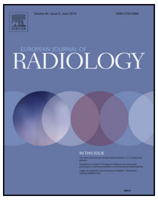
European Journal of Radiology 89 (2017) 27–32

Contents lists available at ScienceDirect

European Journal of Radiology

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



Fourier domain image fusion for differential X-ray phase-contrast breast imaging

Eduardo Coello[a,b,*], Jonathan I. Sperl[a], Dirk Bequé[a], Tobias Benz[b], Kai Scherer[c], Julia Herzen[c], Anikó Sztrókay-Gaul[d], Karin Hellerhoff[d], Franz Pfeiffer[c], Cristina Cozzini[a], Susanne Grandl[d]

[a] *GE Global Research, Garching, Germany*
[b] *Lehrstuhl für Informatikanwendungen in der Medizin & Augmented Reality, Institut für Informatik, Technische Universität München, Garching, Germany*
[c] *Lehrstuhl für Biomedizinische Physik, Physik-Department & Institut für Medizintechnik, Technische Universität München, Garching, Germany*
[d] *Institute for Clinical Radiology, Ludwig-Maximilians-University Hospital, Munich, Germany*

ARTICLE INFO

Article history:
Received 4 May 2016
Received in revised form
25 November 2016
Accepted 18 January 2017

Keywords:
Image enhancement
Image analysis
Medical imaging
X-ray phase-contrast mammography

ABSTRACT

X-Ray Phase-Contrast (XPC) imaging is a novel technology with a great potential for applications in clinical practice, with breast imaging being of special interest. This work introduces an intuitive methodology to combine and visualize relevant diagnostic features, present in the X-ray attenuation, phase shift and scattering information retrieved in XPC imaging, using a Fourier domain fusion algorithm. The method allows to present complementary information from the three acquired signals in one single image, minimizing the noise component and maintaining visual similarity to a conventional X-ray image, but with noticeable enhancement in diagnostic features, details and resolution. Radiologists experienced in mammography applied the image fusion method to XPC measurements of mastectomy samples and evaluated the feature content of each input and the fused image. This assessment validated that the combination of all the relevant diagnostic features, contained in the XPC images, was present in the fused image as well.

1. Introduction

Differential X-Ray Phase-Contrast (XPC) imaging [1,2] is a technique capable of retrieving information about X-ray attenuation, refraction and scattering, and visualize it in an attenuation contrast (AC), differential phase contrast (DPC) and dark-field contrast (DFC) image, respectively. Because of the presence of complementary information in these images, this imaging modality has the potential to improve medical diagnosis compared to conventional absorption-based X-ray imaging. In the field of breast imaging [3], XPC is of special interest as it may potentially overcome the limitations that X-ray mammography currently faces regarding screening and diagnosis of breast cancer, e.g. the lack of sensitivity and specificity. Recent studies [4–6] have shown that features, valuable for the diagnosis of breast cancer, are visible in the DPC and DFC images. However, for a successful translation into the clinical field, an effective methodology to combine and present the diagnostic information of the three images has to be designed and needs to be compliant with the experience of experts in radiology for its correct interpretation.

Image fusion [7] can be used to merge the acquired images representing different physical properties of the sample into a single enhanced image, making the visualization and analysis easier for diagnosis. The simultaneous acquisition of the XPC signals [1] is particularly convenient for image fusion, as the reconstructed AC, DPC and DFC images are spatially and temporally registered. This avoids the need of a preprocessing step that may introduce errors in the fusion process, thus preserving the reliability of the information presented.

