this process, showing how the efficacy of the segmentation method is reinforced by the used denoising plan.

2. Materials and methods

2.1. Datasets and ground truth

Various image datasets were used to show the effect of filtering using various methods of segmentation in a wide variety of images with various resolutions and various signal-to-background (S/B) ratios and noise levels. International Electrotechnical Commission (IEC) phantom images with hot inserts were used, considering various S/B ratios. The evaluation mask (the "Ground Truth") was determined by manual segmentation in CT images using a spherical 3D region of interest (ROI) which was later downsampled. This phantom was not without some limitations [6]; among others, the wall effect on the inserts [14] and its regular shape. Taking into account both considerations, a synthetic phantom with highly irregular lesions and a high number of radioactive environments was used. The evaluation mask in this case was the contour used for the generation of the lesion. In order to introduce an approximation to the clinical situation, simulated lesions were generated in six patients and were postprocessed with each filter. To assess the influence of filtering on manual contouring, lesions of known size dimensions were contoured by an expert radiotherapy oncologist. The details of each data set are reported below.

2.1.1. IEC phantom series: spherical objects

A NEMA IEC Body methacrylate Phantom 2001 was used, simulating a human thorax. It has an internal length of 194 mm and contains six spheres with internal diameters of 10, 13, 17, 22, 28 and 37 mm and a wall thickness of 1 mm. It includes a cylindrical cold central insert 180 mm in length and 51 mm in diameter. To simulate lesions of various sizes in distinct radioactive environments, the thorax volume was filled with variable activity concentrations of 18F, from 7.1 $kBq\,ml^{-1}$ to 23.3 $kBq\,ml^{-1}$; and the spheres were subsequently filled with an approximate concentration of 115 $kBq\,ml^{-1}$. Three scenarios were considered with approximate (S/B) ratios of 20:1 (high contrast), 10:1 (medium contrast) and 5:1 (low contrast).

The acquisitions were performed using a GE Discovery LS PET/CT scanner (General Electric Medical Systems, Milwaukee, USA). This hybrid scanner combines CT multislice LightSpeed with an 18-ring (14.5 cm) PET Advance NXi with bismuth germanate detector blocks. The PET data were acquired in two-dimensional mode, with a field of view of 50 cm and 4 min scan time. The PET images were reconstructed with CT-based attenuation correction without PSF correction, using the iterative ordered subset expectation maximisation (OSEM) method, with two iterations and 28 subsets. The PET images were reconstructed in a 128×128 matrix (35 slices) with a voxel size of $3.906\,mm \times 3.906\,mm \times 4.250\,mm$.

With this pixel size, some algorithms were unable to segment the smaller spheres. This becomes noticeable in low-contrast scenarios. Therefore, an extra reconstruction was performed in a 256×256 matrix with a voxel size of $1.953\,mm \times 1.953\,mm \times 4.250\,mm$ for the low-contrast case. This acquisition was named ~5:1 HR (low contrast and high resolution).

2.1.2. Simulated phantom series: irregular objects

Synthetic images were built using the PETSTEP simulator [15]. PETSTEP is a series of open-source routines developed in the Matlab environment (MathWorks, Natick, MA). PETSTEP operates in the framework of the computational environment for radiotherapy research (CERR) [16]. A GE Discovery 690 PET/CT scanner was modelled, using images of a 20-cm diameter cylindrical phantom, where irregular target tumours were manually contoured. Values used in the simulated scanner were as follows: random fraction, 0.07; scatter fraction, 0.37; sensitivity, 7.4; and true counts/kBq/s and PSF, 4.9 mm. The images were projected for obtaining sinograms in which the desired Poisson noise level was introduced and reconstructed using OSEM (two iterations and 24 subsets) with CT-based attenuation correction and without PSF correction. Images were in a 256×256 matrix with a voxel size of $2.058\,mm \times 2.058\,mm \times 4.250\,mm$. The tumours were simulated with an S/B ratio ~ 3.5 and a background activity of 13.3 kBq/ml. Seven lesions with volumes between 2.3 ml and 14.7 ml were generated Fig. 2 at the top shows a representative slice of the lesions) in four different noise environments, with varying acquisition times of 30 s, 60 s, 180 s and 360 s, corresponding to total counts of 1.58×10^7, 3.16×10^7, 9.48×10^7 and 1.90×10^8, respectively. The values of the background level noise of the nonfiltered images are shown in Table 1. The various filters described below were applied after the OSEM reconstruction.

2.1.3. Simulated clinical series

The PETSTEP simulator [15] was used as in the previous case to build the synthetic clinical images. In this case, the GE DLS PET/CT scanner was modelled, and the values were as follows: random fraction, 0.08; scatter fraction, 0.43; sensitivity, 6.4; and true counts/kBq/s and PSF, 5.1 mm. Reconstruction, as with the original images, was performed using a 2D-OSEM with CT-based correction without PSF correction, obtaining reconstructed images of 128×128 matrix with a voxel size of $3.906\,mm \times 3.906\,mm \times 4.250\,mm$. Synthetic realistic lesions were implanted in images from six patients: three head and neck and three lung and mediastinum. The lesions were modelled based on clinical images and were manually contoured in CT images and assigned an uptake level. The simulation was then performed using these contours. As in previous cases, the considered filters were applied after the reconstruction. Volumes were obtained via manual contouring by an expert radiation oncologist and were compared with the masks used