# CORRELATION OF STEADY STATE AND TRANSIENT TEMPERATURE PROFILES IN PERFUSED FIXED KIDNEYS: IMPLICATIONS FOR THERMAL MODELS

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## 1. INTRODUCTION

Thermal models are used in hyperthermia to predict temperature distributions for treatment and applicator optimization. It is known that blood flow can significantly influence temperature profiles but an accurate description of this effect is unknown. Two models that have been used to model microvascular effects are the Pennes Bioheat Transfer Equation (BHTE) and the Effective Thermal Conductivity Equation (ETCE) [1], while an advection term is used in combination with the above to model large vessel effects [2]. The purpose of this work is to compare model predictions in an experimental system and to critically examine the effects of thermally significant vessels.

## 2. METHODS

An experimental system [3] was built to examine steady state and transient temperature profiles in a perfused phantom near a line source of heat and to compare the results to theoretical predictions. The flow dependence of the temperature profiles was carefully examined (for both low and higher organ flows) with respect to the regional cooling of the microvasculature and the localized cooling of thermally significant vessels ($\delta > 0.2$mm). The experimental system consisted of five 60$\mu$m diameter type K thermocouples scanned in steps of 0.1mm inside quartz tubing across an alcohol-fixed kidney submerged in distilled water, perfused by a pump and heated by a hot water needle. In the steady state experiments the needle was perfused continuously with hot water (60-70°C) while for the transient experiments a 20 second thermal was delivered through the needle and the temperature rise and decay were recorded as a function to flow to the kidney. The high spatial resolution experimental temperature profiles are the result of a complex interaction of regional and localized cooling.

## 3. RESULTS

For no kidney flow, a bell-shaped temperature profile is expected peaking when the thermocouple is closest to the source. Data not shown in this manuscript demonstrated that for thermocouples that do not feature localized cooling, the profiles are better explained by the predictions of the BHTE for both the steady state and transient experiments. In other steady state experiments with flow, flow dependent gradients of up to 4°C/mm were measured close to significant vessels. Neither the BHTE nor the ETCE could predict such profiles which were detected in four of the five thermocouple paths. At these locations thermally significant vessels were implied. The features of steady state temperature profiles were spatially correlated to transient profiles by recording the steady state temperature profiles and then performing transient experiments for specific pre-determined regions, scanning again in steps of 0.1mm and repeating the pulse. Figure 1 demonstrates the readings of

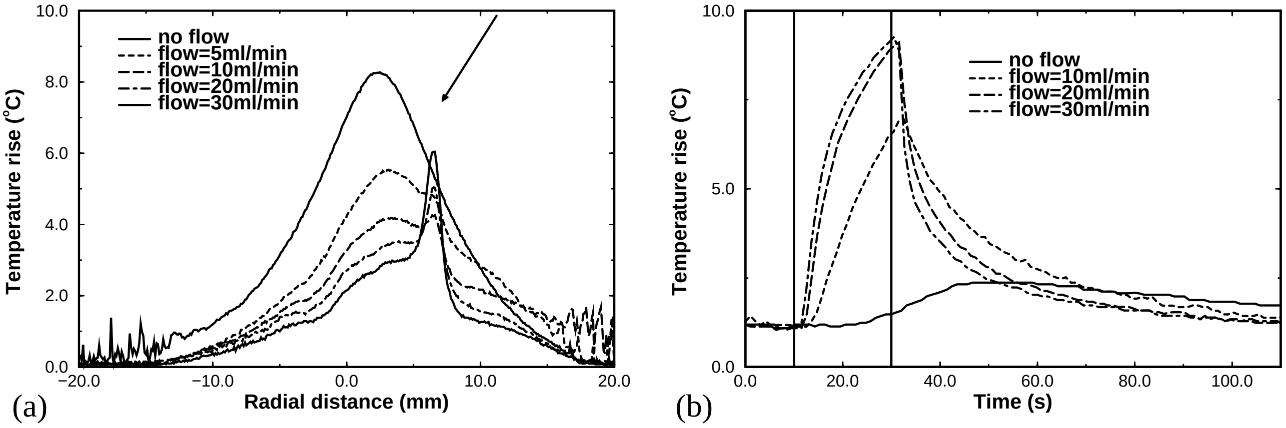

Figure 1: Steady state (a) and transient (b) temperature profiles measured by a scanned thermocouple. Arrow indicates location at which transient temperature profile was measured in (b). Vertical bars indicate the pulse on and off times. Note the distinct peak in (a) and the transient response at that location in (b).

one of the thermocouples for a series of flow rates through the kidney. A localized temperature peak appears approximately 6-8mm away from the source which indicates transport of heat from one region to another (Fig.1(a), arrow). The transient temperature profiles examined at the location of the peak (Fig.1(b)) illustrate a four-fold increase of maximum temperature between no flow and flow conditions and a reduction in the delay time (time of onset of temperature rise after the pulse start) of $\sim$15-20s. Figure 2 illustrates significant vessel cooling recorded by another thermocouple. In the steady state measurements the temperatures are reduced and regions of localized cooling occur (Fig.2(a), arrow) amongst other more subtle features. Interestingly, in the transient experiments the region of localized cooling for the steady state experiment corresponded to a greater temperature increase and a reduced delay time for higher flows (Fig.2(b)). The vessel thus displayed features of a heat source as in figure 1.

