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A DYNAMIC HUMAN WATER & SALT BALANCE MODEL FOR VERIFICATION AND OPTIMIZATION OF LIFE SUPPORT SYSTEMS IN SPACE FLIGHT APPLICATIONS

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Abstract

The scope of this paper is the development of a dynamic MATLAB SIMULINK® model for the water and electrolyte balance inside the human body. This model is part of an environmentally sensitive dynamic human model for the optimization and verification of Environmental Control and Life Support Systems (ECLSS) in space flight applications. The ECLSS provides all vital supplies for supporting human life on board a spacecraft. As medium to long-term missions become the focus of human space flight, the strategy in ECLSS is shifting to closed loop systems. For these systems the stability and function over long duration is essential. In contrary to this, the only evaluation and rating methods for ECLSS up to now are either expensive trial and error breadboarding strategies or static and semi-dynamic simulations. In order to change this mismatch the Exploration Group at Technische Universität München (TUM) is developing a dynamic environmental simulation, the “Virtual Habitat” (V-HAB). The central element of this simulation is the dynamic and environmentally sensitive human model. The water sub-system simulation of the human model discussed in this paper is of vital importance for the efficiency of possible ECLSS optimizations, as an over-scaled or sub-optimally functioning water sub-system will add a major negative contribution to the overall mass budget. On the other hand water has a pivotal role in the human organism.

Water accounts for about 60 % of total body mass and is educt and product of numerous metabolic reactions. It is transport medium for solutes and provides the most potent medium for heat load dissipation due to its high evaporation enthalpy. In a system engineering approach the human water balance was divided into different sub-systems and their interactions were worked out. The body fluids were organized into three compartments, consisting of blood plasma, interstitial fluid and intracellular fluid. In addition, the active and passive transport of water and solutes between those compartments was modeled dynamically. A kidney model regulates the electrolyte concentration in body fluids (osmolality) in narrow confines and a thirst mechanism models the urge to ingest water. A controlled exchange of water and electrolytes with other human sub-systems, as well as with the environment, is implemented. Finally the changes in body composition due to muscle growth are accounted for. The outcome of this is a dynamic water and electrolyte balance which is capable of representing body reactions like thirst and headaches, as well as heat stroke and collapse, as response to its work load and environment.

1. INTRODUCTION

In the past nearly fifty years many components of environmental control life support systems (ECLSS) for closed habitats in human spaceflight have been proposed but few have been tested and verified, and even less were used in space. As human exploration of the Moon and Mars once more comes into the focus of the space travelling nations, often studies are performed to evaluate the feasibility of permanent establishments in space. For ECLSS that often implies the comparison via the equivalent-system-mass (ESM) [1] which is well suited metric for first estimations and a preliminary layout on Phase 0 or Phase A level. But the ESM does not account for the dynamics which occur if a human is placed in a habitat together with an ECLSS. In order to judge the functionality of such a complex dynamic system it needs to be tested and verified. In order to minimize hazards for human subjects and cost of expensive and complex long time tests, computer simulations as state of the art approach to complex systems, is applied. The Institute of Astronautics of the Technische Universität München develops a tool in MATLAB/SIMULINK® which enables an evaluation of the functionality and long time stability of ECLSS. This concept is called the ``Virtual Habitat'' (V-HAB) [2].

Beside the functionality of physical, chemical and biological equipment, the human within the system is the most important controller and source of perturbations in ECLSS. Its survival is the exclusive task of an ECLSS. Existing models [3, 4] simulate the behavior of the entire human body with static equations that provide linear responses to predefined interferences. Other more sophisticated models are highly specific for certain effects within the human body [e.g. 5, 6, 7]. The dynamic human model, introduced in the course of the V-HAB project, is unique in its intention to dynamically simulate the global behavior and to interact with the ECLSS. It is important to state, that the V-HAB human model does not lay claim to a fully medical reproduction of each and every physiological interaction of the human body. It is an engineering model which reproduces the main physiological responses of the human body to external influences caused by and important for ECLSS.

So far different top level functionalities have been modeled, beside the water & salt balance presented in this paper. These are the ability to exchange oxygen and carbon dioxide with the environment (respiration), as well as nutrition and aerobic and anaerobic effects within the human body, e.g. training caused muscle growth (metabolism). Moreover cardiovascular and a thermal functionalities were implemented. In Figure 1 the main functionalities of the V-HAB Human Model are depicted. For further information about the status of the overall V-HAB Human model the interested reader is asked to refer to [8].

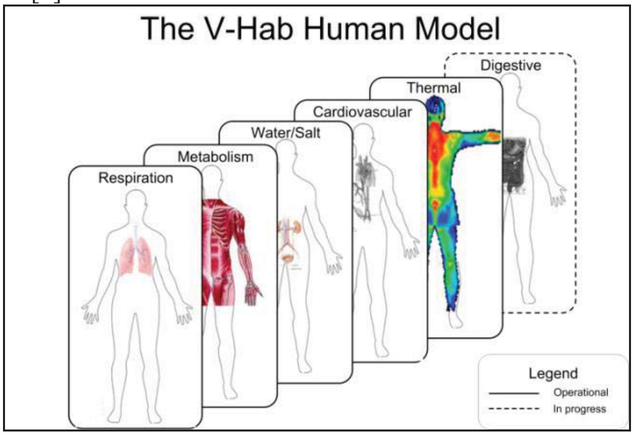

Figure 1. Functionalities of the V-HAB Human Model

2. APPROACH (METHODS)

The human water balance model has the goal to simulate the dynamic processes that alter the water balance of a human being. Almost every organ is connected and impacted by the human water & salt balance. With respect to the large influence of the human water and salt balance not only to the intake and excess of water, but also to overall body performance, the main targets of the model are:

- Model the distribution of water within the human body with respect to body properties.
- Model the fluid shift and thus the transport of water and solutes namely electrolytes within the human body.
- Simulate the regulating mechanisms within the body, (i.e. the concentration and excretion of water and electrolytes with respect to body conditions)
- Connect the water balance to consumers such as thermoregulation and respiratory tract and highlight their interaction with the environment
- Control and regulate the distribution of water in situations of low water and electrolyte conditions with respect to the consumer's demand
- Signal the overall dynamic human off-nominal situations such as thirst and need to water, thus physical and psychological stressors
- Secure mass preservation and avoid negative material flows

The basic modeling strategy of the V-HAB simulation is characterized by a global top-down, and an individual bottom-up approach.

