Time-of-Arrival Mapping for 3D Time-Resolved Contrast-Enhanced MRA

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Introduction. A number of methods have recently been demonstrated for providing a time series of 3D image sets for contrast-enhanced MR angiography. Although the resultant sequence of 3D data sets can be interpreted on its own, it may be useful to provide this combined spatial-temporal information more concisely, such as in a single 3D image. The purpose of this work is to describe how the image series generated with time-resolved MRA can be converted into time-of-arrival (TOA) maps.

Fig. 1. Two individual frames from time series.

Methods. *Description of the Basic Method* The idea of the TOA map is to consider all voxels in the 3D volume of interest and analyze the signal values obtained over time at each location. For the case of contrast material injected outside the volume of interest, each voxel in the volume initially has an average value of some baseline, and when contrast material arrives at that voxel location the signal will be altered over time. This information is then used to assign an "arrival time" for the contrast material in that voxel. This process is done separately for all voxels in the volume.

This process is illustrated in Figs. 1-2. Figs 1a-b show MIP images from two time frames of a time-resolved sequence of the lower legs and illustrates progressive filling of the vasculature. Fig. 2 is a plot of the signal values for a single voxel at the bifurcation of the right posterior tibial and peroneal arteries. It should be noted that TOA determination is not made from the 2D MIP projections images but rather on all partitions in the 3D volumes. Although other algorithms are possible, for this work the TOA value was defined as that time at which the signal first attained 70% of the maximum value obtained over the full time series. The TOA was determined by linear interpolation between those time points whose signal values straddled this 70% level, partway between Frames 5 and 6 in Fig. 2.

Desirable Properties of MR Image Acquisition for TOA Mapping Generation of a TOA map uses a time series of 3D MR image sets, each set corresponding to a specific time point. Due to the flexible manner in which MR images are formed, there is considerable latitude in what "time point" means. The acquisition time required to generate a single 3D image set for CE-MRA is generally a minimum of ten seconds. This can be further complicated if view sharing, e.g. [1], is performed as well as where within the acquisition time the central k-space views are sampled. One obvious requirement for generation of a TOA image is that the MR acquisition has an adequately high frame rate. Additionally, other properties of the acquisition are desirable: (i) the MR image acquisition strategy should be consistent; (ii) the k-space center should be compactly measured; and (iii) artifactual signals should be minimized or avoided. Detailed study of each of these is beyond the scope of this abstract but can be briefly explained as follows.

Fig. 2. TOA determination.

A consistently-acquired time series can be defined as one in which the distribution of k-space views is the same for all image sets in the series; e.g. if central k-space is sampled "early" in the acquisition for one time frame, it is sampled at the same early point for all time frames. This insures that objects moving at fixed velocity are portrayed at equal displacements in the image time series. Compact sampling of the k-space center is desired to freeze motion. For 3D Cartesian sampling this can be done with centric phase encoding. Artifactual signal can occur if, for a given image, considerable peripheral k-space is sampled later in time than central k-space. This may cause non-zero signal ahead of the actual bolus leading edge. These three criteria have been studied in a preliminary fashion previously [2].

MR Image Acquisition: Time-of-arrival maps were generated from time series of 3D MR images formed using the CAPR technique [3], shown previously [2] to have the desired properties discussed above. CAPR uses an RF-spoiled GRE acquisition with: TR/TE 4.6/2.6 msec; flip angle 30º, and bandwidth ±62.5 kHz. 2D SENSE and 2D homodyne were performed in the transverse plane to give a net acceleration of 14.4. For the calves the image update time (IUT) and acquisition time per image (temporal footprint FP) were 5 sec and 20 sec, respectively, with 1 mm isotropic resolution. For the hands the IUT and FP were 3 sec and 12 sec, and resolution was 0.7x0.7x1.8 mm^3. The resultant time series were subjected to the TOA processing discussed previously.

