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Original Research Article

Four-dimensional image processing of myocardial CT perfusion for improved image quality and noise reduction

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ABSTRACT

Background: Image noise and multiple sources of artifact may affect the accurate interpretation of myocardial CT perfusion (CTP) studies. Although artifact within the image is often time dependent, tissue characteristics remain unchanged irrespective of cardiac phase.
Objective: We assessed a new technique of 4-dimensional, spatiotemporal analysis, using redundant time domain information within additional phase acquisitions to reduce CTP image noise.
Methods: Four-dimensional analysis was assessed in a static phantom and in 10 CTP studies with invasive fractional flow reserve (FFR) correlation. For each voxel within the CTP study the distribution of local Hounsfield values was measured in both time and space with the use of a customized program within MATLAB software. These values were filtered to eliminate those likely to represent noise or rapidly changing beam hardening artifact. All CTP images were acquired within a single heartbeat with 320 detector-row CT. Image noise was quantified as the SD of voxel values within myocardial segments. Contrast was measured between normal and abnormal vascular territories as assessed by FFR.
Results: The mean image noise within the unprocessed CTP images was 30 HU (range, 23–42 HU). After 4-dimensional filtering the mean image noise was 22 HU (range, 15–29 HU). The mean reduction in image noise was 28% ($P < 0.001$). The mean contrast between normally perfused and ischemic segments was not significantly changed. The mean increase in contrast-to-noise ratio between ischemic territories and the myocardial average was 52% ($P < 0.001$).

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Conclusion: Four-dimensional analysis of CTP significantly reduces image noise and may assist in the assessment of myocardial perfusion studies.

1. Introduction

Myocardial CT perfusion (CTP) is a promising technique for the assessment of the hemodynamic significance of coronary disease, but it has 2 main difficulties. First, the difference between normal and underperfused myocardial segments is small compared with both the range of Hounsfield values within the image and the degree of noise present. Second, multiple sources of artifact affect interpretation, including motion, beam hardening, and detector electronic noise. Typically, multiple cardiac phases are acquired to mitigate these issues.

Two- and 3-dimensional (3D) image filtrations are commonly used to reduce image noise[1] and artifact[2]; however, the additional information present within the time dimension, reflected by additional phases, has largely been ignored.

Although artifact is often time dependent, tissue characteristics remain unchanged irrespective of cardiac phase. We developed a 4-dimensional (4D) image processing technique that analyses CTP voxels over both time and space, which may be used to eliminate rapidly changing and outlying values. The aim of the technique is to combine information contained within multiple redundant phases into a single image of improved image clarity to improve the diagnostic effectiveness of the CTP technique.

We assessed the effects of 4D image analysis on image quality in both a static phantom and a clinical cohort of 10 patients undergoing both CTP and invasive fractional flow reserve (FFR) assessment.

2. Methods

Four-dimensional filtering was initially assessed with a TOS Phantom (Toshiba Medical, Tokyo, Japan) incorporating well-demarcated areas of varying CT number, as well as clinically performed CT perfusion studies to assess the effect on noise and subjective image quality. Quantitative assessment of 4D filtering in the setting of CTP was performed in a consecutive cohort of 10 patients in whom both myocardial CTP and FFR assessment was performed and in whom at least 1 coronary artery had an FFR measurement of <0.8 or was occluded. All participants gave written informed consent, and the study protocol was approved by the local ethical review board.

2.1. *Four-dimensional filtering*

With the use of a customized program within Matlab software version 2010b (MathWorks, Natick MA, USA) we developed a method to collate image data from available phases within CTP images to create a 4D matrix of CT values across time and space. For each voxel within the myocardial volume, the Hounsfield values of immediately surrounding voxels were extracted across all phases. Outlying values more likely to represent noise were eliminated by applying a median filter across the extracted voxels.

To illustrate, a single voxel within the myocardium may be assigned a particular Hounsfield value. A 3D median filter might extract that Hounsfield value, as well as each adjacent voxel (9 values in total) and take the median value. In 4D filtration, these voxels are also extracted across every phase. When 10 phases are analyzed therefore, 90 voxel values will be extracted. Taking the median value of these voxels will present the value that is most prevalent and stable over both time and neighboring space. Transient changes in voxel values, as may be caused by motion or artifact passing through an area, will not be included in the filtered image because they are present in a minority of analyzed phases.

We used a median value filter because of its benefits in dealing with non-Gaussian noise, preservation of edge boundaries[3] (which is important for subendocardial ischemia detection), and robustness to small degrees of myocardial motion. The 4D filter was then applied and formally assessed in clinical myocardial CTP imaging.

2.2. *Assessment of 4D filtering within clinical CTP images*

All CTP acquisitions were acquired within a single heartbeat with the use of a 320 detector-row CT system (Toshiba Aquilion One) in accordance with previously described methodology.[4] Image acquisition occurred after 4 minutes of intravenous adenosine infusion at 0.14 mg/kg per minute and covered 75%–95% of the available R-R interval. Images were reconstructed at 2% phase intervals (14–20 milliseconds). Adaptive iterative dose reduction (AIDR) was used for 6 scans, whereas standard filtered back projection (FC02 kernel with beam hardening correction) was used for reconstruction of the remaining 4 scans.

Sequential phases with the least motion artifact derived from at least 10% of the R-R interval were selected to enable a sufficient time component for 4D analysis. On the basis of visual analysis, when additional motion free phases were present, these were also used for used for 4D analysis.

All patients underwent confirmatory invasive angiography and FFR measurement. Image noise was measured as the SD of Hounsfield values within each myocardial segment[5] at the mid-ventricular level at 0.5-mm slice thickness. Equally spaced circular regions of interest were placed in each myocardial segment in the same location on both filtered and unfiltered images with the use of ImageJ[6] image analysis software (National Institute of Health, Bethesda, MD, USA).