Fourier-based Reduction of Directed Streak Arifacts in Cone-Beam CT

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Abstract. Due to its adjustable scan trajectory, C-arm cone-beam CT has been used recently to acquire knee scans in an upright position. However, stabilization devices located outside the FOV introduce streak artifacts in the reconstructed images. This paper proposes a method to remove those streak artifacts. Using selective filtering of the Fourier transforms of the reconstructions, we propose a filter design that attenuates the frequencies that are responsible for the streak artifacts. The filter is constructed by taking both the frequency and the orientation of the introduced streaks into account. We compare our approach to a bandpass-filter. Our proposed method is able to reduce the streaks in the reconstruction remarkably while preserving edge information, whereas the bandpass-filter is not capable of preserving sharp edges in the filtered image. Moreover, our method yields an improved SSIM when comparing both filter techniques to simulated ground truth data.

1 Introduction

C-Arm Cone-Beam Computed Tomography (CBCT) is a versatile acquisition technique. There is a large scope of applications due to its flexible construction and big field of view (FOV) ranging from interventional to diagnostical applications. Nonetheless, several artifacts are present in CBCT scans such as scatter, beam hardening, truncation or ring artifacts.

To further improve the understanding of the knee function during loaded situations, CBCT scans under weight-bearing conditions are acquired [1]. Stabilization pipes for the patients are part of the acquisition set-up for those scans. However, since those pipes are located outside the FOV, vertical directed streak artifacts are present in the scans, as can be seen in Fig. 4 (a). In this case, only a fraction of the acquired projections contains information about this object, which is thus not sufficiently sampled and causing streak artifacts in the reconstructed images. Streak artifacts, which mostly appear from metal or sharp objects outside the FOV, are commonly reduced by metal artifact reduction algorithms [2] or view-alias alleviation techniques [3]. Spectral inpainting in the gradient domain was used to remove streaks in CT projections [4].

This paper proposes a technique to remove directed streaks artifacts by applying selective filtering in the frequency domain of the reconstructed images.

Compared to a standard bandpass-filter, our approach yields improved SSIM values compared to a simulated reconstruction.

2 Materials and Methods

2.1 Fourier Transform

For filtering in the frequency domain, the Fourier Transform of the respective image has to be computed. However, since an image $f(x, y)$ can be considered as a matrix containing discrete values, a 2D discrete Fourier Transform (DFT) is applied, where $F(u, v)$ is the frequency domain representation. Only the magnitude image $|F(u, v)|$ of the complex valued DFT result is relevant for our task, since each pixel represents a particular frequency contained in the spatial domain image. Consequently, if one wants to eliminate certain frequencies from an image, the corresponding pixels in the magnitude image $|F(u, v)|$ have to be attenuated before it is transformed back to spatial domain. In order to find the pixels responsible for the streaks artifacts in our CBCT knee scans, basic properties of the Fourier transformation have to be pointed out [5]. The magnitude image $|F(u, v)|$ is shifted so that its center is the origin of the frequency coordinate system. At this point, the horizontal component u and the vertical component v are zero. The value at this point $F(0, 0)$ represents the offset of the spatial image. As Fig. 1 illustrates, the further away a point is from the center in frequency domain, the higher the corresponding frequency. If the spatial image has vertically oriented streaks, its DFT is located near the horizontal axis u (right image in Fig. 1). Hence, points in the frequency domain image are perpendicular to edges in the spatial image.

2.2 Wedge-Filter

With these properties in mind, we design a custom tailored frequency selective filter, which aims at eliminating the streak artifacts in the CBCT reconstructions described before. A bandpass passes frequencies within a defined range and attenuates frequencies outside that range. For our application this represents a coarse solution. High frequencies should be attenuated, since they represent the streak artifacts. Moreover, low frequencies are rejected in order to sharpen the filtered image. In Fig. 2 (b) the frequency domain representation of a

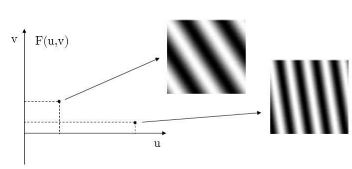
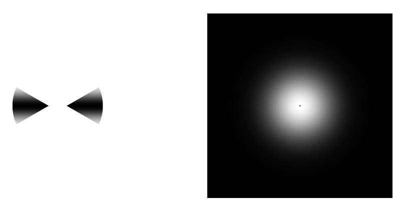


