THERMODYNAMIC PROPERTIES OF HUMAN TISSUES

by

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This paper reports empirical formulas, enthalpies of formation, molar entropies, Gibbs energies of formation, and molar heat capacities at 25 °C and 37 °C for human soft tissues. The results show that Gibbs energy, except for certain tissues (adipose), is relatively low compared with the constituent elements, the average value being –17.57 kJ/C-mol. The average constant pressure heat capacity of hydrated human body soft tissues is 3.24 J/gK in agreement with other data in the literature.

Key words: *entropy, enthalpy of formation, Gibbs energy of formation, heat capacity, human soft tissue*

Introduction

Biophysical research on living organisms has become a very important field in life sciences, bringing benefits to medicine, pharmacy, biology and other disciplines. All these fields benefit from quantitative analyses and predictions that can be made by applying mathematical frameworks to life phenomena. To this end, this paper reports elemental compositions, empirical formulas, enthalpies of formation, molar entropies, Gibbs energies of formation and molar heat capacities at 25 °C and 37 °C for human soft tissues.

Elemental composition of organisms can be reported as hydrated or dry matter. Elemental composition of hydrated matter is usually reported in the form of mass fractions of each element constituting the organism. Dry matter includes all substances present in an organism except water. Organism dry matter is important since it is the product of organism growth and contains the biological structures. Composition is usually expressed as empirical formulas or unit carbon formulas (UCF), *i. e.* C-mole formulas [1]. A UCF represents elemental composition of an organism as a single pseudo-compound, normalized per mole of carbon. UCF are available in the literature for some microorganisms, but none have been reported for human tissues. A literature review [2] found elemental composition data for 32 microorganism species, including 14 bacteria, 7 yeast, and 11 algae species [3-23]. However, the large majority reported only C, H, N and O content.

Thermodynamic properties of organisms that are of particular interest include heat capacity, enthalpy, entropy and Gibbs energy. These properties are of use in life sciences and bioengineering. Thermodynamics is used in microbiology for analysis of microorganism activities and communities [24-29]. Furthermore, activities of both unicellular and multicellular organisms are both biological and thermodynamic phenomena. Thus, knowledge of thermodynamic parameters is useful in the field of life sciences.

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The properties published in this paper can contribute to better understanding of processes and reactions in the human organism. Moreover, diseases represent change in state of the organism, which are characterized by change in state parameters. For example, Gibbs energy indicates spontaneity of processes. Thus, thermodynamic properties are important for description of life processes and development of formalisms to describe them [3, 30-36].

Methods

This section first reviews human body and tissue elemental composition and heat capacity data available in the literature. Next, a correction is made for tissue water content since water is not part of the structures that are the subject of this analysis. The corrected composition data is then used to find thermodynamic properties of tissue dry matter at 25 ºC. Thermodynamic properties of tissue dry matter are also determined at 37 ºC.

Elemental composition and heat capacity of hydrated tissues

Elemental composition of the soft tissues of the human body from the literature is given in tab. 1. The data in tab. 1 is presented as mass fractions in hydrated tissues. Composition data for skeleton and cartilage tissues are not included, since the methods discussed here do not apply. Entire body soft tissue average elemental composition has been reported by Snyder *et al.* (Ref. [37], page 290) and Wang *et al.* (Ref. [38], page 128). The data by Wang *et al.* [38] was collected on 16 healthy males 35 ± 13 years of age. Total body contents of six elements (C, K, Ca, P, Cl, and Na) were determined experimentally, along with total body water content and N/H ratio (Ref. [38], page 125). The content of remaining elements (H, N, O, S) were calculated from these data using well-known stoichiometric relationships (Ref. [38], page 126). Snyder *et al.* (Ref. [37], page 3) defined a *reference man* and decided it was neither feasible nor necessary to specify a well-defined population group. Out of necessity, the data were taken from a wide variety of sources, and the individuals sampled to obtain these data lived in many different countries or geographical areas at many different times (Ref. [37], page 3). However, for practical purposes, the reference man is defined as *being between 20-30 years of age, weighing 70 kg, is 170 cm in height, and lives in a climate with an average temperature of from 10 °C to 20 °C* (Ref. [37], page 4).

Elemental compositions of various human tissues have been reported by Woodard and White [39] and by Snyder *et al.* (Ref. [37], page 290). The work of Woodard and White [39] is a revision of the data presented by Snyder *et al.* [37]. However, while Woodard and White [39] present more precise values for the most abundant elements in the body, Snyder *et al.* [37] give tissue contents of almost all elements of the periodic table. Since thermodynamic properties are influenced the most by high abundance elements (C, H, N, O, P and S), the more precise values given by Woodard and White [39] were chosen for the analysis here. The data by Woodard and White [39] have been collected from many references and apply to *healthy, adult humans*. Whenever the available data for a body tissue permitted the range of compositions to be calculated, the resulting three compositions are presented as No. 1, 2, 3, referring to values derived from $M - \sigma$, M and $M + \sigma$, respectively, where M is the average and σ the standard deviation [39]. Entire human body soft tissue average elemental composition and elemental compositions of various tissues were reported for matter containing water. However, the biological structures of interest to this study are those present in dry cells and tissues [5]. Thus, a correction was made to subtract H and O to correct for the water content using data on water content from (Ref. [37], page 280; Ref. [38], page 128; Ref. [39], page 1213).

Entire human body soft tissue average heat capacity and heat capacities of analyzed tissues are presented in tab. 2. Where available, the experimental data were taken from the ITIS

Table 1. Element mass fractions and water content of human body soft tissues; average human body compositions 1 and 2 were taken from [38] and [37], respectively, while tissue compositions were taken from [39].

Name	C	H	O	N	P	S	Na	K	Mg	Ca	Fe	Cl	I	w_{water}
Human body 1 (average, from [38])	0.210	0.102	0.637	0.027	0.007	0.002	0.001	0.002	0.000	0.012	0.000	0.001	0	0.635
Human body 2 (average, from [37])	0.229	0.100	0.614	0.026	0.011	0.002	0.001	0.002	2.71E–04	0.014	0.000	0.001	1.86E–07	0.600
Adipose tissue 1	0.517	0.112	0.355	0.013	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.305
Adipose tissue 2	0.598	0.114	0.278	0.007	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.212
Adipose tissue 3	0.681	0.116	0.198	0.002	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.114
Adrenal gland	0.284	0.106	0.578	0.026	0.001	0.002	0.000	0.001	0.000	0.000	0.000	0.002	0.000	0.581
Aorta	0.147	0.099	0.698	0.042	0.004	0.003	0.002	0.001	0.000	0.004	0.000	0.000	0.000	0.721
Blood-erythrocytes	0.190	0.095	0.646	0.059	0.001	0.003	0.000	0.003	0.000	0.000	0.001	0.002	0.000	0.640
Blood-plasma	0.041	0.108	0.832	0.011	0.000	0.001	0.003	0.000	0.000	0.000	0.000	0.004	0.000	0.919
Blood-whole	0.110	0.102	0.745	0.033	0.001	0.002	0.001	0.002	0.000	0.000	0.001	0.003	0.000	0.790
Brain-grey matter	0.095	0.107	0.767	0.018	0.003	0.002	0.002	0.003	0.000	0.000	0.000	0.003	0.000	0.826
Brain-white matter	0.194	0.106	0.661	0.025	0.004	0.002	0.002	0.003	0.000	0.000	0.000	0.003	0.000	0.685
Connective tissue	0.207	0.094	0.622	0.062	0.000	0.006	0.006	0.000	0.000	0.000	0.000	0.003	0.000	0.604
Eye lens	0.195	0.096	0.646	0.057	0.001	0.003	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.641
Gallblader - wall	0.142	0.102	0.712	0.033	0.002	0.003	0.001	0.004	0.000	0.000	0.000	0.001	0.000	0.742
Gastrointestinal tract - oesophagus	0.142	0.102	0.712	0.033	0.002	0.003	0.001	0.004	0.000	0.000	0.000	0.001	0.000	0.742
Gastrointestinal tract - small intestine (wall)	0.115	0.106	0.751	0.022	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.002	0.000	0.806
Gastrointestinal tract - stomach	0.139	0.104	0.721	0.029	0.001	0.002	0.001	0.002	0.000	0.000	0.000	0.001	0.000	0.763
Heart 1	0.175	0.103	0.681	0.031	0.002	0.002	0.001	0.003	0.000	0.000	0.000	0.002	0.000	0.710
Heart 2	0.139	0.104	0.718	0.029	0.002	0.002	0.001	0.003	0.000	0.000	0.000	0.002	0.000	0.759
Heart 3	0.103	0.104	0.756	0.027	0.002	0.002	0.001	0.003	0.000	0.000	0.000	0.002	0.000	0.809

