A Robust Method for Reducing Inflow Artifacts in the Arterial Input Function of Dynamic Contrast Enhanced Data Sets

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Introduction: Conventional methods for renal perfusion quantification not only require timed blood and/or urine collections, but also carry the risk of nephropathy due to nephrotoxic contrast agents and lengthy exposure to ionizing radiation, whereas MRI methods using gadolinium chelates (most commonly Gd-DTPA), which are solely filtered through glomeruli, can noninvasively provide excellent anatomical resolution and an accurate estimate of glomerular filtration rate (GFR). Most models for estimating renal perfusion require the Arterial Input Function (AIF) to model the accumulation of the contrast agent (CA). The quality of the AIF is an important determinant in the accuracy of the MR-GFR estimate. The pulsatile inflow effect due to the heartbeat, however, causes distinct noise in the AIF signal measured within the descending aorta which leads to overestimation of AIF [1, 2]. This study presents techniques that smooth the curve by removing the spikes from the curve, and a simulation test that validates this optimization utilizing multiple sets of noise reproducing the inflow effect.

Material and Methods: The patient group consisted of four long-term survivors of unilateral Wilms' tumor with typical AIF curves. MRI scans were performed on a 1.5T Siemens Avanto scanner (Siemens, Erlangen, Germany); a multi-slice T1-weighted 2D FLASH sequence with nonselective saturation recovery preparation was used; imaging parameters were as follows: TE/TR = 0.98 ms/347 ms, flip angle = 8°, matrix = 192*192, FOV = 400 mm*400 mm, voxel size = 2.6*2.1*8.0 mm. Images were acquired in oblique-coronal planes passing through the kidney or aorta. Followed by 20 mL of saline flush, half of the regular clinical dose of contrast agent, 0.05 mmol/kg body weight of Gd-DTPA (Magnevist; Bayer HealthCare Pharmaceuticals, Wayne, NJ) was injected in order to avoid failure of the linear relation between CA concentration and signal intensity (SI) at high concentration due to T2* effect. Ten breath-hold pre-contrast images were obtained as the baseline scan for each patient before contrast agent was injected. A customized signal analysis tool was used for image registration, motion correction, and signal intensity analysis. The average SI baseline was subtracted from the absolute SI to get relative SI which was finally used for AIF. To optimize the curve several algorithms were developed and coded in Matlab (MathWorks, Natick, MA) involving simple/cumulative moving average, linearly/exponentially weighted moving average, locally weighted linear least-square fit with first and second degree polynomial, and the Savitzky-Golay filter. The span (subset size) for the smoothing process was set to 30, which guarantees the smoothness of the resulting curve while assuring that it is close enough to the original data. The smoothing method was only applied to the part of the AIF after the first and second peak, representing the first pass of CA bolus and recirculation of bolus respectively. A two gamma variate function was used to fit the AIF curves and served as the mathematically accurate AIF in order to produce reference MR-GFR results. Four sets of noise were extracted from each patient's data and used to simulate the abrupt spikes due to the inflow effect. After noise was applied, GFR values were calculated and compared with the reference GFR.

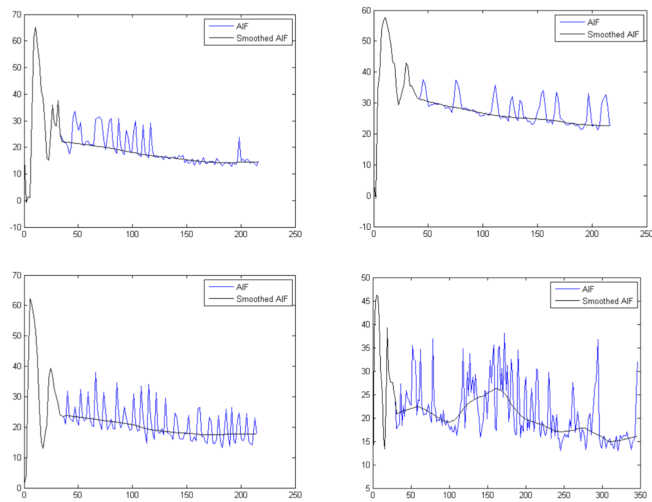

Fig. 1. AIFs of four patients with varied noise levels. The blue line represents the original data, and the black line represents the smoothed curve.

Results: A robust version of locally weighted linear least-square fit with first degree polynomial was found to be most resistant to outliers and was validated in the simulation test. From Fig. 1 it can be seen visually that after the smoothing filter was applied, the fluctuation of original data was significant reduced and the curves became smooth and continuous: in the first two AIF plots where there was relatively low noise, the results were free of undesired spikes and closely adhered to the bottom line of the original curve; in the third plot with medium noise, the result showed a slight elevation above the bottom line as compared with the first two; in the fourth plot with huge noise, the smoothing method removed most of the abnormal artifacts. The correlation coefficient R^2 between the original AIF and data calculated from the two gamma variate function varied from 0.95 to 0.99; an example is shown in Fig. 2,. GFR results of the simulation test are shown in Table 1. Percent error ranges from 0.7% to 2.5%.

Patient No.	Ref. GFR/V	Noise 1 GFR/V	Noise 2 GFR/V	Noise 3 GFR/V	Noise 4 GFR/V
1	0.354	0.363 (2.5%)	0.363 (2.5%)	0.363 (2.5%)	0.357 (0.8%)
2	0.264	0.258 (2.3%)	0.261 (2.3%)	0.258 (2.3%)	0.258 (1.1%)
3	0.405	0.408 (0.7%)	0.408 (0.7%)	0.408 (0.7%)	0.411 (1.4%)
4	0.279	0.273 (2.2%)	0.273 (2.2%)	0.273 (2.2%)	0.276 (1.1%)

Table 1. GFR/V in the unit of mL/(min•1.73 m^2•cm^3). In parentheses are percent errors compared with the reference values.

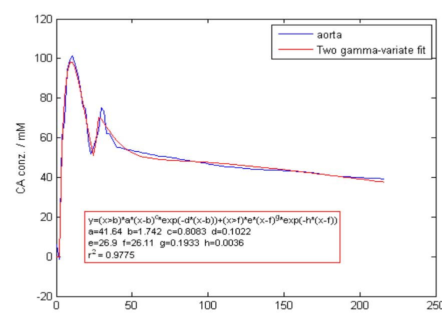

Fig. 2. The two gamma variate function fits the smoothed AIF very accurately (R^2=0.98), corresponding to the top-right patient of Fig. 1.

Discussion and Conclusion: The high correlation between the original AIF and data calculated from the two gamma variate function shows that the two gamma variate function is a highly reliable mathematical formula for modeling the AIF. The smoothing results for the first three patients were satisfactory while for the fourth patient at a high noise level, the smoothed curve though very close to the original data is not smooth enough to reveal the real concentration change. For all four patients, the GFR/V result of the first three sets of noise being identical indicates that at low noise levels, this method was robust enough to eliminate whatever noise was applied thereby restoring the correct curve. The residual percent error is due to the fact that the spikes, though apparently having been removed, still slightly contributed to the resulting curve at a reduced weight and elevated the curve to a small extent. In conclusion this smoothing method was able to reduce the inflow artifact on the AIF signal thereby allowing for more accurate estimate of renal perfusion and GFR estimation.

References: (1) Ivancevic et al., Proc. ISMRM 11, 149 (2003). (2) Peeters et al., MRM51, 710-717 (2004).