Several image fusion algorithms have been proposed in the last years to combine reconstructed XPC images [8–11]. The fusion of AC and DPC signals using filtering functions that minimized noise was originally introduced in [8]. However the DFC signal was not taken into consideration for the process and no user interaction was allowed as the choice of the parameter values was fixed. Haas et al. [9] proposed an intuitive and tunable fusion approach to combine the three reconstructed XPC images via a linear combination of the inputs using barycentric coordinates, but without handling noise in the final result. In XPC mammography, wavelet-based image fusion methods that incorporate noise handling steps have been recently proposed [10,11]. Although a robust

---

* Corresponding author at: GE Global Research Europe, Freisinger Landstr. 50, 85748 Garching, Germany.
E-mail address: eduardo.coello@tum.de (E. Coello).

http://dx.doi.org/10.1016/j.ejrad.2017.01.019
0720-048X/

fusion is achieved using wavelet transforms, the optimization of the parameter values that control the fusion process is a rather complex task as the result highly depends on the wavelet function used and the decomposition levels chosen.

In the present work, we propose a Fourier domain image fusion framework that enables radiologists to intuitively and quantitatively combine, visualize and analyze relevant diagnostic information, obtained from XPC imaging, in a single fused image. Additionally, the method incorporates denoising of the input images to improve image quality. The algorithm performs the fusion in Fourier space where weighting functions are defined to select a frequency band with reduced noise. Then, the contribution of every channel is scaled and the fused image is retrieved via the inverse Fourier transform of the sum of the processed signals.

An evaluation of fused XPC images that contained relevant diagnostic information was performed in collaboration with experts in breast diagnostics. They applied the proposed methodology to preclinical ex-vivo data of XPC mammography in order to generate fused images and analyze the diagnostic features in them.

2. Materials and methods

2.1. Fourier domain fusion algorithm

A flexible and intuitive framework was designed to fuse the reconstructed XPC images in the Fourier domain by tuning a total of nine parameters. Through this approach the AC, DPC and DFC signals are combined following two principles: (i) individual image quality optimization, by weighting the spatial frequency components that best represent clinically relevant image features while removing noise and (ii) optimal weighted sum of the input channels, by scaling the content of each image according to the relevance of the clinical information contained in it. An overview of this method is presented in Fig. 1.

The algorithm takes as input the reconstructed XPC images $I_{\mathrm{AC}}(x, y)$, $I_{\mathrm{DPC}}(x, y)$ and $I_{\mathrm{DFC}}(x, y)$, which are assumed to be spatially registered. Initially, the images are normalized to unit intensity range:

$$I_{\mathrm{N}}(x, y) = \frac{I(x, y) - \min(I)}{\max(I) - \min(I)} \in [0, 1], \tag{1}$$

where $min(I)$ and $max(I)$ correspond to the minimum and maximum intensity values of the image I, respectively. In the case of $I_{\mathrm{DPC}}(x, y)$, due to the differential nature of the signal, the absolute value of the intensity is computed before normalization. After the images are normalized, the 2D discrete Fourier transform is computed:

$$\begin{aligned} Y_{\mathrm{AC}}(u, v) &= \mathcal{F}\{I_{\mathrm{AC,N}}(x, y)\},\\ Y_{|\mathrm{DPC}|}(u, v) &= \mathcal{F}\{I_{|\mathrm{DPC}|,\mathrm{N}}(x, y)\},\\ Y_{\mathrm{DFC}}(u, v) &= \mathcal{F}\{I_{\mathrm{DFC,N}}(x, y)\}. \end{aligned} \tag{2}$$

For each transformed image $Y(u, v)$, containing the spatial frequency components of $I(x, y)$, a 2D radial Gaussian function $G(\mu, \sigma; r)$, with unit amplitude and a constant angular value depending on the distance from the center r, is defined in Fourier space:

$$G(\mu, \sigma; r) = \exp\left(-\frac{(r-\mu)^2}{2\sigma^2}\right), \quad \text{with} \quad r(u, v) = \sqrt{u^2 + v^2}, \tag{3}$$

where μ corresponds to the mean and σ to the standard deviation of the Gaussian function chosen to select, respectively, the center and the range of the spatial frequency band to be weighted. Then, a scaling parameter s is assigned to weight the selected frequencies of each specific channel according to their information content. Finally, the fused image is retrieved by the inverse Fourier transform of this weighted sum of the signals and normalization is applied:

$$\begin{aligned} I_{\mathrm{Fused,N}}(x, y) = N(\mathcal{F}^{-1}\{&s_{\mathrm{AC}}\ \ G_{\mathrm{AC}}\ \ Y_{\mathrm{AC}} + s_{|\mathrm{DPC}|}\ \ G_{|\mathrm{DPC}|}\ \ Y_{|\mathrm{DPC}|}\\ &+ s_{\mathrm{DFC}}\ \ G_{\mathrm{DFC}}\ \ Y_{\mathrm{DFC}}\}). \end{aligned} \tag{4}$$