→

Table 1. (Continuation)

Name	C	H	O	N	P	S	Na	K	Mg	Ca	Fe	Cl	I	w_{water}
Kidney 1	0.160	0.102	0.693	0.034	0.002	0.002	0.002	0.002	0.000	0.001	0.000	0.002	0.000	0.723
Kidney 2	0.132	0.103	0.724	0.030	0.002	0.002	0.002	0.002	0.000	0.001	0.000	0.002	0.000	0.766
Kidney 3	0.106	0.104	0.752	0.027	0.002	0.002	0.002	0.002	0.000	0.001	0.000	0.002	0.000	0.805
Liver 1	0.156	0.103	0.701	0.027	0.003	0.003	0.002	0.003	0.000	0.000	0.000	0.002	0.000	0.728
Liver 2	0.139	0.102	0.716	0.030	0.003	0.003	0.002	0.003	0.000	0.000	0.000	0.002	0.000	0.745
Liver 3	0.126	0.101	0.727	0.033	0.003	0.003	0.002	0.003	0.000	0.000	0.000	0.002	0.000	0.756
Lung - parenchyma	0.101	0.103	0.755	0.029	0.002	0.003	0.002	0.002	0.000	0.000	0.000	0.003	0.000	0.806
Mammary gland 1	0.506	0.109	0.358	0.023	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.302
Mammary gland 2	0.332	0.106	0.527	0.030	0.001	0.002	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.514
Mammary gland 3	0.158	0.102	0.698	0.037	0.001	0.002	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.726
Muscle - skeletal 1	0.171	0.101	0.681	0.036	0.002	0.003	0.001	0.004	0.000	0.000	0.000	0.001	0.000	0.700
Muscle - skeletal 2	0.143	0.102	0.710	0.034	0.002	0.003	0.001	0.004	0.000	0.000	0.000	0.001	0.000	0.741
Muscle - skeletal 3	0.112	0.102	0.745	0.030	0.002	0.003	0.001	0.004	0.000	0.000	0.000	0.001	0.000	0.786
Ovary	0.093	0.105	0.768	0.024	0.002	0.002	0.002	0.002	0.000	0.000	0.000	0.002	0.000	0.828
Pancreas	0.169	0.106	0.694	0.022	0.002	0.001	0.002	0.002	0.000	0.000	0.000	0.002	0.000	0.733
Prostate	0.089	0.105	0.774	0.025	0.001	0.002	0.002	0.002	0.000	0.000	0.000	0.000	0.000	0.833
Skeleton - red marrow	0.414	0.105	0.439	0.034	0.001	0.002	0.000	0.002	0.000	0.000	0.001	0.002	0.000	0.397
Skeleton - yellow marrow	0.644	0.115	0.231	0.007	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.153
Skin 1	0.250	0.100	0.594	0.046	0.001	0.003	0.002	0.001	0.000	0.000	0.000	0.003	0.000	0.586
Skin 2	0.204	0.100	0.645	0.042	0.001	0.002	0.002	0.001	0.000	0.000	0.000	0.003	0.000	0.653
Skin 3	0.158	0.101	0.695	0.037	0.001	0.002	0.002	0.001	0.000	0.000	0.000	0.003	0.000	0.721
Spleen	0.113	0.103	0.741	0.032	0.003	0.002	0.001	0.003	0.000	0.000	0.000	0.002	0.000	0.787
Testis	0.099	0.106	0.766	0.020	0.001	0.002	0.002	0.002	0.000	0.000	0.000	0.002	0.000	0.827
Thyroid	0.119	0.104	0.745	0.024	0.001	0.001	0.002	0.001	0.000	0.000	0.000	0.002	0.001	0.784
Urinary bladder - wall	0.142	0.102	0.712	0.033	0.002	0.003	0.001	0.004	0.000	0.000	0.000	0.001	0.000	0.742

Table 2. Standard specific heat capacities of hydrated human soft tissues, where more than one reference was available, an average value is given; for tissues that have Equation (1) as reference, there was no experimental data and the heat capacity was calculated using eq. (1)

Name	C_p^0(bio,wet) [$Jg^{-1}K^{-1}$]	Reference
Human body (average)	3.5	[45]
Human body (average, from [38])	3.26	Equation 1
Human body (average, from [37])	3.18	Equation 1
Adipose tissue	2.35	[47-50]
Adrenal gland	3.51	[47]
Aorta	3.48	Equation 1
Blood-erythrocytes	3.28	Equation 1
Blood-plasma	3.93	[41]
Blood-whole	3.62	[47, 51]
Brain-grey matter	3.70	[41, 47, 51]
Brain-white matter	3.58	[41, 47, 51]
Connective tissue	3.43	As Tendon/Ligament from [47, 49]
Eye lens	3.13	[47, 50, 51]
Gallblader - wall	3.72	[47]
Gastrointestinal tract - oesophagus	3.42	[47, 48, 50]
Gastrointestinal tract - small intestine (wall)	3.60	[47]
Gastrointestinal tract - stomach	3.69	[47]
Heart	3.69	[41, 47]
Kidney	3.76	[41, 47]
Liver	3.54	[41, 47]
Lung - parenchyma	3.89	[47]
Mammary gland 1	2.43	Equation 1
Mammary gland 2	2.96	Equation 1
Mammary gland 3	3.49	Equation 1
Muscle - skeletal	3.42	[47, 48, 50]
Ovary	3.78	As testis from [47]
Pancreas	3.16	[47]
Prostate	3.76	[52]
Skeleton - red marrow	2.67	[47]
Skeleton - yellow marrow	2.07	[47]
Skin	3.39	[47, 49-51]
Spleen	3.60	[47]
Testis	3.78	[47]
Thyroid	3.61	[47]
Urinary bladder - wall	3.58	[47, 48, 51]

Foundation [40] database, which presents well-referenced data on various tissue properties. Heat capacities of tissues for which experimental values were not available were calculated with an equation given by Duck (Ref. [41], page 31) that describes the specific (per gram) heat capacity of hydrated human tissues, $C^0_{p,g}$(bio,wet), as a function of water content, w_{water}:

$$C^0_{p,g}\left(\text{bio, wet}\right) = 1.670\frac{\text{J}}{\text{gK}} + 2.510\frac{\text{J}}{\text{gK}}\cdot w_{\text{water}} \tag{1}$$

These values were also corrected to dry matter heat capacities.

Elemental composition and heat capacity of tissue dry matter

Elemental composition of tissue dry matter is presented as empirical formulas, *i. e.*, UCF or C-mole formulas [1]. Thus, a correction for water was first made, then mole fractions of elements were determined, and finally converted into UCF for the analyzed tissues.

