To the Editor-in-Chief:

Recently, Karagoz and Kartal (2006) considered the temperature rise $\Delta T$ in tissue at the focus of a stationary transducer, which is on for some time, after which an off-period follows, which finally is followed by a second on-period. The temperature rise caused by the first heating period remaining at (the beginning of) the second heating period is called the residual temperature rise (see their Fig. 1). This paper contains a surprising result: continuous heating (their Fig. 2) gives a smaller temperature rise than heating at the same power level interrupted for a certain period (their Fig. 4).

The origin of this result lies in their calculation of the temperature drop in the period that the transducer is off. Their equation (eqn 9) considers only the effect of the cooling by perfusion, characterized by the perfusion time constant $\tau$. However, a focused transducer will generate a temperature gradient, which causes fast cooling of the focal region by conduction. This conduction should be included in the calculation of the cooling in the off-period.

To illustrate this effect, I have calculated in Fig. 1 the time course for a particular case that is discussed in the paper of Karagoz and Kartal, using the constants in their paper. One parameter had to be modified to reproduce their results: the attenuation coefficient $\alpha$ should depend on frequency and was chosen to be $0.0575 \, f \, Np/cm$ with frequency $f$ in MHz. This corresponds to $0.5 \, dB \cdot cm^{-1} \cdot MHz^{-1}$. The same calculation program was used [Spheresum, as described in the appendix of Lubbers et al (2003)]. The calculation was done for an initial heating period of 500 s, an off-period of 50 s and a second heating period of various durations (50 s to 1000 s) corresponding to the data in their Fig. 4. The power was 150 mW, the frequency 3 MHz.

The solution of Nyborg (1988) for the linear bioheat transfer equation, which is at the basis of Spheresum, can only calculate temperature rise for continuous heating after a certain begin time. However, as the equation is linear in temperature, heat sources and time, it is allowed to superimpose the effects of several heat sources. To obtain the temperature course of the above mentioned case a first source (A) of 150 mW is started at $t = 0$ s, a second source (B) of negative heat $-150 \, mW$ at $t = 500$ s and a third source (C) of 150 mW at $t = 550$ s. In Fig. 2 it can be seen that now the temperature drops very fast at the interruption of the heating. The drop is as fast as the rise at the beginning of the heating at $t = 0$: $0.45 \, ^\circ C$ in $1$ s and $1.14 \, ^\circ C$ in $10$ s. It can be seen that the case of heating interrupted for 50 s does not produce higher temperatures than continuous heating.

It can be expected that similar results can be obtained for all other cases discussed in Karagoz and Kartal (2006). I conclude that for the case of a single stationary transducer there is no need to consider the effect of residual temperature rise.

It should be noted that also in the earlier paper of Karagoz and Kartal (2005), the same error in the theoretical calculation of the temperature drop in the cooling period occurs. That paper seems to contain in their Fig. 6 and their Table 3 an experimental verification of the concept of residual temperature rise. However, confounding factors, such as applying ultrasound gel on the skin and internal heating of transducer, were not analysed. These factors might have their own characteristic times and, thus, it is difficult to interpret the obtained results. The experiment would have been more convincing if continuous and interrupted heating had been compared.

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Received 3 July 2006; in final form 19 September 2006
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doi:10.1016/j.ultrasmedbio.2006.09.008

RESPONSE TO DR. LUBBER’S LETTER

To the Editor-in-Chief:

In our previous papers (Karagoz and Kartal 2005; 2006), we calculated the residual temperature rise (RTR) at the focus of a transducer by assuming that the uniform temperature field occurs at the end of the first ultrasound examination to obtain worst-case temperature rise. After all, Lubbers (2006) theoretically proposed that there is no need to consider the effect of residual temperature rise for the case of a single stationary transducer. Although Lubbers (2006) superimposed the effects of several heat sources to calculate the temperature rise, experimental results obtained by Horder et al. (1998) show that bioheat transfer equation is nonlinear in power. Therefore, the temperature rise obtained with the method in Lubber (2006) does not give the actual value of temperature rise because of the nonlinearity in power.

Additionally, the behavior of tissue during repeated heating must be considered for investigating the existence of the RTR. There are no other studies about the repeated heating of tissue in literature. However, Davydov et al. (2001) obtained the time variations of the successive processes of heating of the same tissue region that are separated in time by 40 min to answer the question of whether heat transfer in cellular tissue exhibiting anomalous properties can go in the same way under repeated acts of heating. It was found that the temperature increase is characterized solely by a faster growth rate during the repeated heating, although the cooling time between two successive heating is 40 min [see Fig. 3 of Davydov et al. 2001]. However, it can be expected that reducing the cooling time causes the temperature rise induced by the second heating process to be higher than that the first heating process, even though the same heating time is used. Davydov et al. (2001) show that the heat transfer in cellular tissue is a more complex phenomenon than a simple heat diffusion and conclude that heat propagation in cellular tissue under local strong heating must be nonlinear. In the light of this approach, it should be considered that there are differences between the first and second heat propagations in tissue during the repeated heating. Although these differences occur during the repeated heating, Lubbers (2006) ignored these differences in the calculation of temperature rise induced by the repeated ultrasound exposure.

The nonlinear behavior of tissue during the repeated heating can cause the temperature rise obtained in the interrupted heating to be higher than continuous heating because of strongly heating at focus.

There are many studies on the effects of residual heat in high-intensity focused ultrasound (HIFU) examination. HIFU beams are used to produce selective thermal damage deep within the body. Fan et al. (1996), Malcolm and ter Haar (1996) and Wan et al. (1996) conclude that thermal buildup results because of cumulative ultrasound exposure near the transducer when closely spaced sonications are delivered without a sufficient intersonication delay. McDannold et al. (1999) show that the peak temperature rise, after seven sonications with an intersonication delay of 11 s, was 156% greater than the peak temperature rise of the first sonication. These results conclude that the higher temperature rise is obtained in the presence of the residual heat.

In our previous papers, we calculated an RTR at focus (Karagoz and Kartal 2005; 2006). In this study, we also obtained the temperature rise at other locations in the presence of the RTR. The same constants in our previous papers were used in this study. The attenuation coefficient $\alpha$ depends on frequency, and was chosen to be 0.5 dB cm$^{-1}$ MHz$^{-1}$ in our previous and present studies. The same simulation program was used (Lubbers et al. 2003). In this study, it was assumed that the transducer had a diameter of 1 cm, a beam diameter of 1 mm at focus, a focal depth of 4 cm, a power of 150 mW and a frequency of 2 MHz. The RTR was calculated for an observation point $z = 1$ cm. The origin of the coordinate system is at the front face of the transducer $(x,y,z) = (0,0,0)$, and the $z$ axis coincides with the beam axis. Figure 1 shows the temperature rise as a function of depth for a first heating of 500 s. The temperature rise is equal to 1.05°C up to $z = 3$ cm. The temperature rise increases to 2.0°C at a depth of 5 cm.

Fig. 1. The temperature rise as a function of depth for a first heating of 500 s.