TRI–PICCS in Single Source and Dual Source CT

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Abstract—Recently, temporal resolution improved prior image constrained compressed sensing (TRI–PICCS), an algorithm promising improved temporal resolution in cardiac CT, was proposed. Here, we extend the ideas to dual source CT. Single source and dual source CT simulations of a heart phantom as well as a single source cardiac CT measurement are used to evaluate the temporal resolution of CT images reconstructed with TRI–PICCS. Short scan reconstructions of the same data are used for comparison. The result of this study is that there seems to be an advantage in temporal resolution when using TRI–PICCS, however, this impression is actually caused by a slight shift of the motion phase when using TRI–PICCS. Comparing short scan reconstructions and TRI–PICCS reconstructions at the same motion phase, no temporal resolution improvement could be confirmed.

I. INTRODUCTION

The coronary artery disease is one of the most dominating causes for death in the industrial countries. More than a decade ago new CT applications including new classes of reconstruction algorithms were introduced to allow for the non–invasive imaging of the heart and the coronary arteries [1], [2], [3]. Today, modern spiral cone–beam cardiac CT scanners help to reliably detect the coronary artery disease. Thereby, high temporal resolution is one of the most important parameters to obtain high quality CT images of the beating heart.

Recently a new method called TRI–PICCS was proposed to improve the temporal resolution of a cardiac CT scan [4]. This method aims at doubling the temporal resolution and at maintaining homogeneous temporal resolution by using only 120◦ of data instead of the standard 240◦ short scan range. Further, it aims at providing a homogeneous temporal resolution independently of the location of the vessel and of the motion direction.

In this study the TRI–PICCS image quality is independently evaluated regarding the reliability of the reported temporal resolution improvements. Additionally the dependency of the temporal resolution on the motion direction and on the location of the vessel with respect to the source positions is investigated. These properties are compared for dual source CT and single source CT configurations.

II. METHODS

The patient data were acquired with a state–of–the–art dual–source spiral cone–beam CT scanner (Somatom Definition Flash, Siemens Healthcare, Forchheim, Germany). The scanner rotation time is 280 ms. The simulations do also use this scanner configuration.

A. Single source TRI–PICCS

Fig. 1. To avoid limited angle artifacts the reconstructed angular rawdata coverage must be at least 180◦ (short scan), but using less data may improve the temporal resolution. TRI–PICCS is an iterative method that aims to combine an artifact free short scan reconstruction (prior image) with an iterative SART reconstruction that uses less rawdata. To avoid limited angle artifacts a cost function aims for both prior image similarity and low total variation of the reconstructed image.

The TRI–PICCS algorithm [4] combines a short scan reconstruction (called prior image) with a limited angle reconstruction (cf. figure 1). Because the limited angle reconstruction comprises less rawdata, the time to acquire those data is lower than in a short scan reconstruction. In this study the rawdata range, which is used for the limited angle reconstruction (TRI–PICCS rawdata), is half of the short scan range because this configuration was found to be optimal in [5]. We use 240◦ angular rawdata coverage for the short scan reconstruction and accordingly 120◦ for the TRI–PICCS reconstruction. Usually, one would conclude that the temporal resolution of the CT image equals the time that is needed to acquire all rawdata that are reconstructed. However, since the prior image that is part of the TRI–PICCS method is reconstructed from a short scan, the rawdata required for TRI–PICCS reconstruction are the same like for the short scan. Thus, in order to report a temporal resolution improvement, the classical definition of the temporal resolution cannot be used. Therefore, temporal resolution improvement is shown experimentally here and in references [4] and [5]. The TRI–PICCS algorithm has the parameter α to adjust the influence of the prior image and of the temporal resolution improved image. We use α = 0.6 in all reconstructions. The rawdata used for the iterative TRI–PICCS scheme can be centered with respect to the short scan rawdata (shown in figure 2) or the rawdata range can be slightly shifted. In this study three cases are compared, where TRI–PICCS rawdata are 1) at the center, are 2) at the beginning, and are 3) at the end of the short scan rawdata. We do not look at
cases where TRI–PICCS rawdata are not a subset of the short scan rawdata.

B. Dual source TRI–PICCS

Fig. 2. The straightforward extension of single source TRI–PICCS is to use only half of the short scan rawdata of each source during the iterative TRI–PICCS scheme. The depicted rawdata ranges yield matched motion phases for short scan and TRI–PICCS reconstructions. In this study also a slight shift of the angular range of the TRI–PICCS rawdata is within the short scan rawdata is investigated.