The stoichiometric correction for H and O coming from water was done using the water content data in tab. 1. Mass fractions of all elements, except H and O, were then determined by renormalizing to tissue mass without water:

$$w_J = \frac{w_{J,\mathrm{wet}}}{1 - w_{\mathrm{water}}} \tag{2}$$

where w_J is the mass fraction of element J in tissue dry matter, $w_{J,\mathrm{wet}}$ – the mass fraction of element J in hydrated tissue, and w_{water} – the tissue water content. Since water contains H and O, their amounts present as water were subtracted before renormalizing:

$$w_H = \frac{w_{H,\mathrm{wet}} - \frac{2}{18} w_{\mathrm{water}}}{1 - w_{\mathrm{water}}} \tag{3}$$

$$w_O = \frac{w_{O,\mathrm{wet}} - \frac{16}{18} w_{\mathrm{water}}}{1 - w_{\mathrm{water}}} \tag{4}$$

The obtained element mass fractions in cell dry matter were then converted into mole fractions:

$$x_J = \frac{\frac{w_J}{M_{r,J}}}{\sum_i \frac{w_i}{M_{r,i}}} \tag{5}$$

where x_J is the mole fraction of element J in dry matter and $M_{r,J}$ is the atomic weight of element J. The summation is over all elements present. Finally, from the mole fraction data, UCF were obtained by dividing the mole fraction of each element with that of carbon, x_C:

$$n_J = \frac{x_J}{x_C} \tag{6}$$

where n_J is the number of atoms of element J in the UCF.

Thermodynamic properties of dry matter at 25 °C

Elemental composition of dry matter can be used to determine the enthalpy of formation, the entropy and Gibbs energy of formation.

The enthalpy of dry matter is determined from the elemental composition in two steps: the enthalpy of combustion is calculated with a predictive model and the enthalpy of combustion is converted into enthalpy of formation using Hess' law. The enthalpy of combustion of an organic substance is proportional to the number of electrons, E, transferred to oxygen during the combustion process for complete oxidation:

$$E = 4n_C + n_H - 2n_O - 0n_N + 5n_P + 4n_S \tag{7}$$

where n_C, n_H, n_O, n_N, n_P, and n_S are the number of C, H, O, N, P and S atoms in the empirical formula. The E is related to the enthalpy of combustion, $\Delta_C H^o$(bio), by the Patel-Erickson equation [34, 42]:

$$\Delta_C H^0(\text{bio}) = -111.14 \frac{\text{kJ}}{\text{mol}} E \tag{8}$$

The Patel-Erickson equation is an empirical correlation based on a large dataset of organic substances, the accuracy of which is discussed in section *Uncertainties*. Once $\Delta_C H^o$(bio) is known, the enthalpy of formation is calculated with Hess' law for the oxidation reaction:

$$\begin{gathered} C_{nC}H_{nH}O_{nO}N_{nN}P_{nP}S_{nS}Na_{nNa}K_{nK}Mg_{nMg}Ca_{nCa}Fe_{nFe}Cl_{nCl}I_{nI\,(s)} + (n_C + \tfrac{1}{4}n_H + 1\tfrac{1}{4}n_P + \\ + 1\tfrac{1}{2}n_S + \tfrac{1}{4}n_{Na} + \tfrac{1}{4}n_K + \tfrac{1}{2}n_{Mg} + \tfrac{1}{2}n_{Ca} + \tfrac{3}{4}n_{Fe} - \tfrac{1}{2}n_O - \tfrac{1}{4}n_{Cl})O_{2(g)} \rightarrow n_C\,CO_{2(g)} + \\ + \tfrac{1}{2}n_H H_2O_{(l)} + \tfrac{1}{2}n_N N_{2(g)} + \tfrac{1}{4}n_P P_4O_{10(s)} + n_S SO_{3(g)} + \tfrac{1}{2}n_K K_2O_{(s)} + n_{Mg}MgO_{(s)} + \\ + n_{Ca}CaO_{(s)} + \tfrac{1}{2}n_{Fe}Fe_2O_{3(s)} + n_{Cl}HCl_{(aq)} + \tfrac{1}{2}n_I I_{2(s)} \end{gathered} \tag{9}$$

The enthalpy of formation from the elements at 25 °C, $\Delta_f H^o$(bio), is:

$$\begin{gathered} \Delta_f H^0(\text{bio}) = n_C \Delta_f H^0(\text{CO}_2) + \frac{1}{2} n_H \Delta_f H^0(\text{H}_2\text{O}) + \frac{1}{4} n_P \Delta_f H^0(P_4 O_{10}) + \\ + n_S \Delta_f H^0(\text{SO}_3) + \frac{1}{2} n_{Na} \Delta_f H^0(\text{Na}_2\text{O}) + \frac{1}{2} n_K \Delta_f H^0(\text{K}_2\text{O}) + \\ + n_{Mg} \Delta_f H^0(\text{MgO}) + n_{Ca} \Delta_f H^0(\text{CaO}) + n_{Cl} \Delta_f H^0(\text{HCl}) - \Delta_C H^0(\text{bio}) \end{gathered} \tag{10}$$

where $\Delta_f H^o(X)$ is enthalpy of formation of substance X.

The entropy of dry matter at 25 °C, S_m^o(bio), is related to the composition by the Battley equation [5]:

$$S_m^o(\text{bio}) = 0.187 \sum_J \frac{S_m^o(J)}{a_J} n_J \tag{11}$$

where n_J is the number of atoms of element J in the empirical formula of the biomass, $S_m^o(J)$ – the molar entropy of element J, and a_J – the number of atoms per molecule of element J in its standard state elemental form. For example, the standard state elemental form of carbon is graphite, which is simply written as C, which makes $a_C = 1$. On the other hand, hydrogen, oxygen and nitrogen are all diatomic gases, H_2, O_2 and N_2, respectively, in their standard state elemental form which implies that $a_H = a_O = a_N = 2$. The summation is over all elements constituting the matter. The Battley equation simply states that molar entropy of biomass equals a constant 0.187 times the standard molar entropy of its constituent elements, the sum term. After the contributions of all elements are summed, they are multiplied by the constant 0.187, which takes into account the fact that the elements are no longer in their standard state pure forms, but are a part of the biomass. The Battley equation is a consequence of additivity of entropy; entropy of biomass is a sum of contributions of all its constituent elements.

The Battley equation can also be used to find molar entropies of formation of organic matter at 25 °C, $\Delta_f S^o$(bio), which is given by the equation [5]:

$$\Delta_f S^0(\text{bio}) = -0.813 \sum_J \frac{S_m^o(J)}{a_J} n_J \tag{12}$$

Since $\Delta_f S^o$(bio) is by definition the entropy of reaction (15), $\Delta_f S^o$(bio) is the difference between S^o_m(bio), given by eq. (11), and the sum of entropies of the elements $\Sigma_J[S^o_m(J)/a_J]n_J$, which is equal to the sum term in eq. (11) [5]. Thus, $\Delta_f S^o(\mathrm{bio}) = 0.187\ \Sigma_J[S^o_m(J)/a_J]n_J - \Sigma_J[S^o_m(J)/a_J]n_J$. resulting in eq. (12).