Fig. 1. Visual comparison of DFTs from two periodic signals with different frequency and orientation.

bandpass-filter is depicted. We introduce a more thorough approach by defining a frequency selective filter referred to as wedge-filter, attenuating only a defined frequency range. A possible configuration of a wedge-filter is displayed in Fig. 2 (a). A wedge-filter consists of two point symmetric wedges and attenuates only pixels in the magnitude image $|F(u,v)|$ that are located in the defined wedge. Each wedge-filter can be customized based on the respective CBCT data that features streak artifacts. If the spatial domain image features vertical streaks, the customized wedges are rotated such that they will attenuate frequency on and near the horizontal axis (Fig. 2 (a)). Moreover, the frequency of the streak artifacts is also regarded by defining the radius of the wedge. The bigger the radius of the wedges, the higher frequencies are eliminated. The attenuation in each wedge is modeled with a Gaussian distribution, where the mean values are located along the frequencies causing the most common streaks. Hence, if the streaks' orientation is not constant but slightly varying, one can set a standard deviation value that defines how strong the attenuation is in the neighborhood of the mean value, so that also frequencies similar to the dominant ones are attenuated.

For each scan, we selected the filter parameters empirically. For a filter size of 512 x 512 pixels, the bandpass attenuates intensities in a circle with an inner radius of 2 and an outer radius of 250 pixels (Fig. 2 (b)). Consequently, high frequencies representing streaks are suppressed, whereas the offset of the spatial image is only slightly modified. The radius of the wedges is set accordingly. Due to vertical streaks in coronar and sagittal views, the wedges are located on the horizontal axis in the filter. For axial slices, the orientation of the wedges was rotated by an angle of $\pi/3$, since the streaks have the same angle in the reconstructions with respect to the vertical axis. The mean value of the Gaussian distribution in a wedge was set to 0.3 and the standard deviation to 50 pixels, in order not to fully suppress to targeted frequencies and to allow a certain variation of the streaks' direction.



(a) wedge-filter (b) bandpass-filter

Fig. 2. Comparison of a wedge- and a bandpass-filter.

2.3 Experiments

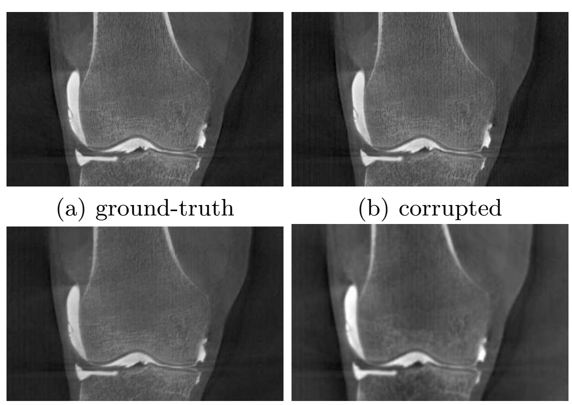
To test our proposed filter, we evaluated four subjects whose knees were scanned in an upright position under weight-bearing conditions. Additionally, a simulated dataset consisting of one ground truth acquisition and a simulated streak image generated by [4] was used for evaluation purposes.

3 Results

3.1 Qualitative Results

First, we compare the filtering results of our proposed filter to the results of the bandpass-filter on a simulated data slice. The results are depicted in Fig. 3, where subfig. (a) shows the ground-truth streak-free coronar slice, subfig. (b) the streak-corrupted data, subfig. (c) the wedge-filtered and subfig. (d) the bandpass-filtered slice. One can see that the wedge-filtered image features less streaks than the corrupted image. The bandpass-filtered image also eliminates the streaks, but is not able of preserving sharp edges, since the bandpass-filter attenuates edges independent of their orientation.