In order to generate an ECLSS specific human model the main or top-level functionalities for the interaction between human and ECLSS were defined and separated in several work packages. Those functionalities were modeled separately as stand-alone models, within relevant environments. With the aim of raising the validity of the modeled top-level effects it was supported by a bottom-up view on the biochemical relations, which were simplified and put into mathematical equations, were it was appropriate. The fidelity of those models was correlated against medical data, taken from literature.

This approach enabled the investigation and verification of the created responses prior to connecting the different top-level functionalities. Were it was necessary, simplified "dummy" models were implemented which served as external triggers. The same approach was chosen for the development of the functionalities themselves and thus is true also for the water & salt balance model.

The first step in the evolving process of the water & salt balance model was to apply a systems engineering view and define the related sub-systems that take part in the water and salt balance of the human body. Their interactions were located and illustrated in flow charts and diagrams in order to obtain a better overview and improve the understanding. The top level diagram of the water and salt balance, as product of this process, is presented in Figure 2. Main objectives, in- and outputs and restrictive factors for these water and salt balance relevant sub-systems were identified, categorized and organized in work packages.

Once the relevant sub-systems were defined, the complexity of the human water & salt balance model was increased stepwise. At first, simple water balances were implemented, the body fluids, the different water compartments and, as a central feature, the osmolality (the concentration of electrolytes per kilogram of body fluid) was modeled in MATLAB/SIMULINK®.

Therewith movement of water from one compartment to another was traceable. Beside the osmolality induced passive diffusive transport, active transport mechanisms were mimicked. The kidney as most important and potent organ, responsible of controlling the overall water balance was added. Once water and electrolytes were excreted by the kidney continuously, a simplified mechanism for water ingestion became indispensable. Hence a simplified "dummy" model for the digestive tract was added. As soon as these basic circulatory mechanisms were approved, loads were added, such as water lost via respiration and evaporation. Evaporation demanded the implementation of a rudimentary thermoregulation model, which in turn is coupled to the metabolism. One by one other sub-systems were added to gain the system illustrated in Figure 2. Subsequently controllers and feedback effects were implemented to raise the dynamic interaction between the different sub-

systems. In this way the fundamental impact, the water balance has for example on sweat excretion, was modeled.
Finally thirst and urination mechanism were added to provide interfaces to an overall human model controller and the environment.

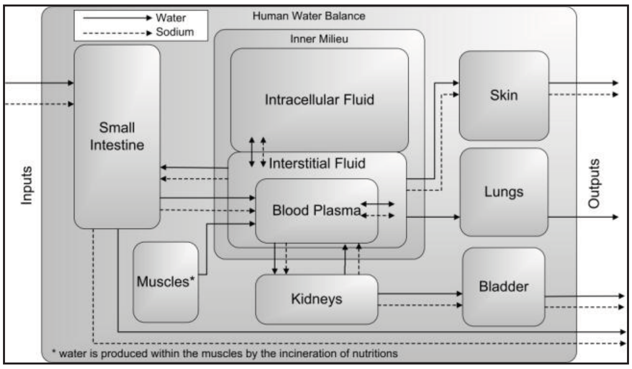

Figure 2. Basic interrelations of the water and salt balance within the V-HAB human model.

3. SUMMARY OF PHYSIOLOGICAL BACKGROUND

As already pointed out, water has an outstanding role in the human body. In the following several important aspects like the human water balance, the water distribution in the human body and the properties of human body fluids are highlighted and their impact on the modeling process are pointed out.

3.1.1. Human Water Balance (global in- and outputs)

The individual water balance of a human varies on a large scale depending e.g. on external factors like temperature, activity, daily schedule or the availability of fluids. For a standard human in a standard environment, the daily throughput of water will be around 2.6 l (Figure 3) [9].
In a climate environment a sedentary healthy human will consume about 1.4 l of fluids per day and will gain an additional volume of approximately 0.9 l from nutrition since up to 70 % of the normal food consists of water. Additionally 0.3 l of water is produced by the metabolism within the human body for a moderate activity.
The kidneys produce around 1.5 l of urine per day. The humidification of air in the trachea, the diffusion of water through the skin (Perspiratio Insensibilis) and the active cooling via evaporation causes the loss of another 0.9 l in a climate environment. Finally, 0.2 l of water is excreted together with feces.

3.1.2. Water Distribution in the Human Body

The overall body water content is mainly related to differing body composition within the demographic groups and can vary from 50 to 75% water [9, 10]. E.g. adipose tissue (fat) has a water content of only 15 % whereas in contrast the gut, as the most aqueous organ has a water content of ~79 % [11]. The water distribution for a standard human of 1.75 m height and 70 kg weight is given in Figure 3 on the right hand side. The total body water will be around 60 % which means 42 l. Two thirds of this water is concentrated within the cells and is called intracellular fluid (ICF). One third is labeled as extracellular fluid (ECF) which in turn is made up from 76 % interstitial fluid (INT), 18 % blood plasma (BP) and 6 % transcellular fluid. Interstitial fluid is the liquid that is bathing the cells. Blood plasma is the transport medium and solute in which the blood cells are floating and transcellular fluid is e.g. intraocular i.e. the fluid within the eyes.