The Gibbs energy of organic matter formation from elements at 25 °C, $\Delta_f G^o$(bio), is calculated by combining the enthalpy and entropy according to the Gibbs equation:

$$\Delta_f G^0(\mathrm{bio}) = \Delta_f H^0(\mathrm{bio}) - 298.15\,\mathrm{K}\cdot\Delta_f S^0(\mathrm{bio}) \tag{13}$$

Thermodynamic properties of dry matter at physiological temperature

Thermodynamic properties $\Delta_f H^o$(bio), S^o_m(bio), and $\Delta_f G^o$(bio) at 25 °C were corrected to 37 °C or 310.15 K as follows. Molar enthalpy of formation of tissue dry matter from elements at 37 °C, $\Delta_f H^{37C}$(bio), is [43]:

$$\Delta_f H^{37C}(\mathrm{bio}) = \Delta_f H^0(\mathrm{bio}) + \Delta_f C_p^0(\mathrm{bio})\cdot(310.16\ \mathrm{K} - 298.15\ \mathrm{K}) \tag{14}$$

where $\Delta_f C_P^o$(bio) is the heat capacity of formation of organic matter from the elements:

$$n_c\mathrm{C} + \tfrac{1}{2}n_\mathrm{H}\mathrm{H_2} + \tfrac{1}{2}n_\mathrm{O}\mathrm{O_2} + \tfrac{1}{2}n_\mathrm{N}\mathrm{N_2} + n_\mathrm{P}\mathrm{P} + n_\mathrm{S}\mathrm{S} + n_\mathrm{Na}\mathrm{Na} + n_\mathrm{K}\mathrm{K} + n_\mathrm{Mg}\mathrm{Mg} + n_\mathrm{Ca}\mathrm{Ca} + n_\mathrm{Fe}\mathrm{Fe} + \tfrac{1}{2}n_\mathrm{Cl}\mathrm{Cl} + \tfrac{1}{2}n_\mathrm{I}\mathrm{I_2} \rightarrow \mathrm{C_{nC}H_{nH}O_{nO}N_{nN}P_{nP}S_{nS}Na_{nNa}K_{nK}Mg_{nMg}Ca_{nCa}Fe_{nFe}Cl_{nCl}I_{nI}} \tag{15}$$

$$\begin{aligned}\Delta_f C^0_{p,m}(\mathrm{bio}) &= C^0_{p,m}(\mathrm{bio}) - C^0_{p,m}(\mathrm{C}) - \frac{1}{2}n_\mathrm{H}C^0_{p,m}(\mathrm{H_2}) - \frac{1}{2}n_\mathrm{O}C^0_{p,m}(\mathrm{O_2}) - \frac{1}{2}n_\mathrm{N}C^0_{p,m}(\mathrm{N_2}) - \\ &- n_\mathrm{P}C^0_{p,m}(P) - n_\mathrm{S}C^0_{p,m}(\mathrm{S}) - n_\mathrm{K}C^0_{p,m}(\mathrm{K}) - n_\mathrm{Na}C^0_{p,m}(\mathrm{Na}) - n_\mathrm{Mg}C^0_{p,m}(\mathrm{Mg}) - n_\mathrm{Ca}C^0_{p,m}(\mathrm{Ca}) - \\ &- n_\mathrm{Fe}C^0_{p,m}(\mathrm{Fe}) - \frac{1}{2}n_\mathrm{Cl}C^0_{p,m}(\mathrm{Cl_2}) - \frac{1}{2}n_\mathrm{I}C^0_{p,m}(\mathrm{I_2})\end{aligned} \tag{16}$$

The entropy at 37 °C, S^{37C}_m(bio), is [43]:

$$S_m^{37C}(\mathrm{bio}) = S_m^o(\mathrm{bio}) + C^0_{p,m}(\mathrm{bio})\cdot\ln\frac{310.15\mathrm{K}}{298.15\mathrm{K}} \tag{17}$$

The $C^o_{P,m}$(bio) is the heat capacity at constant pressure and the entropy of formation at 37 °C, $\Delta_f S^{37C}$(bio), is [43]:

$$\Delta_f S^{37C}(\mathrm{bio}) = \Delta_f S^0(\mathrm{bio}) + \Delta_f C_p^0(\mathrm{bio})\cdot\ln\frac{310.15\mathrm{K}}{298.15\mathrm{K}} \tag{18}$$

The Gibbs energy of formation from the elements at 37 °C, $\Delta_f G^{37C}$(bio) is calculated by combining $\Delta_f H^{37C}$(bio) and $\Delta_f S^{37C}$(bio) according to the Gibbs equation:

$$\Delta_f G^{37C}(\mathrm{bio}) = \Delta_f H^{37C}(\mathrm{bio}) - 310.15\,\mathrm{K}\cdot\Delta_f S^{37C}(\mathrm{bio}) \tag{19}$$

Uncertainties

Uncertainty in the enthalpy of combustion of organic matter estimated with Patel-Erickson equation is 5.36% [2]. The $\Delta_f H^o$(bio) is calculated using $\Delta_C H^o$(bio) and $\Delta_f H^o$ values of the oxides which have been accurately determined by experiment (more details in Ref. [44]) and have a negligible error compared to the uncertainty in $\Delta_C H^o$(bio). The Battley equation used to predict the entropies has been shown to be applicable to dry microorganism biomass, proteins, amino acids, nucleotides and fatty acids [5] with an uncertainty of 2% [5]. In case of hydrated biomass, the uncertainty in the entropy of hydration increases the uncertainty to 19.7% [5].

Therefore, the uncertainties, $\delta(X)$, in thermodynamic properties presented in tabs. 4 and 5 were estimated with the equations [2]:

$$\delta(\Delta_f H) = 0.0536 \cdot \Delta_C H \tag{20}$$

$$\delta(S) = 0.197 \cdot S \tag{21}$$

$$\delta(\Delta_f G) = \delta(\Delta_f H) + T \cdot \delta(S) \tag{22}$$

where T is temperature.

Results and discussion

Empirical formulas of the analyzed human tissues are given in tab. 3, thermodynamic properties at 25 ºC are given in tab. 4, and thermodynamic properties at 37 ºC are in tab. 5. Each property, X, in tabs. 4 and 5 is given per mole of carbon, X_m, and per gram, X_g, of tissue dry mass. The conversion between the two conventions is made through the equation $X_g = X_m/M_r$, where M_r is the UCF molar mass.

Gibbs energies of formation at 37 ºC are negative for the entire body soft tissue average and the majority of other constituent tissues. The average is –17.57 kJ/C-mol, and the minimum and maximum values are 4.27 and –33.42 kJ/C-mol for adipose tissue and liver, respectively. The fat content of adipose tissue, 74.1%, accounts for the positive Gibbs energy. The relatively low lipid content, 4.6%, accounts for the highly negative Gibbs energy of liver tissue. Enthalpies of formation at 37 ºC are negative for all tissues with an average of –57.20 kJ/C-mol, and maximum and minimum values are –75.77 and –29.79 kJ/C-mol for liver and adipose tissue, respectively. Standard heat capacities are positive for all tissues, the average being 35.85 J/C-molK, while maximum and minimum values are 60.99 J/C-molK and 8.07 J/C-molK for lung – parenchyma and pancreas, respectively.