Besides the original TRI–PICCS algorithm, which was proposed for single source CT, we investigate a straightforward extension of the method to dual source CT in this study. Figure 2 illustrates the angular rawdata coverage used for short scan image calculation and for TRI–PICCS iterations in single source and dual source scanner configurations. Thereby an idealized parallel geometry is assumed for the diagrams visualizing the angular rawdata coverage and the time required for rawdata acquisition. The true angular rawdata coverages and rawdata acquisition times when considering the fan beam geometry are: 240°/187 ms for single source short scan, 120°/93 ms for single source TRI–PICCS iterations and dual source short scan, and 60°/47 ms for dual source TRI–PICCS iterations.

C. Heart motion phantom

Besides patient data, simulations are utilized in order to ensure known and well–defined vessel motion. As shown in figure 3 a static cardiac CT volume is extended by sixteen simulated inserts, which mimic calcifications. The inserts are equiangularly distributed on two circles, which have slightly different radii and are centered in the middle of the heart of the static cardiac CT volume. Inserts on the inner circle (40 mm radius) move radially; those on the outer circle (50 mm radius) move azimuthally. We did also use this phantom in reference [6] and a similar phantom is used for quantitative evaluation of the TRI–PICCS algorithm in reference [5].

All calcifications move with the same motion profile according to figure 4. The motion profile consists of motion with constant velocity of 65 mm/s, which was found to be a realistic velocity in [7], that is interrupted by a rest phase. In all simulations the rest phase duration exactly matches the time for acquiring the rawdata that are used for the iterative TRI–PICCS scheme (93 ms for single source and 47 ms for dual source). This means that there are completely consistent rawdata for TRI–PICCS iterations while only 50% of the short scan rawdata are consistent and the remaining rawdata are inconsistent because of the calcification motion. Since there are many parameters, table I gives an overview of the fixed simulation study parameters.

The simulation study aims to compare the image quality of single source and dual source CT short scan and TRI–PICCS reconstruction. It thereby focuses on the motion phase which is actually reconstructed. We define the short scan motion phase as the motion phase of the phantom at the half time of the short scan rawdata acquisition. The reconstructed TRI–PICCS motion phase is defined as the motion phase of the phantom at the half time of the acquisition of the rawdata that are used for the iterative TRI–PICCS scheme.
Fig. 5. Simulation results for single source configuration. The top row images show the motion phase that is reconstructed in the short scan images (second row) and TRI–PICCS images (third row). The corresponding angular coverage (source positions) of the rawdata is marked by arcs in each image. The bottom row shows the difference image short scan minus TRI–PICCS. Standard images C/W=200/1000 HU; difference images C/W=0/400 HU.

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<tr>
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<th>Single source</th>
<th>Dual source</th>
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TABLE I
SUMMARY OF THE PARAMETERS USED IN THE SIMULATION STUDY.

D. Patient study

A patient measurement using only one source of the Siemens Somatom Definition Flash scanner is used to evaluate the findings of the simulations on patient data. The scan comprises 400° of rawdata measured on a circular source trajectory with a scanner rotation time of 280 ms. In perfusion measurements, the temporal resolution defines how fast the reconstructed CT–values follow a change of the true CT–values. In contrast thereto, the temporal resolution in cardiac CT is a property that is totally inconspicuously if it is sufficient, and that can only be seen (as motion artifact) in CT images if it is too low. Consequently, to show temporal resolution improvement in cardiac CT, motion artifacts are looked for and then the ability of different algorithms to reconstruct this motion phase can be compared. Here, we use short scan reconstructions where we shift the rawdata range that is used for reconstruction in steps of 10° to find a motion phase where the right coronary artery undergoes a quick displacement, which causes it to appear as double structure in the reconstruction. This is a similar case like shown in references [4] and [5]. Note that this is a different case than shown in the simulation study: In the simulation study there is fast motion that is paused for a given time while in the patient study there are two rest phases that are connected by an (assumedly) short, abrupt displacement.
III. RESULTS

A. Simulation study

Figure 5 shows the simulation results for single source configuration. From left to right the motion phase of the rawdata that are put into the TRI–PICCS scheme is kept constant while the motion phase of the short scan prior image, which is shown in the top row, varies. Note that the FOV is only a clipping of the phantom in figure 3. The anatomic details of the patient are well preserved in all TRI–PICCS reconstructions.