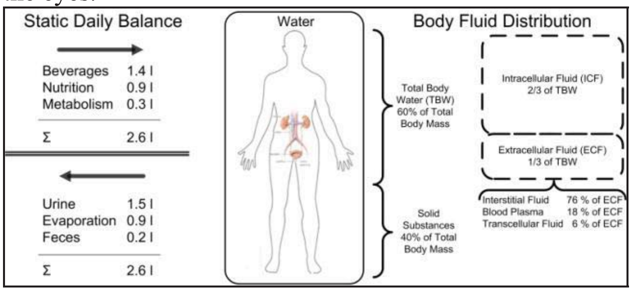

Figure 3. Static daily water turnover under standard conditions and body fluid distribution in an average human.

3.1.3. Human Body Fluids

The water within the human body is a solution of different components. Most important for the water and salt balance are the electrolytes of which potassium is predominant in the intracellular and sodium in the extracellular fluid. Other agents e.g. proteins and urea also are soluted in the body fluids. Osmolality [osm/kg_{H2O}] represents the concentration of all osmotic active particles in a solution, irrespective of the kind of agent or mixtures, standardized with the mass of the solvent [12].
The osmolality within the human body is under stringent control. The absolute value however differs in literature from 287 to 300 mosm/kg_{H2O} [9, 11, 12, 13, 14]. Apart from a few exceptions this range of osmolality is true for all body fluids.

4. MODEL DESCRIPTION

4.1. Standard Human

As standard human, a male person of an age between 20 and 30 years, a body mass of 70 kg and a body height of 1.75 was assumed. In the following values, important as initial conditions for the modeled water functionalities, are gathered in TAB 1.

Tissue	Water content [%]	Mass faction of total body mass [%]	Mass in standard human [kg]
Skeletal muscle	0.78	44.7	31.3
Adipose tissue	0.15	15	10.5
Bones	0.17	14.9	10.4
Organs&Remnants	0.75	25.4	17.8

TAB 1. Water Distribution in a Standard Human with a body mass of 70 kg; adopted from [9, 11, 16]

4.2. Model Structure

The water & salt balance model is structured in functional units or blocks, depicted in Figure 4. There is the *inner milieu* block which hosts the different water compartments and the movement between those compartments according to physical and physiological equations. The *kidney* block serves as controller and regulates the water and salt contents of the blood plasma via a sophisticated control algorithm adopted from [17, 18]. The *dummy systems* functional block hosts the consumers and providers of water and salt within the human body (e.g. a dummy cardiovascular model and a respiratory model). They are necessary in order to control the validity of the human water & salt balance model as a stand-alone model according to the requirements given in the methods section. In the *water & electrolyte controller* block, the impact of hydration status is modeled.
Further there is an *initial conditions & schedule* block, which provides the interface for the user to allow the input of data prior to running the simulation, and a *metabolism induced changes* block, which accounts for longtime changes in body mass due to training and detraining. A *micturation* block controls the bladder status. The latter three blocks will not be discussed within this paper.

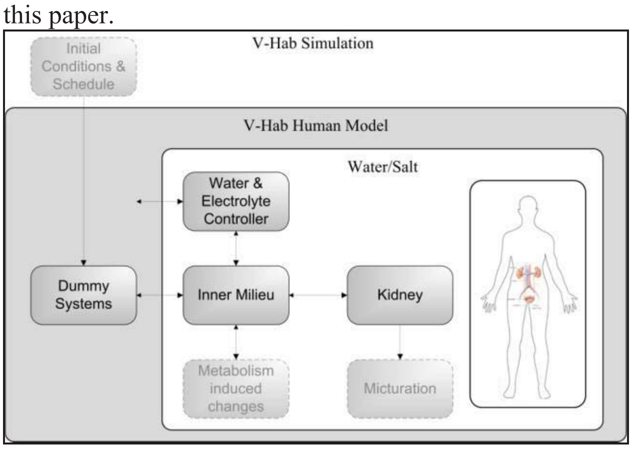

Figure 4. Structure of the Water and Salt Model. Only the solid blocks are discussed in this paper.

4.2.1. Inner Milieu

Within the *inner milieu* block the main water compartments, blood plasma (BP), interstitial fluid (INT) and intracellular fluid (ICF) are modeled. Moreover the fluid shifts induced by osmotic gradients, the accompanying solvent drag the active transport and the concentration induced diffusion is implemented.
The processes responsible for the maintenance of the *inner milieu* are numerous and complex. It is not possible to model each and every last ATPase, channel and carrier or transporter protein. Therefore some assumptions were made for the *inner milieu* block:

- Blood plasma and interstitial fluid are treated separately, whereas interstitial fluid comprises the transcellular fluid.
- The osmolality in each compartment has an initial value of 290 mosm/kg_{H2O}. Osmotic coefficients are equal for each compartment and every solute.
- Electrochemical gradients are neglected.
- Hydrostatic pressure induced ultrafiltration along the Endothelium is neglected.
- Lymph fluid is not addressed separately.
- Urea is not monitored
- The water content in each tissue is a constant.

The electrolytes were modeled according to standard values obtained from literature. Since these values are subject to change due to nutrition, age and gender, a basic distribution was based on [12] and was slightly modified to allow an easier handling of the osmolality (see TAB 2). Together with a model osmotic coefficient of 0.96 [-] and the water density for standard body core temperature $\rho_{H2O,37°C}$=0.99332 kg/l, the osmolality of 290 mosm/kg_{H2O} was obtained.
All electrolytes listed in TAB 2 are accounted for in the model with different significance. Especially Na^+ and K^+ have a higher priority and are traced more accurately. CA^{2+}, Mg^{2+}, HCO_3^-, HPO_4^{2-}, Proteins and Remnants are mere containers that fulfill the movement and contribute to the osmolality but have no further impact on the water & salt model. They were modeled separately to allow their utilization in latter phases of the model.

