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A SIMULATION PROGRAMME FOR HEAT BALANCE IN MARINE MAMMALS.

by

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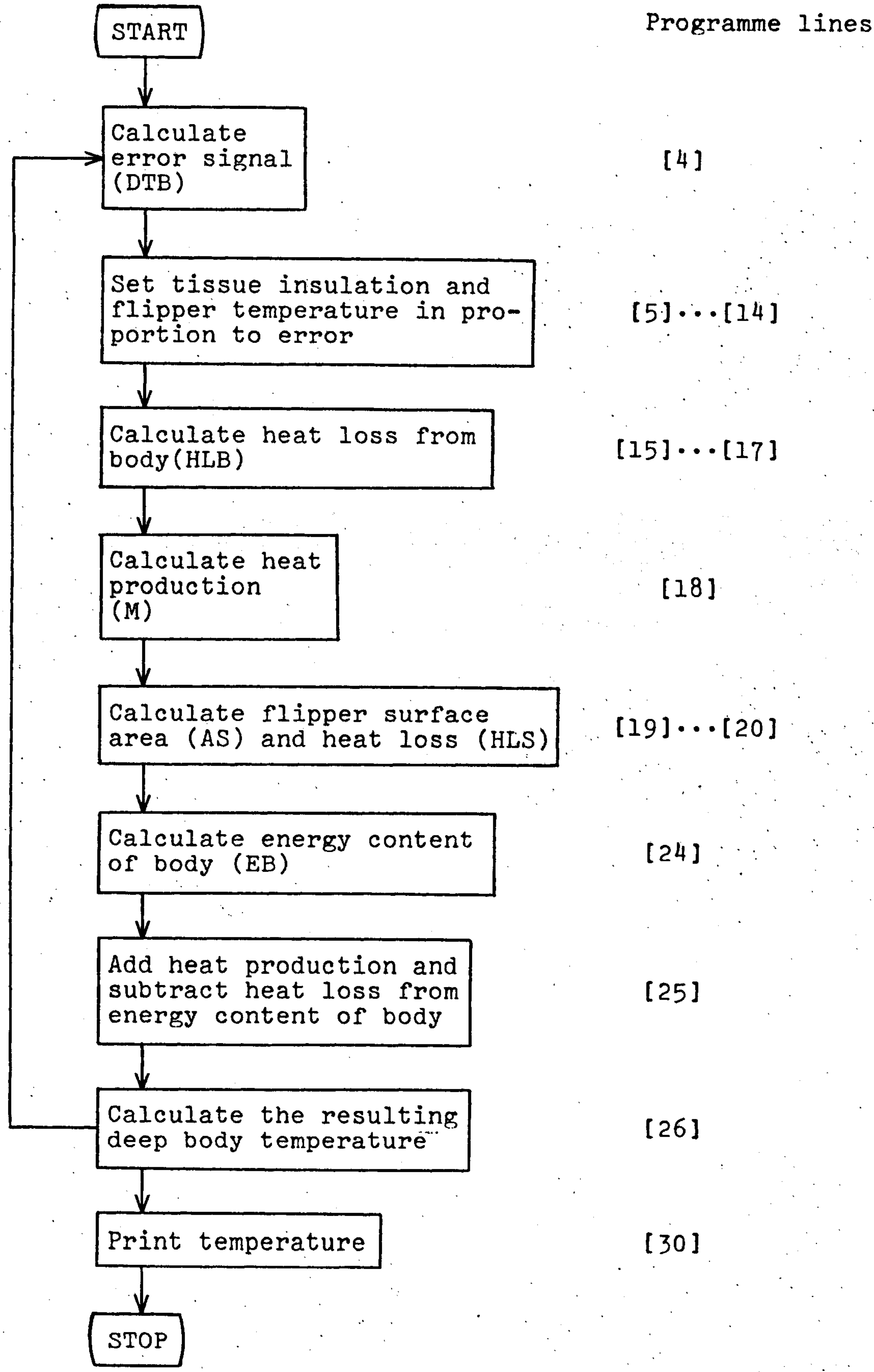
Summary

A mathematical model for heat balance in seals is implemented in APL.The model employs proportional control of blubber insulation and flipper temperatures while fur insulation is not controlled. Heat production and body surfaces are in conventional proportions to body weight.Some general aspects of applicatins of the model are discussed and the actual APL algorithms and programme are presented in detail.