Due to the rawdata selection, only in the center column the reconstructed motion phase between the short scan image and the TRI–PICCS image is the same. In the center column TRI–PICCS image, we cannot report an improvement of the motion artifacts that appear in the short scan image. In the left and right column, the rawdata range, which was selected for the short scan prior image, is slightly changed, such that the short scan rawdata range is not optimally centered in the rest phase of the motion, while the reconstructed motion phase of the TRI–PICCS image is kept constant. We show those images because earlier publications validate TRI–PICCS using this motion phase–changing rawdata selection [4], [5]. In the results a significant improvement of the prior image can be noticed. However, comparing all reconstructions in figure 5 that show the same motion phase (i.e. all images in the third row and the center image in the second row), no image can be selected to have superior image quality. We therefore conclude that no temporal resolution improvement can be achieved by TRI–PICCS, however, an advantageous shift of the motion phase is possible. This shift of the motion phase can be very helpful in cases where the measured rawdata are insufficient to reconstruct a desired motion phase with the short scan method. For example, if only those rawdata, which are necessary for the short scan in the left column of figure 5, were measured, the motion artifacts could be improved by TRI–PICCS.

Figure 6 shows the configuration just discussed but for the dual source case. In dual source short scans the temporal resolution is naturally doubled with respect to the single source short scan. We therefore shortened the duration of the rest
Fig. 7. Results of the patient study showing different motion phases for short scan and TRI-PICCS reconstructions. The short scan image (top row) is reconstructed in a phase with abrupt motion of the RCA (arrow). This image is the prior image for all TRI-PICCS reconstructions (center row). Performing TRI-PICCS reconstructions using different raw data portions allows to shift the reconstructed motion phase of the RCA slightly (left and right column). In the bottom row the difference of each TRI-PICCS reconstruction to the prior image is visualized. Standard images C/W=0/1000 HU; difference images C/W=0/400 HU.

phase accordingly. Again, only the center column short scan image is optimally centered in the rest phase. Despite the adaption of the rest phase, we find that the dual source short scan result is almost free of motion artifacts. We especially find that the dual source short scan reconstruction of the 47 ms rest phase shows less motion artifacts than the single source TRI-PICCS reconstruction of the 93 ms rest phase. Both methods are claimed to have the same temporal resolution. The findings regarding the motion phase–shifting TRI-PICCS reconstructions in the left and right column of figure 6 are the same like for the single source simulation: The TRI-PICCS image is superior to its motion phase–shifted prior image but it does not outperform the short scan image of the optimal motion phase.

B. Patient study

In order to validate our conclusions on single source TRI-PICCS, patient data with unknown vessel motion were utilized. Short scan and TRI-PICCS reconstruction results are shown in figure 7.

In the center column images show the same motion phase. The arrows point at the RCA, which is shown as a doubled structure in the top row short scan image due to abrupt displacement during the scan. Using the same motion phase, the TRI-PICCS reconstruction does not improve the reconstruction quality of the RCA. However, using TRI-PICCS to slightly shift the reconstructed motion phase, the RCA can be reconstructed without motion artifacts. This is found in the left column for the starting position (before displacement) and in the right column for the ending position (after displacement). The difference images show the improvement of the RCA very clearly.

Earlier studies concluded from this improvement that TRI-PICCS can improve the temporal resolution by a factor of two with respect to the short scan. In fact, the example shows that two different motion phases can be reconstructed from the raw data that were acquired for one single short scan image and this is an considerable improvement. However, to be sure that the temporal resolution is higher, one has to prove that there is no short scan image that can resolve the motion phases shown in the TRI-PICCS study at the same quality. We have therefore reconstructed the images in figure 8. The short scan reconstruction in the right column of the top row shows that the short scan can reconstruct the RCA as well when data are selected for the given reconstruction phase. The difference image in the bottom row shows the difference between the short scan and the TRI-PICCS image. The top center image is the prior image for all the TRI-PICCS reconstructions of this figure. The left column, however, shows the above discussed advantage of the TRI-PICCS method again: There are simply not enough raw data acquired by this scan to reconstruct the same motion phase of the RCA with the short scan image.
IV. CONCLUSIONS

We are not able to report an improvement of the temporal resolution with TRI–PICCS as it was found in references [4] and [5]. In all cases of this study (simulations and patient data) there are only marginal differences between the short scan reconstruction and the TRI–PICCS reconstruction of the same motion phase, even if motion artifacts are present. However, both the single source simulations and the single source patient study show that TRI–PICCS can be used to shift the reconstructed motion phase by about one eighth of the scanner’s rotation time compared to the short scan motion phase. Since shifting of the motion phase by TRI–PICCS does not require additional rawdata to be measured, this can be useful if one desires to reconstruct motion phases that correspond to the beginning or to the end of the acquired rawdata range.

The above conclusions on single source TRI–PICCS were also confirmed for a straightforward extension of TRI–PICCS to dual source CT. Regarding the temporal resolution, even in the unfair case of this paper, where the motion speed was doubled for dual source simulations, the dual source reconstructions still show less motion artifacts than single source TRI–PICCS reconstructions.

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REFERENCES