VALIDATION OF A SIMULATION PROGRAM FOR THE THERMOREGULATION OF PATIENTS AND FIRE FIGHTERS

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INTRODUCTION

There are a few simulation programs known for the thermoregulation of humans. Bussmann [1] has shown that the thermoregulation of preterm newborns cared in incubators can be simulated in a relatively simple model. This model uses a three compartment model (head, core and periphery) including the variation of the metabolism and blood flow depending on the temperature difference between set and afferent body temperature; however there is no validation known (Fig. 1).

Xu [2] has developed an 8-cylinder model for adults in which each compartment can be exposed to different ambient conditions. Simulation models of newborns are known from Dane [3] and Ultmann [4], however both models have not been validated. Fiala [5] developed a multiseg mental, multi-layered representation of the human body with spatial subdivisions which includes a detailed representation of the anatomic, thermophysical and thermophysiological properties of the human body; however it can be shown that general functions of the thermoregulation can be described also with very simple models and the results can be produced very fast online. This allows using such programs simultaneously for prognosis of the temperature profile.

METHODS

The three compartment model of Bussmann [1], which was primarily developed for newborn babies, was used. Additionally the insulation of the body by blankets (patients) or by clothing (fire fighters) was included. Furthermore the thickness of fat within the tissue was implemented which has an enormous impact on the insulation. The heat loss by evaporation (insensible water loss and sweat) has also been included in the thermo model of the fabric. During anaesthesia, the patient's blood flow between periphery and core increases and the metabolic rate decreases due to the applied anesthesiological drugs. On the other hand, fire fighters work very hard and
increase their muscular heat production to a very high level. This has been implemented in the thermoregulation model.

![Graph showing blood flow and metabolism]

Fig.1: Block model of the thermoregulation with three compartments (head, core and periphery) and the blood flow (BF) between the compartments, which is controlled by the set and afferent body temperature. The metabolism can vary between minimum (Pmeta) and maximum (Max), also controlled by the set and afferent body temperature.

a) For the validation of the patient model the rectal temperature of 40 patients was measured [6] and compared to the simulated core temperature. Additionally, peripheral temperature was measured on the lower leg of the patient and compared with the simulated temperature of the peripheral compartment. The measurement started in the ward and continued during surgery until the patient was transferred back to the recovery room. 20 patients were cared by actively warmed blankets (forced air devices) and 20 patients were kept warm by insulation blankets.

b) For the validation of the fire fighter model the rectal temperature of 20 subjects was measured [7]. To stabilize the temperatures and provide baseline recordings of rectal, nasopharyngeal, and skin temperatures as well as heart rates, the subjects first rested, seated, at a room temperature of 24.3 ± 0.7°C and relative humidity of 25.7 ± 6.1% outside the climatic chamber for 30 min. The subjects were then moved to the climatic chamber where they performed a work/rest schedule. The total experimental time at 25°C was 145 min, (other results at 10°C and at 40°C are not shown here). Thermal (rectal, skin temperatures) and cardiovascular recordings were collected continuously before, during, and after the different experimental setups from 25% to 55% maximal intensity work load at different environmental temperatures. Other parameters such as oxygen uptake, body weight loss, sweat accumulation in the different clothing layers, and fluid intake were taken into consideration in establishing the physical status of the test subject during the experiments and for safety reasons. However, in view of the limited space available, these data will not be reported in the present paper.

To compare simulated and actual temperature measurements, Bland-Altman analysis was used.
RESULTS

a) Overall more than 277 measurement pairs were obtained (every 5 min) in the clinical study. Limits of agreement < ± 0.5 °C were defined a priori as clinically acceptable. The limits of agreement between core temperature and simulated temperature were ± 0.56 °C (Fig. 3) for all patients. The limits of agreement of the study group treated with forced air were within 0.5°C (-0.47°C to 0.67°C). The limits of agreement of the study group treated with warm blankets were slightly above 0.5°C (-0.61 °C to 0.67 °C). Still, 99.54% of the results from the forced air group and 96.48% of the results from the warm blanket group were within the limits of ±0.5 °C.

![Fig. 2: Example of the measurements of a patient with the real (lines) and simulated (dotted lines) core (above lines) and peripheral temperatures (bottom lines). The body temperatures drop during surgery and are kept stable during first recovery](image2)

![Fig. 3: Bland Altman plot of all 40 patients kept warm by blankets or a forced air devices with a mean of 0.04°C (dotted line in the middle) and a standard deviation of 0.28°C. The correlation within the Bland Altman plot is r= 0.09. The limits of agreement (+2 SD/ -2 SD) are plotted as dotted lines.](image3)
b) Overall more than 186 measurement pairs were obtained (every 5 min). The limits of agreement of the fire fighter study (Fig. 5) were -0.58°C to 0.61°C. Still, 93.86% of the results were within the limits of ±0.5 °C. Another important criterion was whether the temperature differences between the two procedures in the Bland–Altman diagram [6] correlate: which they should not do. The correlation results in a value of \( r = -0.19 \), bias of measurements did not appear to change systematically with the mean core temperature.

![Study SINTEF III Proband Nr. 14 ambient temperature: 25 °C](image1)

Fig. 4: Diagram with the real and simulated core and peripheral temperature (mean of all 20 subjects). The body temperatures rises during 3 times load periods and decreases during resting periods.

![Study SINTEF III: comparison real and simulated temperatures arithm. mean = 0.01°C, SD = 0.30°C, CCC = 0.89, r = -0.13 number of probands: 20, time: 96.82 h at: 25 °C](image2)

Fig. 5: Bland Altman plot of 20 subjects (fire fighters) with a mean of 0.01 °C (line in the middle) and a standard deviation of 0.30 °C. The correlation within the Bland Altman plot is \( r = 0.20 \). The limits of agreement (+ 2 SD: 0.61/ - 2 SD: -0.58) are plotted as dotted lines.
The fire fighters were also tested at ambient temperatures of 10°C and 40 °C. The validation between real and simulated core temperature had a standard deviation of SD=0.21 °C at 10 °C and SD=0.30 °C at 40 °C.

It is interesting that comparison between different core temperature measurements [8, 9] results in a standard deviation between 0.34 and 0.41 °C. Better accuracy can not really be expected by a simulation model.

CONCLUSIONS

The software was able to simulate patient's body temperature satisfyingly accurate. The software can be used to pre-calculate body temperatures of patients before surgery and sensitize anesthesiologists for upcoming problems regarding hypothermia.

The software was able to simulate a fire fighter’s body temperature satisfyingly accurate. The software can be used to pre-calculate body temperature of fire fighters before their mission and can also be used to optimize the equipment including clothing.

It was shown that general functions of the thermoregulation can be described with very simple three compartment models and the results can be produced immediately online. This allows the use of such programs perioperatively or during a firefighter’s mission for the prognosis of the temperature profile.

REFERENCES