	Silbernagl et al. [2001]			V-HAB Model Fluids		
Electrolytes	ICF	INT	BP	ICF	INT	BP
Na^+	12	145	142	12	143	142
K^+	140	4.4	4.3	140	4	4.3
Ca^{2+}	<0.001	3	3.2	0.001	2.6	3
Mg^{2+}	1.6	0.9	1	1.699	1	0.8
Cl^-	3	117	104	3	115	104
HCO_3^-	10	27	24	10	27	24
HPO_4^{2-}	30	2.3	2	30	2	2
Proteins	54	0.4	14	52	0.4	14
Remnants	54	6.2	5.9	51.3	5	5.9
Σ	304	306	300	300	300	300

TAB 2. Values of the electrolyte concentration found in literature [12] compared to the values used in the V-HAB human model water & salt balance. Values are given in mEq/l^{-1}.

The BP compartment is separated from the INT by the endothelium, whereas INT and ICF are separated by the total cell membrane (Figure 5). This artificial barrier is the assumed sum over all cell membranes in the human body.
The movement of water is based on osmosis, i.e. the diffusion of water through a semi-permeable membrane, such as cell membranes. This movement is driven by the concentration difference of solutes on both sides of a membrane.
The movement of all electrolytes is implemented as solvent drag, diffusion and active transport. Solvent drag labels the electrolyte movement caused by the water shift from one to another compartment. The electrolytes are dragged along according to their actual concentration. Diffusion is the transport caused by the random thermic Brownian motion of molecules or ions [12]. This movement depends on the concentration gradient between two compartments. Thus, both passive transport mechanisms are changing dynamically. The real active transport is highly complex and subject of ongoing studies. There are numerous mechanisms that move

solutes through the different membranes in an organism. For the water & salt balance model the active transport was considered to be a gradient, counteracting the passive transport mechanism caused movements, with the aim to resume the basal equilibrium, i.e. the concentrations given in TAB 2.

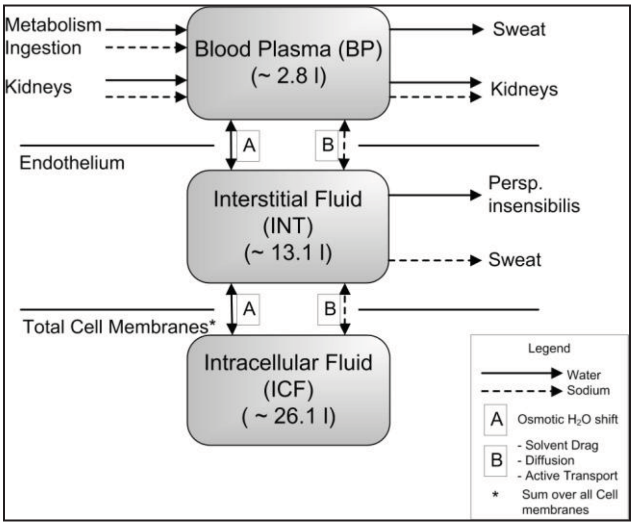

Figure 5. Structure of the inner milieu. The values are based on the standard human introduced in chapter 4.1.

4.2.2. The Kidneys

The kidneys are the decisive organs for the human water balance regulation. The *kidney* block implemented in this model is closely related to the models published in [17] and a slightly altered version presented in [18]. Within those models the kidneys are considered to be one single large nephron consisting of proximal tubule, loop of Henle and distal tubule with collective duct. Moreover the excretion of H_2O and Na^+ is regulated via two endocrine systems (an antidiuretic hormone (ADH) system and a Renin-AngiotensinII-Aldosteron (ALD) system).

Within this *kidney* block (Figure 6), water and salt are filtered from the BP into the proximal tubule and consecutive to the loop of Henle and the distal tubule. Here the water and Na^+ amount is adjusted according to the levels of ADH and ALD in the blood plasma. The ADH concentration in turn is triggered either by an elevated Na^+ level in blood plasma or the depletion of the extracellular fluid (ECF). The concentration of ALD as the last hormone of the Renin AngiotensinII-Aldosterton chain is triggered by the amount of Na^+ filtered into the distal tubule. Whereas ADH controls the amount of water reabsorbed in the distal tubule, ALD adjusts the amount of Na^+ excreted together with the urine.

Due to the fact that hormones are distributed within the human body together with the blood, there is a certain delay between the moment in time when an off-nominal value is detected, the moment the hormone is released and the moment, the hormone reaches its destination together with the blood stream. Therefore these routines are implemented as differential equations taken from [17, 18].

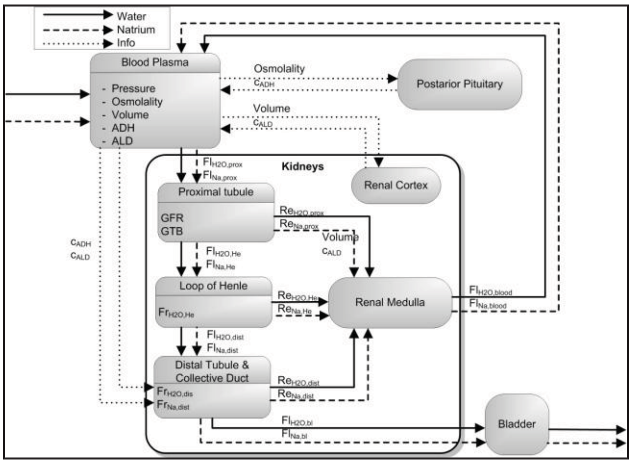

Figure 6. Structure of the kidney block. The functionality was adopted from [18, 19].