## 4. DISCUSSION

Accounting for blood flow in thermal treatments is of great importance for predicting the resulting temperature distributions. Thermal models that do not account for blood flow would predict the temperature profiles labeled as “no-flow” in figures 1 and 2 which clearly are not representative of the profiles measured with flow and thus inadequate for thermal dosimetry. Furthermore, thermal models that only use simplified continuum models such as the BHTE or the ETCE and do not account for large vessels could not predict the temperature profiles recorded by four of the five thermocouple paths of this experiment (of which two are shown in this paper). This demonstrates the importance of thermally significant vessels in shaping the final temperature distribution. It should be noted that the high spatial resolution thermocouple scanning enabled the detection of features that would not be detectable using either single point measurements or scanning in steps greater than or equal to 1mm. Furthermore, preliminary x-ray angiography imaging indicates that vessel diameters near the thermocouples are at least less than 1mm. Clearly, thermally significant vessels can not only produce regions of localized cooling but also of localized heating (Fig. 1). Current models of heat transport by large vessels can predict this effect. This may result in increased cytotoxicity to normal tissues in thermal treatments and may be crucial when critical structures are to be spared in the treatments (*e.g.* in the brain). The heat transport properties of these vessels is illustrated in figures 1(b) and 2(b), in both cases carrying heat away from the heated area and decreasing the delay time and increasing the temperature at locations relatively far from the source.

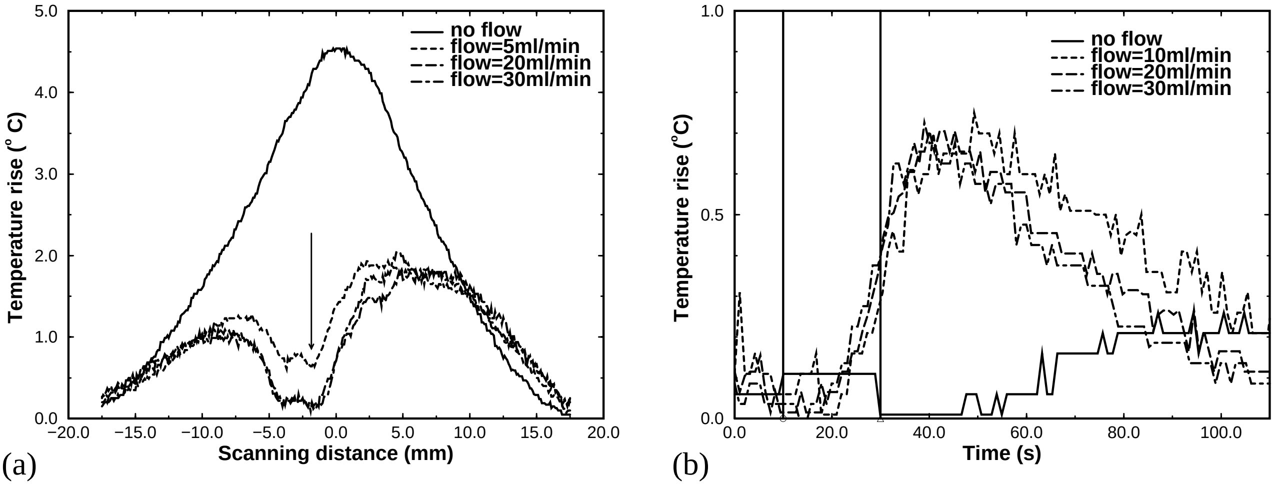

Figure 2: Steady state (a) and transient (b) temperature profiles measured by a scanned thermocouple. Arrow indicates location at which transient temperature profile was measured in (b). Vertical bars indicate the pulse on and off times. Note that the cause of localized cooling in (a) seems to be responsible for the heating in (b).

Interestingly, this is despite the fact that in one case the vessel causes heating in the steady state while in the other it causes cooling. Furthermore, the pulse duration in the transient experiments is 20s. It has been postulated that rapid treatments may overcome the effects of blood flow on temperature distributions: it is apparent however that the transport properties of large vessels still plays an important role for an exposure time of 20s in these experiments.

## 5. CONCLUSIONS

The experimental data suggest that the BHTE model better fits the experimental data in the absence of thermally significant vessels. Thermally significant vessels created flow dependent temperature gradients of up to 4°C/mm in the steady state experiments. The thermal repsonse to a 20s pulse of heat demostrated the transport properties of the vessels. Quantitative analysis of the profiles is currently being pursued by acquiring high-resolution (0.2mm) three dimensional CT scans of the kidney vasculature in combination with Doppler ultrasound measurements of flow through large vessels. The vessel geometry and flow information will be as used as input in thermal models developed to asses their validity, focussing on discrete vessels.

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