The linearity of the Fourier transform allow Eq. (4) to be expressed as:

$$I_{\mathrm{Fused,N}}(x, y) = N(s_{\mathrm{AC}}\ \ I^*_{\mathrm{AC}} + s_{|\mathrm{DPC}|}\ \ I^*_{|\mathrm{DPC}|} + s_{\mathrm{DFC}}\ \ I^*_{\mathrm{DFC}}) \tag{5}$$

where

$$\begin{aligned} I^*_{\mathrm{AC}}(x, y) &= \mathcal{F}^{-1}\{G_{\mathrm{AC}}\ \ Y_{\mathrm{AC}}\},\\ I^*_{|\mathrm{DPC}|}(x, y) &= \mathcal{F}^{-1}\{G_{|\mathrm{DPC}|}\ \ Y_{|\mathrm{DPC}|}\},\\ I^*_{\mathrm{DFC}}(x, y) &= \mathcal{F}^{-1}\{G_{\mathrm{DFC}}\ \ Y_{\mathrm{DFC}}\}. \end{aligned} \tag{6}$$

I^*_{AC}, $I^*_{|\mathrm{DPC}|}$ and I^*_{DFC} correspond to the SNR-optimized input images that were used for feature analysis and comparison with the final fused images. In the following sections, AC, DPC and DFC will refer to these processed images.

Radial Gaussian functions were chosen as they allow to select a frequency band with a smooth transition in a 2D space. Moreover, the effect of this filter function is controlled by only two parameters, μ and σ, which allows a better intuition of the fusion process. The high frequency nature of the information contained in the DPC image, promoted enhanced sharpness and minimal overlap with the feature content from the AC and DFC channels. The differential phase signal was preferred over its integral as it presented better visibility of these complementary high frequency features.

An advantage of this method is that the Fourier transform (FT) represents a well-known image decomposition approach that provides the full frequency spectrum of a signal, in contrast to the discrete wavelet transform (DWT) used in the multi-resolution (MR) framework proposed in [10,11], which creates a limited set of sub-representations with different frequency content. Moreover, the tunable parameters in this method are directly related to the frequencies and scale of each input channel. This allows the users to intuitively control the fusion process as the resulting images are defined in a continuous parameter space.

2.2. Image fusion procedure

In order to standardize the radiologists interaction with the fusion algorithm, a specific workflow was established. First, the individual input images – AC, DPC, and DFC – are visualized to find the features present in each channel and to down select the frequency band that best preserves the relevant information with reduced noise. In this step, the user optimizes the SNR by setting the μ and σ parameters of the Gaussian weighting functions. Then, the different channels are fused into a single image and the scaling factors s are tuned trying to enhance the image features that are of interest for diagnosis. Finally, windowing is performed to optimize the intensity range and the image visualization.

2.3. Mastectomy samples

The XPC data in this work were taken from a preclinical study on mastectomy samples, i.e. surgically removed breasts, which were scanned with the XPC imaging technique. The XPC measurements on the ablated samples were performed taking a craniocaudal projection in a Talbot–Lau grating interferometer of 27 keV design energy operated in the third Talbot order with a $\pi/2$ phase grating. Due to the small field of view (FOV) of the XPC setup, 4×4 sub-images were stitched together yielding to a total FOV of $12.8 \times 12.8\,\mathrm{cm}^2$. Further information on the XPC setup and acquisition parameters is detailed in [12]. In addition to the