FIGURE 1



Programme lines
START
Calculate error signal (DTB)
[4]
Set tissue insulation and flipper temperature in proportion to error
[5]···[14]
Calculate heat loss from body(HLB)
[15]···[17]
Calculate heat production (M)
[18]
Calculate flipper surface area (AS) and heat loss (HLS)
[19]···[20]
Calculate energy content of body (EB)
[24]
Add heat production and subtract heat loss from energy content of body
[25]
Calculate the resulting deep body temperature
[26]
Print temperature
[30]
STOP

Introduction

In order to evaluate the energy requirements on population levels it is necessary to assess the heat balance in individual marine mammals. Regulation of deep body temperature involves physiological and behavioural control of heat loss and heat production and constitutes a significant part of the maintenance energy turnover.

Several models of the heat balance are available for man (Bligh 1973), but only one for the energy balance in a marine mammal, the California sea lion, *Zalophus californianus* (Luecke et al 1975).

The present simulation programme integrates conventional expressions for metabolism and surface areas with values of thermal insulation of fur and tissue samples. The programme has been used in an analysis of temperature regulation in harp seal pups (Øritsland and Ronald 1977), and it is also useful for other marine mammals.

Description of programme

It is assumed that input data are in the form of chronological values of wind speed, air temperature, solar radiation and the time elapsed between each set of values.

Initially an error signal is calculated as the difference between the initial deep body and a constant reference temperatures. Blubber insulation and flipper surface temperature are then set in proportion to the error signal. Heat loss and metabolism are calculated for the relevant time period on the basis of the corresponding weather values. Subsequently the new deep body temperature is determined from the total energy or heat content of the body. This new deep body temperature is fed back to the first part of the programme and used for calculation of another error signal.

Before execution of the feedback the programme will count a period (i.e. data set~~s~~) and execute ~~the loop~~ only if more periods are available. When all periods are counted the corresponding deep body and skin (optional) temperatures are printed and the programme stops.

The major steps indicated above are presented together with a specification of the actual lines of the programme (Fig. 1).

Variables

TB	=	deep body temperature	^{o}C
TBS	=	reference point (for TB)	^{o}C
TBSH	=	deep body temperature corresponding to onset of maximum heat loss	^{o}C
DTB	=	error signal (DTB = TB - TBS)	^{o}C
TA	=	air temperature	^{o}C

V	=	wind speed	ms^{-1}
SR	=	solar irradiance	Wm^{-2}
HCI	=	heat transfer coefficient for peripheral tissues (HCI = KF/BL)	$Wm^{-2}\ {}^{o}C^{-1}$
KF	=	heat conductivity of fat	$Wm^{-2}\ {}^{o}C^{-1}m^{-1}$
BL	=	"functional" blubber thickness	m
AB	=	body surface area, excluding the flippers	m^2
HCV	=	heat transfer coefficient for the fur (HCV = 1.9 + $0.0V^2$ for whitecoats)	$Wm^{-2}\ {}^{o}C^{-1}$
TF	=	flipper surface temperature	^{o}C
AS	=	flipper surface area	m^2
M	=	metabolism	W
HLS	=	heat loss from the flippers	Wm^{-2}
HLB	=	heat loss from the body	Wm^{-2}
DT	=	time between calculated values of TB	s
W	=	body weight	kg
C	=	specific heat capacity of body	$Jkg^{-1}\ {}^{o}C^{-1}$
EB	=	energy (heat) content of body	J

Line by line comments to the programme are given in Appendix A.

An example: harp seal (*Pagophilus groenlandicus*) pups

A demonstration of simulated temperature regulation by means of changes in peripheral circulation is presented (Fig. 2) Air temperature was set at $10^{o}C$, wind speed 0.5 ms^{-1} and solar irradiance to zero. With a reference temperature of 37°C the simulated 20 kg whitecoat, with relevant blubber thickness brings deep body temperature back to 37°C in 20 to 40 min after a one degree offset. Under the above weather conditions the absolute value of the rate of change in deep body temperature is higher going from 30° to 37°C than when going from 36 to 37°C (Fig. 2). The decreasing temperature overshoots the 37°C "target" because the long (lo min) time intervals between each calculation of TB in this example.