The reported average human body heat capacity is 3.5 J/gK (Ref. [45], page 16), for hydrated soft tissues. This heat capacity is approximately the sum of the heat capacities of the two components:

$$C_{p,g}^0\left(\text{bio,wet}\right) = w_{\text{dry}} C_{p,g}^0\left(\text{bio}\right) + w_{\text{water}} C_{p,g}^0\left(\text{H}_2\text{O}\right) \tag{23}$$

where $C^0_{p,g}(\text{bio,wet})$, $C^0_{p,g}(\text{bio})$ and $C^0_{p,g}(H_2O)$ are specific heat capacities of hydrated body matter, body dry matter and water respectively [2]. Dry matter mass fraction, w_{dry}, is related to water content, w_{water}, by the equation: $w_{\text{dry}} + w_{\text{water}} = 1$. Thus, the heat capacity of body dry matter is:

$$C_{p,g}^0\left(\text{bio}\right) = \frac{C_{p,g}^0\left(\text{bio,wet}\right) - w_{\text{water}} C_{p,g}^0\left(\text{H}_2\text{O}\right)}{w_{\text{dry}}} \tag{24}$$

Substituting the $C^0_{p,g}(\text{bio,wet}) = 3.5$ J/gK value from [45] and using the water content of 63.53% reported by Wang *et al.* (Ref. [38], page 128), yields a dry matter heat capacity of 2.30 J/gK. On the other hand, using eq. (24) with entire body water contents reported by Wang *et al.* (Ref. [38], page 128) and Snyder *et al.* (Ref. [37], page 290), tab. 2, results in average human body heat capacities of 3.26 J/gK and 3.18 J/gK, respectively, for hydrated tissues. The average of the two is 3.24 J/gK. When converted to dry mass heat capacities, this results

Table 3. Empirical formulas of human soft tissues: the empirical formula (UCF) of a tissue is represented as $CH_{nH}O_{nO}N_{nN}P_{nP}S_{nS}Na_{nNa}K_{nK}Mg_{nMg}Ca_{nCa}Fe_{nFe}Cl_{nCl}I_{nI}$, where n_H, n_O, n_N, n_P, n_S, n_{Na}, n_K, n_{Mg}, n_{Ca}, n_{Fe}, n_{Cl} and n_I are coefficients given in this table; for example, the empirical formula of Brain-grey matter is $CH_{1.9096}O_{0.2590}N_{0.1625}P_{0.0122}S_{0.0079}Na_{0.0110}K_{0.0097}Cl_{0.0107}$; human body 1 and 2 (average) are based on average entire human body soft tissue compositions reported by Wang *et al.* [38] and Snyder *et al.* [37], respectively. Adipose, heart, kidney, liver, mammary gland, muscle-skeletal tissues have 3 coefficients for each element, due to the spread in elemental composition data reported by Woodard and White [39] (see section *Elemental composition and heat capacity of hydrated tissues* for more details)

Tissue	n_H	n_O	n_N	n_P	n_S	n_{Na}	n_K	n_{Mg}	n_{Ca}	n_{Fe}	n_{Cl}	n_I
Human body 1 (average)	1.7296	0.2591	0.1112	0.0134	0.0030	0.0027	0.0031	0.0000	0.0173	0.0000	0.0018	0.0000
Human body 2 (average)	1.7131	0.2674	0.0965	0.0189	0.0033	0.0033	0.0027	0.0006	0.0187	0.0042	0.0020	7.69E-08
Adipose tissue 1	1.8005	0.1218	0.0216	0.0000	0.0007	0.0010	0.0000	0.0000	0.0000	0.0000	0.0007	0.0000
Adipose tissue 2	1.8024	0.1124	0.0100	0.0000	0.0006	0.0009	0.0000	0.0000	0.0000	0.0000	0.0006	0.0000
Adipose tissue 3	1.8083	0.1066	0.0025	0.0000	0.0006	0.0008	0.0000	0.0000	0.0000	0.0000	0.0005	0.0000
Adrenal gland	1.7391	0.1627	0.0785	0.0014	0.0026	0.0000	0.0011	0.0000	0.0000	0.0000	0.0024	0.0000
Aorta	1.5313	0.2917	0.2450	0.0106	0.0076	0.0071	0.0021	0.0000	0.0082	0.0000	0.0000	0.0000
Blood-erythrocytes	1.4984	0.3047	0.2663	0.0020	0.0059	0.0000	0.0049	0.0000	0.0000	0.0011	0.0036	0.0000
Blood-plasma	1.7117	0.2767	0.2301	0.0000	0.0091	0.0382	0.0000	0.0000	0.0000	0.0000	0.0331	0.0000
Blood-whole	1.5408	0.2919	0.2572	0.0035	0.0068	0.0047	0.0056	0.0000	0.0000	0.0020	0.0092	0.0000
Brain-grey matter	1.9096	0.2590	0.1625	0.0122	0.0079	0.0110	0.0097	0.0000	0.0000	0.0000	0.0107	0.0000
Brain-white matter	1.8361	0.2017	0.1105	0.0080	0.0039	0.0054	0.0048	0.0000	0.0000	0.0000	0.0052	0.0000
Connective tissue	1.5480	0.3087	0.2568	0.0000	0.0109	0.0151	0.0000	0.0000	0.0000	0.0000	0.0049	0.0000
Eye lens	1.5143	0.2934	0.2507	0.0020	0.0058	0.0027	0.0000	0.0000	0.0000	0.0000	0.0017	0.0000
Gallblader - wall	1.6101	0.2757	0.2013	0.0055	0.0079	0.0037	0.0087	0.0000	0.0000	0.0000	0.0024	0.0000
Gastrointestinal tract - oesophagus	1.7041	0.2256	0.1640	0.0034	0.0033	0.0045	0.0027	0.0000	0.0000	0.0000	0.0059	0.0000
Gastrointestinal tract - small intestine (wall)	1.6480	0.2310	0.1789	0.0028	0.0054	0.0038	0.0044	0.0000	0.0000	0.0000	0.0024	0.0000
Gastrointestinal tract - stomach	1.6419	0.2140	0.1519	0.0044	0.0043	0.0030	0.0053	0.0000	0.0000	0.0000	0.0039	0.0000
Heart 1	1.6861	0.2340	0.1789	0.0056	0.0054	0.0038	0.0066	0.0000	0.0000	0.0000	0.0049	0.0000
Heart 2	1.6327	0.2689	0.2248	0.0075	0.0073	0.0051	0.0089	0.0000	0.0000	0.0000	0.0066	0.0000
Heart 3	1.6415	0.2689	0.2268	0.0032	0.0062	0.0043	0.0051	0.0000	0.0000	0.0018	0.0084	0.0000

→

Table 3. (Continuated)

