DSC-MR Perfusion: Leave Tracer Recirculation Alone

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Introduction

Dynamic susceptibility contrast (DSC) MR perfusion is based on the indicator dilution theorem for non-diffusible tracers.[1,2] A common misconception is that tracer recirculation cannot occur in order to make use of the underlying theory (*i.e.*, analysis of the tracer kinetics must be "first-pass").[3-13] As a result, there have been a number of approaches suggested for removing tracer recirculation from DSC-MR data.[3-8] Here we show that it is unnecessary to remove tracer recirculation from DSC-MR data in order to derive perfusion parameters.

Theory

For a generalized injection $C_{AIF}(t)$ (known as the arterial input function, AIF), the tracer concentration within a volume of interest (VOI) is $C_{VOI}(t) = CBF_{VOI} \cdot C_{AIF}(t) \otimes R_{VOI}(t)$, where CBF_{VOI} and $R_{VOI}(t)$ are the cerebral blood flow (CBF) and residue function, respectively, for the VOI and $\otimes$ represents mathematical convolution.[2] This equation defines a linear time-invariant (LTI) system, which means that it must satisfy the *principle of superposition*. That is, for an input signal $C_{AIF}(t)$ composed of the weighted sum of signals $a_i \cdot C_{i\_AIF}(t)$

$$C_{AIF}(t) = \sum_{i=1}^{N} a_i \cdot C_{i\_AIF}(t)$$

where a_i is a scalar, the output response of a LTI system $C_{VOI}(t)$ will be equal to the weighted sum of output signals

$$C_{VOI}(t) = CBF_{VOI} \cdot \sum_{i=1}^{N} C_{i\_VOI}(t)$$

with each output signal $C_{i\_VOI}(t)$ being associated with a particular input signal acting on the system independently of all the other input signals, or $C_{i\_VOI}(t) = a_i \cdot C_{i\_AIF}(t) \otimes R_{VOI}(t)$. Therefore, tracer recirculation in $C_{AIF}(t)$ is reflected in $C_{VOI}(t)$. Deconvolution is used to infer a system impulse response function when a LTI system is probed with an arbitrary input signal. Under the assumption that $C_{VOI}(t)$ is the output of a LTI system with $C_{AIF}(t)$ as the input, we must conclude that CBF derived using deconvoultion [2] is not affected by tracer recirculation. A system that does not uphold the principle of superposition is not an LTI system and the convolution expression above used to derive CBF would therefore be invalid.

Similarly, cerebral blood volume (CBV) estimates are not affected by tracer recirculation. Integration of the convolution expression above yields:

$$\int C_{VOI}(t)dt = CBF_{VOI} \cdot \int C_{AIF}(t) \otimes R_{VOI}(t)dt$$

$$\int C_{VOI}(t)dt = CBF_{VOI} \cdot \int C_{AIF}(t)dt \cdot \int R_{VOI}(t)dt$$

$$\frac{\int C_{VOI}(t)dt}{\int C_{AIF}(t)dt} = CBF_{VOI} \cdot MTT_{VOI}$$

$$CBV_{VOI} = CBF_{VOI} \cdot MTT_{VOI}$$

where we have used the fact that the DC component is preserved in LTI systems (*i.e.*, $\int C_{AIF}(t) \otimes R_{VOI}(t)\, dt = \int C_{AIF}(t)\, dt \cdot \int R_{VOI}(t)\, dt$) and the definition $MTT_{VOI} = \int R_{VOI}(t)dt$.[1] This is a simple restatement of the central volume principle.[1,2] As before, tracer recirculation occurring in $C_{AIF}(t)$ is reflected in $C_{VOI}(t)$ as well. Therefore, CBV estimated as the area under the curve is not affected by tracer recirculation. Furthermore, if recirculation is removed from the AIF only,[13] then CBV will be overestimated.

Discussion

We have shown that there is no need to remove tracer recirculation from DSC-MR data prior to post-processing in order to obtain CBF and CBV, and hence, MTT. Based on simulation analysis, Perkio *et al.*[13] concluded that the area under $C_{VOI}(t)$ produced incorrect CBV estimates even in simulations without noise. However, based on the theoretical considerations presented in this work, their conclusions likely point to a simulation error. We should emphasize that Zierler [1] recognized that deconvolution obviates the need for removing recirculation. Recirculation is only problematic for experiments that do not use deconvolution but rather assume a specific injection profile (*e.g.*, impulse function, step-function, etc.). Yet, many studies incorrectly state that recirculation must be removed. Furthermore, procedures used to remove tracer recirculation may in fact create more artifacts resulting from errors in the fitting procedures. Since these procedures are not required, there is little reason to employ them.

References

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