Applicability to marine mammals

The skin temperatures of phocids in water stay close to that of the water (Irving and Hart 1957, Hart and Irving 1959). Thus by deleting the expressions concerned with fur insulation the present programme may also be used to analyze the heat balance of adult Phocidae in water. Similarly, whales in which the relationship between flipper and remaining body surface area has been determined, may be subjected to the same analysis.

Discussion

The present simulation programme integrates common physiological values. A notable difference to other models (Bligh 1973, Luecke et al 1975) is that the geometry of the body is simplified to that of plane layers. Also the effect of evaporative heat loss was not accounted for. The simulations of harp seal pups (Øritsland and Ronald 1977) however have produced biologically meaningful values. Further confirmation of the accuracy of the present programme depends on the availability of data on environmental conditions and corresponding body and skin surface temperatures. In addition, data on body weight, blubber thickness and the contribution of the limbs to the total body surface area must be provided.

The construction of meaningful simulations, of population dynamics or energy balance, is based on interdisciplinary considerations ranging from cybernetics to practical field biology. Also, within the field of marine mammal research and management the need for better and wider simulation programmes is increasing rapidly. This report is submitted therefore in view of the above consideration and with the belief that detailed programmes also should be available in unrestricted literature.

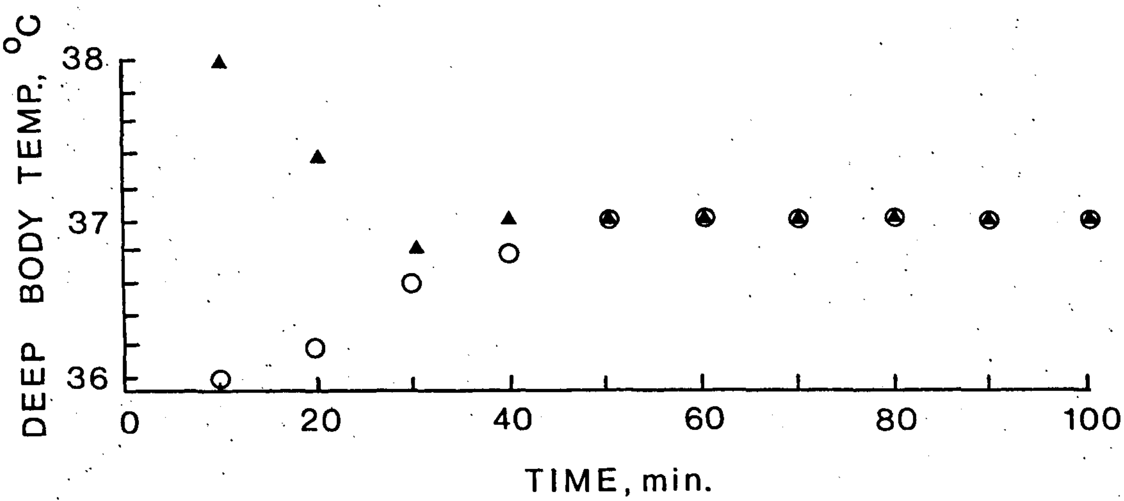


Figure 2. Demonstration of simulation programme acting on a 20 kg harp seal pup with an offset of $\pm$ 1°C in deep body temperature at time 10 min. Air temperature is -10°C, wind speed is 0.5 ms^{-1} and there is no solar radiation. Reference temperature is 37°C and the blubber thickness is 10 cm.

APPENDIX A

Detailed programme.

Programme line number in brackets.

[1] $I \leftarrow 1$

Length (period) counter is set to 1.

[2] $TSN \leftarrow TS \leftarrow 0$

Skin temperature storage vector (TSN) is set equal to skin temperature (TS). Skin temperature is started with 0.

[3] $TBN \leftarrow TB$

Deep body temperature storage vector (TBN) is set equal to deep body temperature.

CONTROLLER PART OF PROGRAMME:

[4] *CH:DTB←TB-TBS*

Labelled (CH) line: Error signed DTB is determined as the difference between TB and the reference temperature TBS.

[5] →((*TB*<*TBS*),(*TB*>*TBSH*),((*TBS*≤*TB*)∧(*TB*≤*TBSH*)))/(*L*1,*L*2,*L*3)

Control is initiated by comparing TB with the reference temperature and the temperature corresponding to onset of maximum heat dissipation. If TB is smaller than TBS the programme branches (goes) to the line labelled L1 (below). If TB is higher than TBSH the programme branches to L2 and if TBS ≤ TB ≤ TBSH the programme goes to L3.