Tissue	n_H	n_O	n_N	n_P	n_S	n_{Na}	n_K	n_{Mg}	n_{Ca}	n_{Fe}	n_{Cl}	n_I
Kidney 1	1.6151	0.2452	0.1949	0.0059	0.0057	0.0079	0.0047	0.0000	0.0023	0.0000	0.0051	0.0000
Kidney 2	1.6364	0.2581	0.2184	0.0073	0.0071	0.0099	0.0058	0.0000	0.0028	0.0000	0.0064	0.0000
Kidney 3	1.6891	0.2593	0.1484	0.0075	0.0077	0.0067	0.0059	0.0000	0.0000	0.0000	0.0043	0.0000
Liver 1	1.6480	0.2904	0.1851	0.0084	0.0081	0.0075	0.0066	0.0000	0.0000	0.0000	0.0049	0.0000
Liver 2	1.6079	0.3277	0.2246	0.0092	0.0089	0.0083	0.0073	0.0000	0.0000	0.0000	0.0054	0.0000
Liver 3	1.5863	0.2866	0.2462	0.0077	0.0111	0.0103	0.0061	0.0000	0.0000	0.0000	0.0101	0.0000
Lung - parenchyma	1.6268	0.2836	0.2532	0.0074	0.0107	0.0100	0.0059	0.0000	0.0000	0.0000	0.0097	0.0000
Mammary gland 1	1.7549	0.1585	0.0775	0.0012	0.0023	0.0016	0.0000	0.0000	0.0000	0.0000	0.0010	0.0000
Mammary gland 2	1.6091	0.2502	0.2008	0.0025	0.0047	0.0033	0.0000	0.0000	0.0000	0.0000	0.0021	0.0000
Mammary gland 3	1.6184	0.2580	0.1805	0.0045	0.0066	0.0031	0.0072	0.0000	0.0000	0.0000	0.0020	0.0000
Muscle - skeletal 1	1.6390	0.2695	0.2039	0.0054	0.0079	0.0037	0.0086	0.0000	0.0000	0.0000	0.0024	0.0000
Muscle - skeletal 2	1.5606	0.3106	0.2297	0.0069	0.0100	0.0047	0.0110	0.0000	0.0000	0.0000	0.0030	0.0000
Muscle - skeletal 3	1.6659	0.2583	0.2213	0.0083	0.0081	0.0112	0.0066	0.0000	0.0000	0.0000	0.0073	0.0000
Ovary	1.7316	0.1885	0.1116	0.0046	0.0022	0.0062	0.0036	0.0000	0.0000	0.0000	0.0040	0.0000
Pancreas	1.6663	0.2830	0.2409	0.0044	0.0084	0.0117	0.0069	0.0000	0.0000	0.0000	0.0000	0.0000
Prostate	1.7527	0.1561	0.0704	0.0009	0.0018	0.0000	0.0015	0.0000	0.0000	0.0005	0.0016	0.0000
Skeleton - red marrow	1.8135	0.1107	0.0093	0.0000	0.0006	0.0008	0.0000	0.0000	0.0000	0.0000	0.0005	0.0000
Skeleton - yellow marrow	1.8135	0.1107	0.0093	0.0000	0.0006	0.0008	0.0000	0.0000	0.0000	0.0000	0.0005	0.0000
Skin 1	1.6631	0.2195	0.1578	0.0016	0.0045	0.0042	0.0012	0.0000	0.0000	0.0000	0.0041	0.0000
Skin 2	1.6032	0.2376	0.1765	0.0019	0.0037	0.0051	0.0015	0.0000	0.0000	0.0000	0.0050	0.0000
Skin 3	1.5756	0.2571	0.2008	0.0025	0.0047	0.0066	0.0019	0.0000	0.0000	0.0000	0.0064	0.0000
Spleen	1.6405	0.2753	0.2428	0.0103	0.0066	0.0046	0.0082	0.0000	0.0000	0.0000	0.0060	0.0000
Testis	1.6986	0.2342	0.1732	0.0039	0.0076	0.0106	0.0062	0.0000	0.0000	0.0000	0.0068	0.0000
Thyroid	1.6913	0.3035	0.1729	0.0033	0.0031	0.0088	0.0026	0.0000	0.0000	0.0000	0.0057	0.0008
Urinary bladder - wall	1.6101	0.2757	0.2013	0.0055	0.0079	0.0037	0.0087	0.0000	0.0000	0.0000	0.0024	0.0000

Table 4. Thermodynamic properties of human tissues at 25 °C or 298.15 K: human body 1 and 2 (average) are based on average entire human body soft tissue compositions reported by Wang *et al.* [38] and Snyder *et al.* [37], respectively; adipose, heart, kidney, liver, mammary gland, muscle-skeletal tissues have 3 calculated values for each thermodynamic property, due to the spread in elemental composition data reported by Woodard and White [39] (see section *Elemental composition and heat capacity of hydrated tissues* for more details). For each property X values are reported per mole of carbon (UCF), X_m, and per gram, X_g, of tissue dry mass

Tissue	M_r [gC-mol^{-1}]	$\Delta_f H^o_m$ [kJC-mol^{-1}]	$\Delta_f G^o_m$ [kJC-mol^{-1}]	S^o_m [JC-mol^{-1}K^{-1}]	$C^o_{p,m}$ [JC-mol^{-1}K^{-1}]	$\Delta_f H^o_g$ [kJg^{-1}]	$\Delta_f G^o_g$ [kJg^{-1}]	S^o_g [Jg^{-1}K^{-1}]	$C^o_{p,g}$ [Jg^{-1}K^{-1}]
Human body 1 (average)	20.91	–75.75	–37.54	29.48	34.70	–3.62	–1.79	1.41	1.66
Human body 2 (average)	21.31	–81.14	–43.21	29.26	35.39	–3.81	–2.03	1.37	1.66
Adipose tissue 1	16.15	–33.36	0.06	25.78	24.90	–2.07	0.00	1.60	1.54
Adipose tissue 2	15.83	–31.32	1.62	25.41	29.34	–1.98	0.10	1.61	1.85
Adipose tissue 3	15.63	–30.19	2.52	25.24	33.00	–1.93	0.16	1.61	2.11
Adrenal gland	17.72	–40.53	–5.66	26.90	45.69	–2.29	–0.32	1.52	2.58
Aorta	22.80	–69.48	–30.58	30.01	37.72	–3.05	–1.34	1.32	1.65
Blood-erythrocytes	22.76	–65.03	–25.95	30.14	37.76	–2.86	–1.14	1.32	1.66
Blood-plasma	23.73	–75.88	–33.77	32.48	24.33	–3.20	–1.42	1.37	1.03
Blood-whole	22.93	–66.01	–26.54	30.45	33.86	–2.88	–1.16	1.33	1.48
Brain-grey matter	22.00	–73.32	–30.76	32.83	30.11	–3.33	–1.40	1.49	1.37
Brain-white matter	19.50	–55.50	–17.11	29.61	44.29	–2.85	–0.88	1.52	2.27
Connective tissue	22.98	–67.79	–27.89	30.78	52.43	–2.95	–1.21	1.34	2.28
Eye lens	22.11	–61.97	–23.39	29.76	27.69	–2.80	–1.06	1.35	1.25
Gallblader - wall	21.79	–63.06	–24.33	29.88	51.48	–2.89	–1.12	1.37	2.36
Gastrointestinal tract - oesophagus	20.26	–55.44	–17.38	29.36	24.68	–2.74	–0.86	1.45	1.22
Gastrointestinal tract - small intestine (wall)	20.48	–53.75	–16.16	29.00	23.34	–2.62	–0.79	1.42	1.14
Gastrointestinal tract - stomach	19.90	–50.63	–14.14	28.15	41.66	–2.54	–0.71	1.41	2.09
Heart 1	20.82	–56.99	–18.59	29.62	51.27	–2.74	–0.89	1.42	2.46
Heart 2	22.27	–63.88	–24.27	30.56	47.02	–2.87	–1.09	1.37	2.11
Heart 3	22.14	–63.78	–24.04	30.66	34.71	–2.88	–1.09	1.38	1.57

→

Table 4. (Continuated)