4.2.3. Water and Electrolyte Controller

Within this block the interactions between the water & salt balance model and its surrounding are modeled. It is partitioned in monitoring units and controlling units. The body water loss (BWL) is being monitored as well as the Na^+ loss and the thirst level. The controlling units are a sweat ratio controller, a peripheral resistance controller and an ingestion controller.

The *sweat ratio controller* unit checks the actual hydration status and restricts the amount of H_2O released as sweat. This controlling device is founded on the studies performed by [19, 20, 21, 22]. In [19] subjects were tested in a hot environment with a temperature of 49°C and relative air moisture of 20 %. The schedule foresaw an exercise interval of 140 min in length, whereas 10 min of rest interrupted 25 min bouts with 25 % $\dot{V}O_{2,max}$. Based on this study, a Newton iteration method was used to determine an equation describing the developing of sweat rate Fl_{sw} [g/min^{-1}], with respect to the hydration status BWL [%] and the sweat flow $Fl_{sw,dem}$ [g/min^{-1}] demanded by the human thermoregulation system.

$$Fl_{sw} = (-0{,}354369 \cdot (BWL)^3 + 2{,}62428 \cdot (BWL)^2 - 6{,}1602 \cdot (BWL) + 100) \cdot \frac{1}{100} \cdot Fl_{sw,dem} \quad (1)$$

Since sweat serves as most potent cooling medium for the human body, these restrictions have a large impact on the overall performance of the thermal regulation and thus the total human.

Beside the direct influence of the total body water status on the thermal aspects of the human body the water and salt status has a mediated impact on the cardiovascular system via the concentration of ADH (c_{ADH}) in the blood plasma (*peripheral resistance ratio* controller). A raised concentration of this hormone accounts for an increase in peripheral resistance (R_{per}) due to vasoconstriction which in turn demands an elevated heart rate or cardiac output respectively. This effect was observed and discussed by [23]. The Newton iteration in this case is given in equation 2.

(2) $$R_{per,act} = (-0{,}018825 \cdot (c_{ADH})^2 + 1{,}76989 \cdot (c_{ADH}) + 91{,}621) \cdot R_{per,0}$$

Whereas the initial peripheral resistance $R_{per,0}$ is given with 1.018108 [$kg/s^{-1}m^{-4}$]. Equation 2 only is valid for the interval $0 < (c_{ADH}) < 40ng/l^{-1}$.

The *thirst controller* block finally models the complicated network of thirst, triggered in the human organism. Based on data published by [22], four different factors, which can lead to a desire to drink, can be distinguished. These factors are blood plasma volume $V_{BP,t}$, blood plasma osmolality $c_{osm,BP,t}$, Angiotensin II (AngII) concentration in blood plasma $c_{AngII,BP,t}$ and the water loss in intracellular fluid $m_{H2O,ICF,t}$. All of these triggers have been implemented into the thirst controller block (Figure 7). According to [22] AngII has the largest impact on thirst together with the change of fluid volume in the ICF. Thus these values have a higher weighting factor (TAB 3).

	Threshold value	Weighting factor
$V_{BP,t}$	< 90 %	0.5
$c_{osm,BP,t}$	> 101 %	0.5
$c_{AngII,BP,t}$	> 101.5 %	1
$\Delta m_{H2O,ICF,t}$	> 1 %	1

TAB3. Values triggering thirst in the human body, their threshold and weighting factors for the water & salt model.

These values are cumulative and are being monitored in the thirst controller block from where they are forwarded to the overall human model to allow the determination whether the ingestion of water is necessary or not. The thirst status is graded based on a four level metric:

- Thirst status < 1 - no thirst is sensed
- Thirst status ≥ 1 - thirst is sensed
- Thirst status ≥ 2 - severe thirst is sensed
- Thirst status ≥ 3 - thirst is not sensed anymore.

The Thirst Mechanism block is a hybrid since it can be used as monitor, to simple output the actual thirst level or can be used as controller for the ingestion of water (and Na^+ respectively).

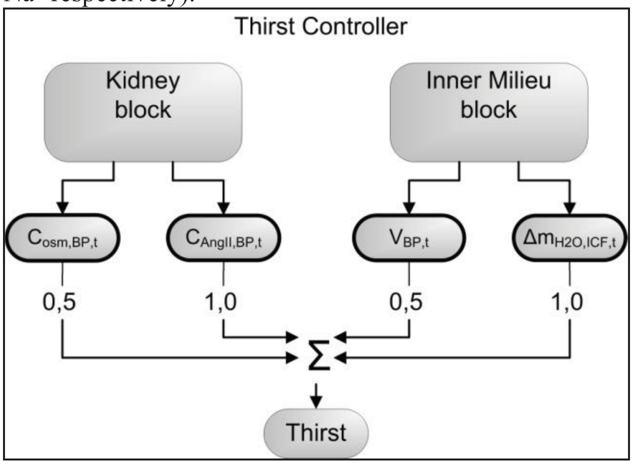

Figure 7. Structure of the thirst mechanism of the water & salt balance model.