[6] *L*1:*BL←TYK*

Labelled line (L1): The functional blubber thickness is set to maximum (real) thickness. (Because TB is lower than the reference temperature TBS).

[7] *TF←TA[I]+0.5*

Flipper surface temperature is at minimum i.e. 0.5 degree warmer than air temperature.

[8] *→STR*

Programme branches to the line labelled STR (lines between [8] and STR are bypassed.

[9] *L2:BL←0.001*

Labelled line: The functional blubber thickness is set to minimum (because TB is higher thant the termperature, TBSH, corresponding to onset of maximum heat dissipation).

[10] *TF←TB-0.5*

Flipper temperature (TF) is set to maximum i.e. 0.5°C lower than deep body temperature in order to provide maximum heat loss from the flippers.

[11] $\rightarrow STR$

Programme branches to the line labelled STR (Lines 12 and 13 are bypassed).

[12] $L3{:}BL \leftarrow 0.001+TYK\times DTB\div(TBSH-TBS)$

Since TB is within the regulation band (TBS to TBSH) the functional blubber thickness is set in linear proportion to the error signal (DTB). The proportionality (sensitivity) is determined by the width of the regulation band.

[13] $TF\leftarrow TA[I]+(TB-{}_{1}-TA[I])\times DTB\div(TBSH-TBS)$

The flipper temperature is set to a value between one degree below deep body temperature and air temperature. The value of TF is in proportion to the error signal.

ACTUATOR PART OF PROGRAMME:

```
[14] STR:HCI←KF÷BL
```

Labelled line: The heat transfer coefficient of the blubber is calculated as the conductivity of blubber divided by the functional blubber thickness.

```
[15] HLB1←HCI×(1.9+0.05×V[I]*2)×(TB-TA[I])
[16] HLB1←HLB1÷(HCI+(1.9+0.05×V[I]*2))
```

Heat loss through the blubber and fur (HLB1) is calculated considering the two layers as a plane wall:

$$\text{HLB1} = \frac{\text{HCI} \times \text{HCV}}{\text{HCI} + \text{HCV}} (\text{TB}-\text{TA})$$

```
[17] HLB←HLB1-0.17×SR[I]×SFB
```

Solar heating is subtracted from the heat loss. Solar heating is applied to 45% of the body surface (SFB = .45).

```
[18] M←3.4×(W*0.75)×MF[I]
```

Metabolism is calculated according to Kleiber's formula multiplied by the metabolic factor MF.

```
[19] AS←0.018×W*(2÷3)
```

Flipper surface area is determined to be 20% of the total surface.

```
[20] HLS←12×(V[I]*0.1)×(TF-TA[I])×AS
```

Heat loss from the flippers:

$HLS = 12V^{0.1}\ (TF-TA)AS$

```
[21] TS←(HLB1÷(1.9+0.05×V[I]*2))+TA[I]
```

Skin temperatures are determined on the basis of the heat loss through the body and the fur's heat transfer coefficient (HCV): $TS = \frac{HLB1}{HCV} + TA$

[22] *TSN←TSN,TS*

The last skin temperature is added as another element in the skin temperature storage vector TSN.

[23] *AB←0.062×W⋆(2÷3)*

Body surface area, excluding the flippers, is determined. $AB = 0.062W^{2/3}$

CONTROLLED PART (SYSTEM):

[24] *EB←3100×W×TB*

Energy content of the body, corresponding to TB, is calculated.

```
[25] EB←EB+(M×DT[I])-((HLB×AB)+HLS)×DT[I]
```

Net balance between heat production and heat loss is calculated for the relevant time period (element I in the DT vector) and the result is added to the previous energy content of the body.

```
[26] TB←EB÷(3100×W)
```

The new deep body temperature is calculated.

```
[27] TBN←TBN,TB
```

The new TB is added to the deep body temperature storage vector.

```
[28] I←I+1
```

A time period is counted and added.

[29] →(*I*<ρ*DT*)/*CH*

If more time periods can be used the programme branches back to the line labelled CH and another assessment of the thermal situation is initiated. If all time periods have been used the programme prints out the values of the temperature storage vectors (lines [30]and [31]).

[30] '*TB*:';*TBN*

[31] '*TS*:';*TSN*

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