Fig. 3. a: TOA image of the lower legs from study of Fig. 1 shows arteries in red. Also seen are central veins in right leg (solid arrow) and peripheral veins in left leg (dashed arrows). b: enlarged oblique from dashed box of (a) illustrates the intrinsic spatial resolution. c: TOA image of right hand taken from a bilateral hand study. Dorsal view as seen by prominence of veins (arrow). Time range shown within each frame indicates endpoints of red-to-blue color scale for TOA values.

Results. TOA images generated from the scan illustrated in Fig. 1 are shown in Fig. 3 in full FOV coronal format (a) and an obliquely oriented subvolume of the left trifurcation (b). A TOA image from one hand taken from a bilateral hand MRA study is shown at an oblique view in Fig. 3c. In all three frames the absolute time range post-contrast-injection used for the red-to-blue color map is shown.

Discussion and Conclusion. TOA mapping has been used in other fields [4]. In MRI TOA estimation was used to provide binary separation of arteries vs. veins [5]. We believe this present work is the first to show MRI TOA results at this level of detail. This has been enabled by recent advances in time-resolved MRA, particularly reduction of acquisition times, improvement in spatial resolution, and improvement of overall temporal fidelity. In conclusion, TOA maps can be generated from time-resolved MRA studies and may be useful in interpretation of vascular disease.

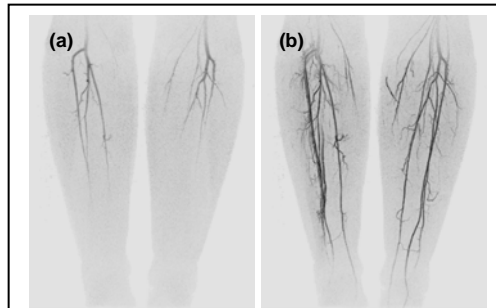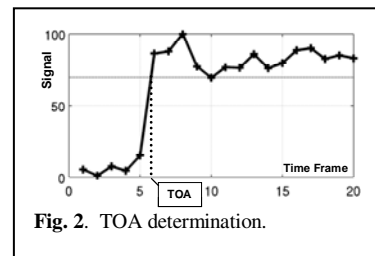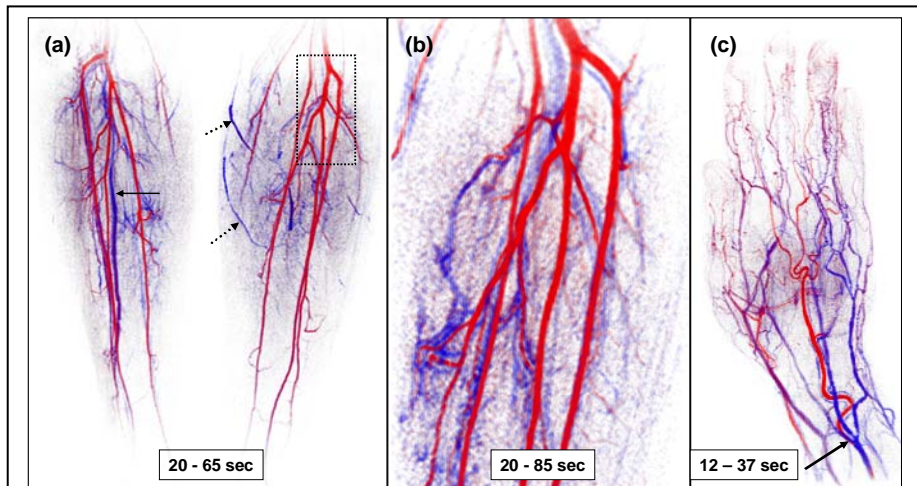**References**. [1] Korosec FR MRM 1996; [2] Mostardi PM Proc ISMRM 2008; [3] Haider CR MRM 2008; [4] Cover K Neurosurg 2007; [5] Du J JMRI 2006