In Fig. 4, filtering results of a wedge- and bandpass-filter for a axial and sagittal slice of a real data set are compared with respect to their difference images. For subfig. (b), (c), (g) and (h) customized wedge- and bandpass-filtered were applied to each respective original image. The difference image (d) between the original slice and the wedge-filtered image reveals that the streaks from the dominant direction were filtered, while high frequency information is preserved. The difference image (f) between the original axial slice and the bandpass approach indicates that the bandpass-filter is also capable of filtering streaks, but not

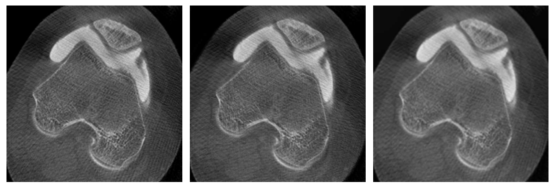


(a) ground-truth (b) corrupted

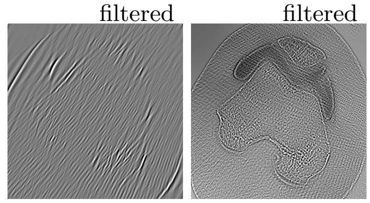
(c) wedge-filtered (d) bandpass-filtered

Fig. 3. Simulated data: Comparison of filtering results of a coronar slice when filtered with a wedge-filter and a bandpass.

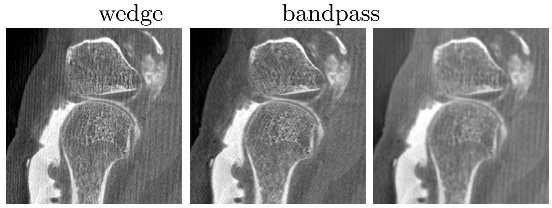
Fig. 4. Images (a) - (c) and (f) - (h) display the original, wedge-filtered and bandpass-filtered slice of a axial and sagittal view. Images (d), (e), (i) and (j) are difference images obtained by subtracting the filtered images from the original slice.



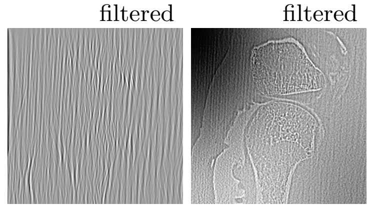
(a) original: axial (b) wedge-filtered (c) bandpass-filtered



(d) difference image: original - wedge (e) difference image: original - bandpass



(f) original: sagittal (g) wedge-filtered (h) bandpass-filtered



(i) difference image: original - wedge (j) difference image: original - bandpass

of preserving edge information. Looking at the filtering results from the sagittal slice that mostly features vertical streaks, one can detect that the bandpass approach is not able to remove those streak, whereas our proposed wedge-filter approach can filter the streaks, as shown in the difference image (i).

3.2 Quantitative Results

For a quantitative analysis, a simulated ground truth and a corrupted image that contains simulated streaks were generated in order to compare the SSIM of the

Table 1. SSIM of a simulated streak image, a bandpass- and wedge-filtered image against ground truth data.

Method	axial	coronar	sagittal
Simulated streaks [4]	0.898	0.889	0.894
Bandpass	0.967	0.877	0.901
Wedge-Filter	0.996	0.989	0.989

wedge-filter to the bandpass approach. For an axial, coronar and sagittal view the SSIM of the wedge-filter, bandpass and simulated streak data are depicted in Tab. 1. The results reveal that the wedge-filter approach yields superior results for every view when compared to a bandpass-filter on simulated data.

4 Discussion

We presented a novel approach to remove streak artifacts in CBCT data caused by objects located outside the FOV during the acquisition of knee scans in an upright position under weight-bearing conditions. We applied wedge- filters that attenuate the frequencies in the FFT images that are responsible for the streaks in the reconstructions. One limitation of our approach is the presence of streaks with multiple different orientations. Moreover, finding the right parameters for generating the proper wedge-filter for each view and subject has to be done manually. Implementing a method that automatically defines the wedge-filter parameters is a future task in this field. We showed that the wedge-filter approach can filter streak artifacts in a more sophisticated manner compared to a bandpass-filter on both simulated and real data. Consequently, the diagnostic value of the acquired images increases, since further post-processing steps are facilitated.

References

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