4.2.4. Dummy Systems

The model was developed as a standalone model. Therefore all water & salt relevant sub-systems of the human body had to be implemented in simplified "dummy" models. Thus simplified static cardiovascular, respiration, metabolism, thermal and digestive models were included. The respiratory dummy model provides a demand of water that is necessary to humidify the inhaled air under the assumption that the exhaled air has a relative air moisture of 100 %. The dummy cardiovascular system provides the heart rate and cardiac output for the metabolism dummy model as well as the blood pressure in the kidney, in order to quantify the amount of water filtered into the kidneys. The digestive dummy model enables the ingestion of water and Na^+. Moreover it provides a delay between ingestion and the moment the water is available within the body by simulating the half-live of water in the different digestive organs. Beside these delays two drinking mechanism were implemented. One mechanism is labeled 'drink on demand' and provides the ingestion of water and Na^+ as soon as the thirst controller signals thirst. The other mechanism triggers the ingestion of water and Na^+ in a predefined drinking schedule.
Finally the thermal dummy model discards the heat produced in the metabolism dummy model via radiation, convection, conduction and evaporation (based on [24]). If the overall human activity level rises or environmental conditions provide heavy heat loads, this dummy model has a severe impact on the water & salt balance model.
These dummy models serve as substitutes to provide the correct interfaces for the integration of all components of the V-HAB human model and mimic the real interactions and feedbacks between the different functional units within the human body.

5. RESULTS

Several conclusive test simulations were performed in MATLAB SIMULINK® on a fixed step solver and their results are discussed to present the functionality of the water & salt balance model. The simulations discussed in section 5.1 represent the regulation of body osmolality under nominal and off-nominal conditions. In section 5.2 several simulations are performed and discussed to show the functionality of control mechanisms implemented in the water & salt balance model and depict the interactions with other sub-systems and therewith the environment.

5.1. Controllability

The first simulation shows the development of the osmolality in the blood plasma over a period of 7200 min (five days) if the model is allowed to 'drink on demand', i.e. drink the necessary amount of water and ingest the necessary amount of Na^+ respectively, as soon as the thirst level increases by one. The simulation was performed on the standard human discussed in 4.2. The environmental conditions were adjusted to standard values (T_{env}=20°C, ; p_{env} = 101333 Nm^{-2} ; φ = 0 %). In Figure 8 on can see the amount of water ingested as soon as the thirst level increases by one. In Figure 9 the oscillating behavior of blood plasma osmolality is shown. It can be seen, that the simulation is stable after a stabilization phase.

If a day and night cycle is applied and the availability of water and Na^+ is restricted to 16 h per day one can see how the water & salt balance model reacts (Figure 10). The shaded areas represent the night phases. As one can see in Figure 11 the osmolality increases during simulated night-phases. The elevated amplitude can be explained by the structure and connection between on demand drinking and thirst mechanism. Due to the delay between water ingested and available in the inner milieu (and therewith sensible for the thirst mechanism) and the fact that only the amount of water and Na^+ is ingested that is lacking and not more, the thirst level will not return to zero. This in turn causes the water & salt balance model to ingest large amounts of water and Na^+ leading to higher amplitudes.

The next case shows the process of rehydration in the water & salt balance model. The regarded time interval is declined to 1440 min (one day). The effect of rehydration is overlaid with the response of the sweat rate controller to body water loss. The standard human (see chapter 4.2) is placed in a hot and humid environment (T_{env} = 40°C ; p_{env} = 101333 Nm^{-2} ; φ = 50 %). The ingestion schedule foresees the rehydration after about 1100 min of simulation time.
Figure 12 shows the discrepancy between the demanded amounts of water for evaporative cooling (blue upper line) and the available water controlled by the sweat ratio controller (green lower oscillating line). In Figure 13 the response of the thermal dummy system is shown. The heat produced in the metabolism cannot be discarded of and thus accumulates in the body tissues with the effect that the body core temperature rises. As soon as the water & salt model is rehydrated i.e. enough water is available to provide evaporative cooling the body core temperature remains on a constant level. The thermal dummy model does not allow the return of body core temperature to nominal values. This functionality is implemented in the overall V-HAB human thermal model.

5.2. Case Studies

A most peculiar case is the total lack of water, which is of special interest for worst case scenarios of ECLSS. It needs to be stated that there is no such thing as to die of thirst, but the influence of water shortage on other human body sub-systems can cause severe harm and even death. In the following two cases, the reaction of the Human Water Balance Model to a constant lack of water under standard and under hot and humid environmental conditions will be discussed.
In the first simulation scenario, the standard human is placed in a moderate environment (T_{env} = 20°C ; p_{env} = 101333 Nm^{-2} ; φ = 0 %) and the simulation time is set to 2880 min (two days). The water ingestion is denied entirely and an overall activity level of 10 percent is assumed.
The total body water deficit is depicted in Figure 14. Most of the lost water is drawn from the intracellular department which depletes almost by the same amount of H_2O lost in total body water. The effects caused by water shortage which will impact the overall performance of the dynamic human model are included in Figure 15. According to [22] a loss of 3 % of total body water will lead to a dry mouth. In the following, after a water loss of 5 % headache, difficulty in concentrating, impatience and sleepiness will occur. Finally, if 7 % of total body water is lost, a collapse is possible.

Within the second scenario discussing water denial, the standard human is placed in a hot and humid environment (T_{env} = 40°C ; p_{env} = 101333 Nm^{-2} ; φ = 50 %). The simulation denies the ingestion of water.
Since the environmental temperature is higher than body core temperature, evaporative cooling is the only mechanism left to discard heat. But due to the high relative air moisture even this mechanism is less effective. According to the restricting factor of total body water loss for the secretion of sweat, discussed in section 4.3.3., the sweat rate is restricted. Thus the potential of evaporative cooling is diminished. In this way not all of the heat, produced by the metabolism, can be disposed of and hence accumulates in the body tissues. The result is an increase of body temperature which is shown in Figure 16. According to [25] this state is called hyperthermia and causes heat stroke as soon as the temperature rises above 40 °C. In the course of proceeding hyperthermia, brain death begins as soon as body temperatures exceed 41 °C. If a body temperature of 45 °C is reached death is almost certain.