Tissue	M_r [gC-mol^{-1}]	$\Delta_f H_m^o$ [kJC-mol^{-1}]	$\Delta_f G_m^o$ [kJC-mol^{-1}]	S_m^o [JC-mol^{-1}K^{-1}]	$C_{p,m}^o$ [JC-mol^{-1}K^{-1}]	$\Delta_f H_g^o$ [kJg^{-1}]	$\Delta_f G_g^o$ [kJg^{-1}]	S_g^o [Jg^{-1}K^{-1}]	$C_{p,g}^o$ [Jg^{-1}K^{-1}]
Kidney 1	21.29	–59.18	–21.21	29.29	56.61	–2.78	–1.00	1.38	2.66
Kidney 2	22.10	–63.82	–24.53	30.31	52.55	–2.89	–1.11	1.37	2.38
Kidney 3	20.96	–62.85	–24.44	29.63	42.27	–3.00	–1.17	1.41	2.02
Liver 1	22.03	–68.92	–29.49	30.42	39.92	–3.13	–1.34	1.38	1.81
Liver 2	23.26	–76.24	–35.55	31.39	38.46	–3.28	–1.53	1.35	1.65
Liver 3	23.07	–66.50	–26.53	30.83	35.51	–2.88	–1.15	1.34	1.54
Lung - parenchyma	23.11	–66.99	–26.32	31.37	60.99	–2.90	–1.14	1.36	2.64
Mammary gland 1	17.58	–40.07	–5.12	26.96	29.32	–2.28	–0.29	1.53	1.67
Mammary gland 2	20.83	–55.95	–18.08	29.21	34.65	–2.69	–0.87	1.40	1.66
Mammary gland 3	21.07	–59.12	–21.24	29.22	34.85	–2.81	–1.01	1.39	1.65
Muscle - skeletal 1	21.75	–62.58	–23.50	30.16	35.60	–2.88	–1.08	1.39	1.64
Muscle - skeletal 2	22.95	–69.68	–30.12	30.52	28.30	–3.04	–1.31	1.33	1.23
Muscle - skeletal 3	22.21	–63.52	–23.65	30.76	13.60	–2.86	–1.06	1.38	0.61
Ovary	18.98	–48.80	–12.46	28.04	34.42	–2.57	–0.66	1.48	1.81
Pancreas	22.54	–67.09	–26.37	31.41	8.07	–2.98	–1.17	1.39	0.36
Prostate	17.49	–39.80	–5.09	26.78	28.60	–2.28	–0.29	1.53	1.64
Skeleton - red marrow	15.80	–31.29	1.77	25.50	26.31	–1.98	0.11	1.61	1.67
Skeleton - yellow marrow	15.80	–31.29	1.77	25.50	26.57	–1.98	0.11	1.61	1.68
Skin 1	19.89	–51.46	–14.43	28.57	45.04	–2.59	–0.73	1.44	2.26
Skin 2	20.43	–54.25	–17.25	28.55	38.68	–2.66	–0.84	1.40	1.89
Skin 3	21.21	–58.17	–20.48	29.08	28.31	–2.74	–0.97	1.37	1.33
Spleen	22.64	–65.95	–25.65	31.09	32.06	–2.91	–1.13	1.37	1.42
Testis	20.99	–58.18	–19.59	29.78	38.36	–2.77	–0.93	1.42	1.83
Thyroid	21.80	–73.20	–33.14	30.90	33.02	–3.36	–1.52	1.42	1.51
Urinary bladder - wall	21.79	–63.06	–24.33	29.88	40.09	–2.89	–1.12	1.37	1.84

Table 5. Thermodynamic properties of human tissues at 37 ºC or 310.15 K: human body 1 and 2 (average) are based on average entire soft tissue human body compositions reported by Wang *et al.* [38] and Snyder *et al.* [37], respectively. Adipose, heart, kidney, liver, mammary gland, muscle-skeletal tissues have 3 calculated values for each thermodynamic property, due to the spread in elemental composition data reported by Woodard and White [39] (see section *Elemental composition and heat capacity of hydrated tissues* for more details). For each property *X* values are reported per mole of carbon (UCF), X_m, and per gram, X_g, of tissue dry mass. Heat capacities at 25 °C are given in this table, since heat capacity does not change significantly from 25 ºC to 37 ºC [43]

Tissue	M_r [gC-mol^{-1}]	$\Delta_f H_m^{37C}$ [kJC-mol^{-1}]	$\Delta_f G_m^{37C}$ [kJC-mol^{-1}]	S_m^{37C} [JC-mol^{-1}K^{-1}]	$C^o_{p,m}$ [JC-mol^{-1}K^{-1}]	$\Delta_f H_g^{37C}$ [kJg^{-1}]	$\Delta_f G_g^{37C}$ [kJg^{-1}]	S_g^{37C} [Jg^{-1}K^{-1}]	$C^o_{p,g}$ [Jg^{-1}K^{-1}]
Human body 1 (average)	20.91	–75.34	–35.52	30.85	34.70	–3.60	–1.70	1.48	1.66
Human body 2 (average)	21.31	–80.71	–41.20	30.66	35.39	–3.79	–1.93	1.44	1.66
Adipose tissue 1	16.15	–33.06	1.84	26.76	24.90	–2.05	0.11	1.66	1.54
Adipose tissue 2	15.83	–30.97	3.39	26.57	29.34	–1.96	0.21	1.68	1.85
Adipose tissue 3	15.63	–29.79	4.27	26.54	33.00	–1.91	0.27	1.70	2.11
Adrenal gland	17.72	–39.98	–3.81	28.70	45.69	–2.26	–0.22	1.62	2.58
Aorta	22.80	–69.03	–28.55	31.50	37.72	–3.03	–1.25	1.38	1.65
Blood-erythrocytes	22.76	–64.57	–23.91	31.63	37.76	–2.84	–1.05	1.39	1.66
Blood-plasma	23.73	–75.59	–31.56	33.44	24.33	–3.19	–1.33	1.41	1.03
Blood-whole	22.93	–65.60	–24.47	31.79	33.86	–2.86	–1.07	1.39	1.48
Brain-grey matter	22.00	–72.95	–28.52	34.02	30.11	–3.32	–1.30	1.55	1.37
Brain-white matter	19.50	–54.97	–15.09	31.36	44.29	–2.82	–0.77	1.61	2.27
Connective tissue	22.98	–67.16	–25.81	32.85	52.43	–2.92	–1.12	1.43	2.28
Eye lens	22.11	–61.64	–21.37	30.86	27.69	–2.79	–0.97	1.40	1.25
Gallblader - wall	21.79	–62.44	–22.30	31.91	51.48	–2.86	–1.02	1.46	2.36
Gastrointestinal tract - oesophagus	20.26	–55.14	–15.37	30.34	24.68	–2.72	–0.76	1.50	1.22
Gastrointestinal tract - small intestine (wall)	20.48	–53.47	–14.18	29.92	23.34	–2.61	–0.69	1.46	1.14
Gastrointestinal tract - stomach	19.90	–50.13	–12.21	29.80	41.66	–2.52	–0.61	1.50	2.09
Heart 1	20.82	–56.37	–16.58	31.64	51.27	–2.71	–0.80	1.52	2.46
Heart 2	22.27	–63.32	–22.20	32.41	47.02	–2.84	–1.00	1.46	2.11
Heart 3	22.14	–63.37	–21.96	32.03	34.71	–2.86	–0.99	1.45	1.57

→

Table 5. (Continuated)

