Input Function Detection in MR Brain Perfusion Using a Blood Circulatory Model Based Algorithm

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Introduction: The arterial input function (AIF) plays a crucial role in mapping Cerebral Blood Volume, Mean Transit Time, and Cerebral Blood Flow (CBV, MTT, and CBF) in MR perfusion studies. Automation of the process of selecting an AIF for use in further calculation could substantially reduce bias in hemodynamic parameters introduced by operator dependency and accelerate perfusion analysis. While a variety of approaches have emerged to predict AIF profile, many of them are too complex to be implemented in practical experiments [2]. In order to be useful, a model based algorithm needs to be easy to assemble, and practical [3, 4]. Thus, an analytical model-based algorithm for detection of AIF would be beneficial to MR perfusion analysis. This study uses a blood circulatory model previously introduced by our research group 5] to construct an automatic algorithm for AIF detection in MR perfusion studies [5]. The aim of this study is to construct an objective function, based on the parameters in the blood circulatory model, for detecting the AIF in MR perfusion studies. The proposed algorithm is applied to 19 slices of four patients with Dynamic Susceptibility Contrast (DSC) MR perfusion studies. Results imply that the proposed algorithm is capable of detecting the AIF with a success rate of 84%, suggesting that this method is a reliable method for the analysis of MR perfusion studies.

Materials and Methods: As shown in Figure-1, the response of the blood circulatory system for a rectangular IV bolus injection function at the measurement site **M**, is defined by first and second passages ($P_1(S)$, and $P_2(S)$) of the bolus in Laplace space [5]. Three parameters define each compartment (volume, flow, and time lag) in four ratios: $[\eta_H=(\pi F^2/V_r^2)_H, \eta_L=(\pi F^2/V_r^2)_L, \eta_B=(\pi F^2/V_r^2)_B$ and $\eta_{W-O}=(\pi F^2/V_r^2)_{W-O}]$ (subscripts denote compartments for four compartments[5]). It has been shown that these four parameters (η_H, η_L, η_B, and η_{W-O}) are adequate to model an AIF signal [5]. In this study, three objective functions are constructed by means of the model parameters to detect the AIF in MR experimental data. To construct the merit functions for each selected point *(x,y)*, a blood circulatory model was fitted to the *AIF(x,y,t)* response ($AIF(x,y,t)=-\ln(S_t/S_0)/TE$) in MR DSC perfusion (128X128, TE=40 msec, TR=1900msec, Slice thickness of 5 mm, pixel spacing=0.1875 with 95 time points), where *TE*, S_t, and S_0 denote Echo time, T_2^* signals at time *t* and T_2^* signal before injection (baseline). For each voxel *(x,y)*, four model parameters (η_H, η_L, η_B, and η_{W-O}) were estimated using a multi-dimensional fitting algorithm. According to the proposed model (see figure-1), the arrival time (AT) in brain for the first passage (***$P_1(S)$***) of the contrast agent in the AIF signal is calculated by the ***HLH*** operator which is calculated as $AT(x,y)=2\tau_H(x,y)+\tau_L(x,y)$, where τ denotes the time lag in each organ. Using the relationship between the time lag and compartmental ratios, the *AT(x,y)* can be re-written as: $AT(x,y)=(V_H^2/F^2)[2\eta_H(x,y)+(V_L^2/V_H^2)\eta_L(x,y)]$. According to the literature, the ratio of the blood volume in lungs and heart for a normal and typical adult human are about 12% and 9% respectively [6]. Therefore, the equation for the arrival time in each voxel (x,y), can be formulated as: $AT(x,y)=(V_H^2/F^2)[2\eta_H(x,y)+(16/9)\eta_L(x,y)]$. In the proposed model [5], the flow (*F*), in all organs is unique and constant. The blood volume (***V_H***) in the heart is also constant and location independent. Thus, the first objective function for the bolus arrival time can be defined as following: $AT(x,y)=Const.[2\eta_H(x,y)+(16/9)\eta_L(x,y)]$ (2). Minimization of the *AT(x,y)* produces a preliminary set of voxels as the potential candidates for the AIF. The second objective function is defined as the area under the fitted model divided by the peak width which is expected to be maximized if an appropriate AIF is selected. The third objective function is the peak height of the first pass which would also be maximized. Combining these three objective functions, constructs a final criteria for choosing a signal with shortest arrival time, larger area under the signal, and highest peak. The proposed algorithm was applied to 19 slices of four DSC MR perfusion studies with GBM tumor. All potential candidates detected by the proposed algorithm were compared to the AIF selected by a radiaologist and the calculated CBV maps to determine the accuracy (rate of success) of the algorithm.

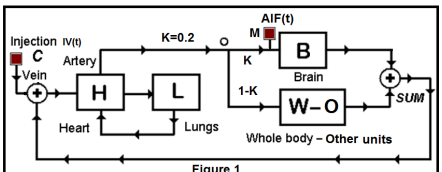


Figure 1

$$P_1(S)=k.\frac{[\eta_H.e^{-\tau_H.S}][\eta_L.e^{-\tau_L.S}][\eta_B.e^{-\tau_B.S}+C^0]}{[\eta_H+S]^2[\eta_L+S]} \quad (1)$$

$$P_2(S)=FP(S)\left[\frac{\eta_B.e^{-\tau_B.S}}{\eta_B+s}+(1-k)\frac{\eta_{WO}.e^{-\tau_{WO}.S}}{\eta_{WO}+s}\right]D(S) \quad (2)$$

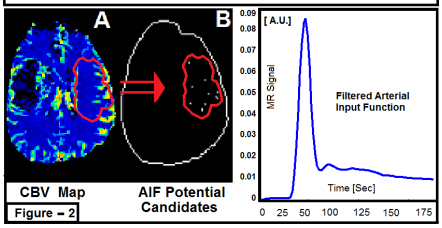
where $D(s)$, η_B, η_L, η_B and η_{WO} are defined as:

$$D(S)=\frac{[\eta_H.e^{-\tau_H.S}+C^1][\eta_L.e^{-\tau_L.S}+C^2][\eta_H.e^{-\tau_H.S}+C^3]}{(\eta_L+s)(\eta_H+s)^2} \quad (3)$$

$$\eta_H=(\frac{F^2\tau_H}{{}^HV_r^2}),\eta_L=(\frac{F^2\tau_L}{{}^LV_r^2}),\eta_B=(\frac{F^2\tau_B}{{}^BV_r^2}),\eta_{WO}=(\frac{F^2\tau_{WO}}{{}^{WO}V_r^2}) \quad (4)$$

$$C^0=C_H^{out}(2\tau_H+\tau_L) \qquad C^2=C_L^{out}(3\tau_H+2\tau_L+\tau_B)$$

$$C^1=C_H^{out}(3\tau_H+\tau_L+\tau_B) \qquad C^3=C_H^{out}(4\tau_H+2\tau_L+\tau_B) \quad (5)$$



Results and Discussion: A model based algorithm is presented for detection of AIF (see Figure-2). This algorithm is constructed using a blood circulatory model and is composed of three objective functions. Most of the detected set (see Figure 2-A) included at least one correct AIF point (rate of success ~ 84%) to generate CBV map (Figure-2 B) with a reasonable range (CBV~0.6% to 1.2% in normal white matter area). Results imply that the proposed algorithm is capable of finding a set of best AIF voxels for the perfusion analysis. To the best of our knowledge, since there is no standard method for testing the AIF, the reported accuracy (~%84) for the AIF detection highly relies on the AIF selected by the radiologist and also the availability of the actual AIF points in the area of the search defined by the radiologist.

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