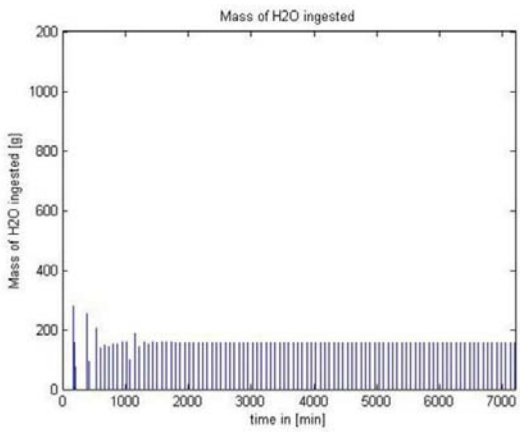

Figure 8. Water ingested according to the drink on demand mechanism if water and Na^+ are abundant.

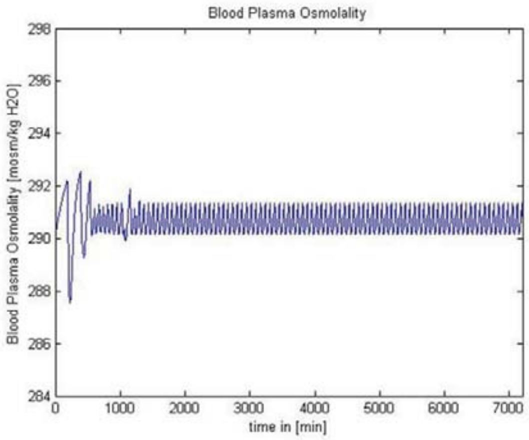

Figure 9. Behavior of blood plasma osmolality if water and Na^+ are available at all times in abundant quantities.

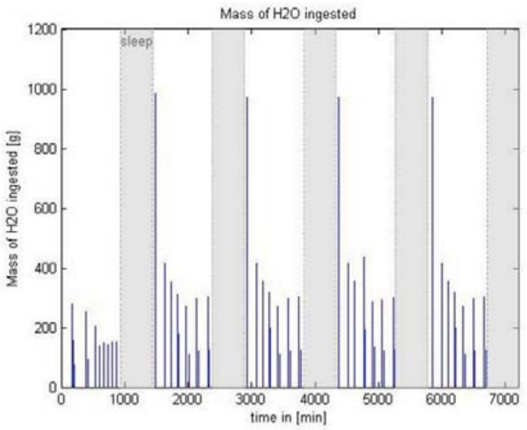

Figure 10. Water ingested according to the drink on demand mechanism if the ingestion of water and Na^+ are denied during a night-phase of 8 hours

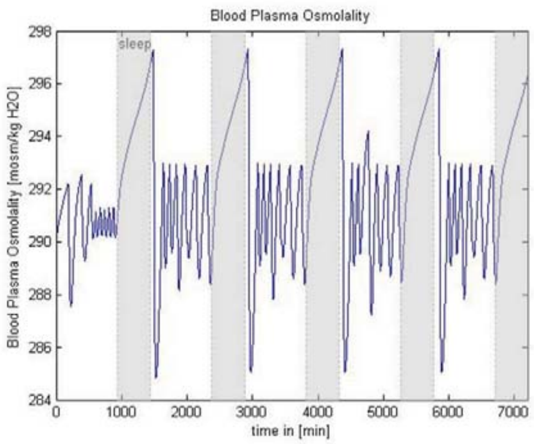

Figure 11. Behavior of blood plasma osmolality if the ingestion of water and Na^+ are denied during a night-phase of 8 hours.

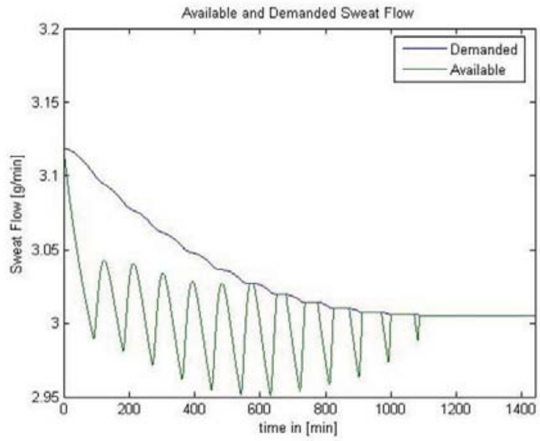

Figure 12. Regulative behavior of the sweat ratio controller during rehydration in a hot and humid environment.

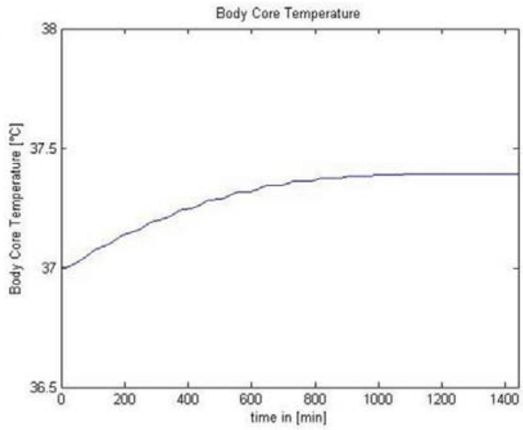

Figure 13. Increase in body core temperature due to restricted water availability for evaporative cooling.