Tissue	M_r [gC-mol^{-1}]	$\Delta_f H_m^{37C}$ [kJC-mol^{-1}]	$\Delta_f G_m^{37C}$ [kJC-mol^{-1}]	S_m^{37C} [JC-mol^{-1}K^{-1}]	$C^o_{p,m}$ [JC-mol^{-1}K^{-1}]	$\Delta_f H_g^{37C}$ [kJg^{-1}]	$\Delta_f G_g^{37C}$ [kJg^{-1}]	S_g^{37C} [Jg^{-1}K^{-1}]	$C^o_{p,g}$ [Jg^{-1}K^{-1}]
Kidney 1	21.29	–58.50	–19.22	31.53	56.61	–2.75	–0.90	1.48	2.66
Kidney 2	22.10	–63.19	–22.47	32.38	52.55	–2.86	–1.02	1.47	2.38
Kidney 3	20.96	–62.34	–22.41	31.30	42.27	–2.97	–1.07	1.49	2.02
Liver 1	22.03	–68.44	–27.42	32.00	39.92	–3.11	–1.24	1.45	1.81
Liver 2	23.26	–75.77	–33.42	32.91	38.46	–3.26	–1.44	1.41	1.65
Liver 3	23.07	–66.07	–24.44	32.23	35.51	–2.86	–1.06	1.40	1.54
Lung - parenchyma	23.11	–66.26	–24.20	33.78	60.99	–2.87	–1.05	1.46	2.64
Mammary gland 1	17.58	–39.72	–3.26	28.12	29.32	–2.26	–0.19	1.60	1.67
Mammary gland 2	20.83	–55.53	–16.09	30.58	34.65	–2.67	–0.77	1.47	1.66
Mammary gland 3	21.07	–58.70	–19.25	30.60	34.85	–2.79	–0.91	1.45	1.65
Muscle - skeletal 1	21.75	–62.16	–21.44	31.56	35.60	–2.86	–0.99	1.45	1.64
Muscle - skeletal 2	22.95	–69.34	–28.04	31.64	28.30	–3.02	–1.22	1.38	1.23
Muscle - skeletal 3	22.21	–63.36	–21.55	31.29	13.60	–2.85	–0.97	1.41	0.61
Ovary	18.98	–48.39	–10.53	29.40	34.42	–2.55	–0.56	1.55	1.81
Pancreas	22.54	–67.00	–24.23	31.73	8.07	–2.97	–1.08	1.41	0.36
Prostate	17.49	–39.46	–3.25	27.90	28.60	–2.26	–0.19	1.60	1.64
Skeleton - red marrow	15.80	–30.97	3.54	26.54	26.31	–1.96	0.22	1.68	1.67
Skeleton - yellow marrow	15.80	–30.97	3.54	26.55	26.57	–1.96	0.22	1.68	1.68
Skin 1	19.89	–50.92	–12.48	30.35	45.04	–2.56	–0.63	1.53	2.26
Skin 2	20.43	–53.79	–15.30	30.07	38.68	–2.63	–0.75	1.47	1.89
Skin 3	21.21	–57.83	–18.49	30.20	28.31	–2.73	–0.87	1.42	1.33
Spleen	22.64	–65.57	–23.54	32.36	32.06	–2.90	–1.04	1.43	1.42
Testis	20.99	–57.72	–17.55	31.29	38.36	–2.75	–0.84	1.49	1.83
Thyroid	21.80	–72.80	–31.04	32.21	33.02	–3.34	–1.42	1.48	1.51
Urinary bladder - wall	21.79	–62.58	–22.30	31.46	40.09	–2.87	–1.02	1.44	1.84

in $C^{o}_{p,g}$(bio) of 1.66 J/gK. The experimentally determined dry matter heat capacity of yeast is 1.299 J/gK [46], while the average of all the tissues analyzed in this work is 1.73 J/gK. The entire body dry matter heat capacities calculated above are 2.30 J/gK based on [45] and 1.66 J/gK based on [37, 38]. The latter value of 1.66 J/gK is much closer to both the result for experimental yeast heat capacity and the tissue average. This suggests that 1.66 J/gK as the average constant pressure heat capacity of human body dry matter and 3.24 J/gK as the average constant pressure heat capacity of hydrated human body are the more accurate values.

Popovic [2] reports thermodynamic properties of 32 microorganism species. For the analyzed microorganisms, the average enthalpy of formation is –106.51 kJ/C-mol, the average molar entropy is 34.02 J/C-molK, and the average standard Gibbs energy of formation is –62.41 kJ/C-mol. The most accurately known organism thermodynamic properties are those of *Saccharomyces cerevisiae* determined by Battley [34]: the enthalpy of formation is –133.13 kJ/C-mol, the molar entropy is 34.167 J/C-molK, and the standard Gibbs energy of formation is –88.00 kJ/C-mol. Comparing the thermodynamic properties of microorganisms and human tissues shows a very small difference in molar entropy, 34.02 J/C-molK as microorganism average, 34.167 J/C-molK for *S. cerevisiae* and 30.77 J/C-molK for human tissues. The difference in enthalpies of formation is significant, –106.51 kJ/C-mol as microorganism average, –133.13 kJ/C-mol for *S. cerevisiae* and –57.20 kJ/C-mol for human tissues. The difference in enthalpies leads to difference in Gibbs energies, –62.41 kJ/C-mol as microorganism average, –88.00 kJ/C-mol for *S. cerevisiae* and –17.57 kJ/C-mol for human tissues.

Conclusions

A complete thermodynamic characterization was made for the first time for human soft tissues for the entire human organism, tabs. 4 and 5. Empirical formulas of human tissue and entire organism soft tissue dry matter were determined for the first time, tab. 3. By comparison with literature values as well as those of individual tissues, it was found that it is more accurate to use 1.66 J/gK as the average constant pressure heat capacity of human body dry matter and 3.24 J/gK as the average constant pressure heat capacity of hydrated human body soft tissue.

Nomenclature

a_J – number of atoms per molecule of element *J* in its standard state elemental form
$C^{o}_{p,m}$(bio) – standard molar heat capacity of tissue dry matter, [J C-mol^{-1}K^{-1}]
$C^{o}_{p,g}(X)$ – standard specific (per gram) heat capacity of substance *X*, [J g^{-1}K^{-1}]
$C^{o}_{p,g}(H_2O)$ – standard specific (per gram) heat capacity of water. [J g^{-1}K^{-1}]
$C^{o}_{p,g}$(bio) – standard specific (per gram) heat capacity of tissue dry matter, [J C-mol^{-1}K^{-1}]
$C^{o}_{p,g}$(bio,wet) – standard specific (per gram) heat capacity of hydrated tissue, [J g^{-1}K^{-1}]
$\Delta_f C^{o}_p$(bio) – standard heat capacity of formation of tissue dry matter, [JC-mol^{-1}K^{-1}]
E – number of electrons transferred to oxygen during complete combustion
$\Delta_f G^{o}$(bio) – standard (at 25 ºC) Gibbs energy of formation of tissue dry matter, [kJ C-mol^{-1}]
$\Delta_f G^{37C}$(bio) – Gibbs energy of formation of tissue dry matter at 37 ºC, [kJC-mol^{-1}]
$\Delta_C H^{o}$(bio) – standard (at 25 ºC) enthalpy of combustion of tissue dry matter, [kJC-mol^{-1}]
$\Delta_f H^{o}$(bio) – standard (at 25 ºC) enthalpy of formation of tissue dry matter, [kJC-mol^{-1}]
$\Delta_f H^{o}(X)$ – standard (at 25 ºC) enthalpy of formation of substance *X*, [kJmol^{-1}]

$\Delta_f H^{37C}(\text{bio})$ – enthalpy of formation of tissue dry matter at 37 ºC, [kJ C-mol^{-1}]
$M_{r,J}$ – molar mass of element J, [gmol^{-1}]
n_J – number of atoms of element J in tissue UCF
$S_m^o(\text{bio})$ – standard (at 25 ºC) molar entropy of tissue dry matter, [JC-mol^{-1}K^{-1}]
$S_m^o(J)$ – standard (at 25 ºC) molar entropy of element J, [Jmol^{-1}K^{-1}]
$\Delta_f S^o(\text{bio})$ – standard (at 25 ºC) molar entropy of formation tissue dry matter, [JC-mol^{-1}K^{-1}]
$S_m^{37C}(\text{bio})$ – molar entropy of tissue dry matter at 37 ºC, [JC-mol^{-1}K^{-1}]
$\Delta_f S^{37C}(\text{bio})$ – entropy of formation of tissue dry matter at 37ºC [JC-mol^{-1}K^{-1}]
w_J – mass fraction of element J in tissue dry matter
$w_{J,\text{wet}}$ – mass fraction of element J in hydrated tissue
x_c – mole fraction of carbon
x_J – mole fraction of element J in dry matter
$\delta(X)$ – uncertainty in thermodynamic property X

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