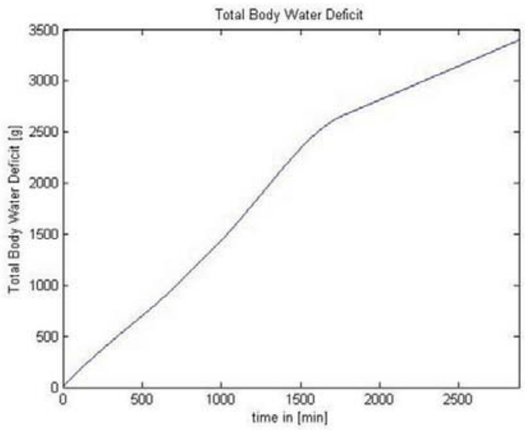

Figure 14. Accumulated total body water deficit for a standard human in a moderate environment for a complete water and Na^+ denial.

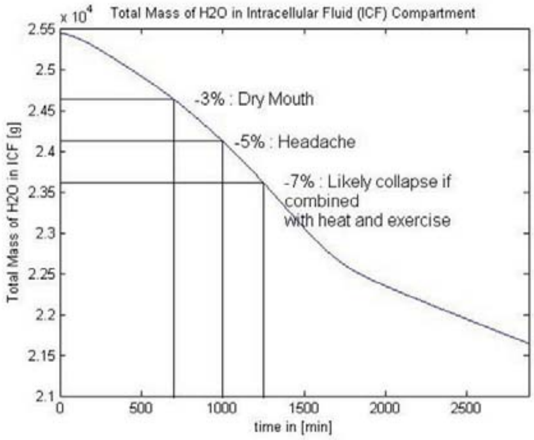

Figure 15. Indication of the reaction of the entire human model facing water shortage, based on the findings of [22].

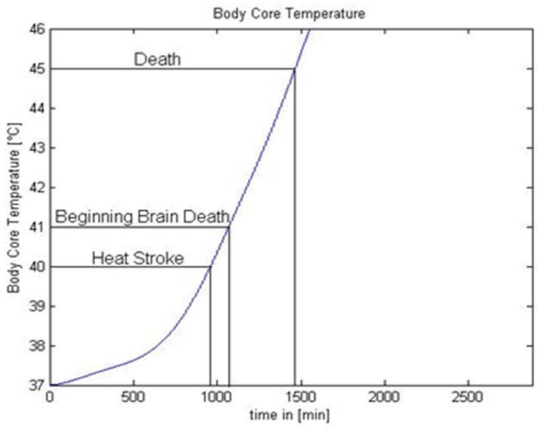

Figure 16. Response of the thermal dummy to water denial in a hot and humid environment, based on [25].

6. DISCUSSION

Based on a broad and complex physiological and biochemical background the most important mechanisms, related to the human water and salt balance, were implemented into the water & salt balance model.

The model is able to reproduce the movement of water and electrolytes between different body compartments via passive (osmosis, diffusion and solvent drag) and active transport mechanisms. The traced electrolytes are Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, HPO_4^{2-}, whereas Na^+ has an outstanding role. Containers for further agents in solution in the body fluids are designated (e.g. for proteins).

In this way the osmolality of the body fluids is known in every time-step of the simulation. The osmolality, as an important trigger and indicator within the human body, is controlled by a kidney model around a basal value of 290 mosm/kg_{H2O}. The kidney regulates the excretion of NA^+ and water via a sophisticated and complex endocrine system. Furthermore the human water & salt balance model governs parameters important for other human sub-systems, such as the thermoregulation and the cardiovascular system. Hence control strategies for the sweat secretion and total peripheral resistance are implemented.

Several functionalities need a further refinement and additional discussion or have to be implemented in the future. The distribution of water in the human body is not accounted for in the present model, thus pressure induced changes are not represented. Moreover most longtime effects are neglected so far (e.g. the ability of the human body to adapt to a hot and humid environment by regulating the amount of Na^+ excreted with sweat). Furthermore urea, as the final product of protein incineration and as a potentially hazardous agent in the human body, is not implemented yet. The excretion of K^+ together with urine is neglected, thus the coupling of Na^+ and K^+, important for osteoporoses (e.g. in a space environment) cannot be traced so far. Other issues such as the availability and the purity of water, as well as the schedule settings and stress factors (e.g. in case of water or micturition denial) are not accounted for, yet.

Alongside the ongoing development of the V-HAB Simulation a metric called Model Confidence Level (MCL) was developed at the Institute of Astronautics of the Technische Universität München in order to evaluate the fidelity of the created models. This metric, adopted from the Technology Readiness level (TRL) used in astronautics, classifies the model confidence in a scale of 10 levels. These levels are clustered in three main branches which are static, dynamic and correlated [26]. The presented water and salt balance model would be a level 5 model in this MCL metric, i.e. a “model with time dependent in- and outputs and true responses to environmental conditions” [26].

Altogether, the water and salt balance was lifted onto a dynamic level that not only provides information about the intrinsic status and storage of water and Na^+ within, as well as the fluxes in and out of the human body, but also its feedback to other sub-systems of the V-HAB human model and therewith to its environment. Moreover with its restricting effects to other sub-systems it is able to predict overall behavior of the dynamic human model such as thirst, headache, collapse and heat stroke. In this way the water and salt balance model can be used to assist the optimization and verification of environmental control and life support systems for human space flight.

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8. ABBREVIATIONS

ADH	Antidiuretic hormone
ALD	Aldosteron
AngII	Angiotensin II
BP	Blood plasma
BWL	Body water loss
ECLSS	Environmental control live support

	system
ESM	Equivalent system mass
ICF	Intracellular fluid
INT	Interstitial fluid
MCL	Model confidence level
TRL	Technology Readiness Level
V-HAB	Virtual habitat
c_{ADH}	Concentration of ADH
Fl_{sw}	Actual sweat flow
$Fl_{sw,dem}$	Demanded sweat flow
p_{env}	Environmental pressure
$R_{per,act}$	Actual peripheral resistance
$R_{per,0}$	Basal peripheral resistance
T_{env}	Environmental temperature
φ	Relative air moisture

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