

Oxidative phosphorylation:

ATP-Synthetase [1, 2]

(ATP \rightarrow ADP + Pi)

$$v_{syn} = V_{max}^{syn} \cdot \left(ADP_{mito} \cdot P_{mito} - \frac{ATP_{mito}}{K_{eq-syn}} \right)$$

$$K_{eq-syn} = \exp\left(\frac{dG_0^{syn}}{R \cdot T} - k \cdot U\right) \cdot \left(\frac{h_{cyt}}{h_{mito}}\right)^k$$

$$dG_0^{syn} = 30500$$

$$k = 3$$

ATP-exchanger: [3]

(ATP_mito + ADP_cyt \leftrightarrow ADP_mito + ATP_cyt)

$$v_{ATP-exchanger} = V_{max}^{ATP-exchanger} \cdot \left(\frac{1 - \frac{ATP_{in} \cdot ADP_{mito}}{ADP_{in} \cdot ATP_{mito}} \exp(U)}{\left(1 + \frac{ATP_{in}}{ADP_{in}} \exp(S_{V_{mm}} \cdot U) \left(1 + \frac{ADP_{mito}}{ATP_{mito}}\right)\right)} \right)$$

$$S_{V_{mm}} = 0.3$$

ATP-consumption

ATP consumption is modeled as a Michaelis-Menten equation with low K_m -value:

$$v_{ATP-use} = V_{max-ATP-use} \frac{ATP_{in}}{ATP_{in} + K_m^{ATP}}$$

$$K_m^{ATP} = 0.1$$

Electrophysiology:

$$U = \frac{V_{mm} \cdot F}{1000 \cdot R \cdot T}$$

$$F = 96490.0 \frac{C}{mol}$$

$$R = 8.314 \frac{J}{K \cdot mol}$$

$$T = 310 \text{ K}$$

Electro diffusion:

The passive efflux of sodium ions, potassium ions, chloride ions and protons is modeled by the Goldman-Hodgkin equation.

Potassium [4]

$$I_{Pot_{mito}}^{ed} = A_m \cdot P_{Pot_{mito}} \cdot U \cdot F \cdot \left(\frac{K_{in} - K_{mito} \cdot \exp(U)}{1 - \exp(U)} \right)$$

$$P_{Pot_{mito}} = 2 \cdot 10^{-10} \frac{m}{S}$$

Sodium

$$I_{Na_{mito}}^{ed} = A_m \cdot P_{Na_{mito}} \cdot U \cdot F \cdot \left(\frac{Na_{in} - Na_{mito} \cdot \exp(U)}{1 - \exp(U)} \right)$$

$$P_{Na_{mito}} = 1 \cdot 10^{-11} \frac{m}{S}$$

Protons: [5], [6]

$$I_{H_{mito}}^{ed} = -A_m \cdot P_{H_{mito}} \cdot U \cdot F \cdot \left(\frac{H_{in} - H_{mito} \cdot \exp(U)}{1 - \exp(U)} \right)$$

$$P_{H_{mito}} = 4 \cdot 10^{-4} \frac{m}{S}$$

Pumps: [7]

The pumping of sodium, potassium and phosphate is modeled as electro-neutral proton driven antiport:

$$v_{Phos-exchanger} = V_{max}^{Phos-exchanger} (P_{in} \cdot H_{in} - P_{mito} \cdot H_{mito})$$

$$I_{Na_{mito}}^{pump} = V_{max}^{Na-pump} (Na_{in} \cdot H_{mito} - Na_{mito} \cdot H_{in})$$

$$I_{Pot_{mito}}^{pump} = V_{max}^{Pot-pump} (K_{in} \cdot H_{mito} - K_{mito} \cdot H_{in})$$

Complex III: [8], [9], [10]

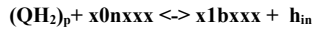
The state of complex III is described as an array consisting of two numbers, a letter, two numbers and another letter. The numbers denote the reduction state, 0 for oxidized, 1 for reduced, of the corresponding complex III elements, the letter the binding, b, or not binding, n, of the ubisemiquinone. From left to right the array position denotes the reduction state of the cytochrome c1 (c1), the reduction state of the Iron sulfur cluster (Fe-S), the binding of the ubisemiquinone at p site (SQ_p), the reduction state of the low b-type heme (b_L), the reduction state of the high b-type heme (b_H) and the binding of the ubisemiquinone at n site (SQ_n).

$$\begin{array}{cccccc} c1 & Fe-S & SQ_p & b_L & b_H & SQ_n \\ 0/ & 0/ & n/ & 0/ & 0/ & n/ \\ 1 & 1 & b & 1 & 1 & b \end{array}$$

As examples 00n00n describes the fully oxidized complex III, with no bound ubisemiquinone, while 11b11b describes the fully reduced complex III with ubisemiquinone bound at n and p site, and 10n11b describes the state of complex III with reduced cytochrome c1, oxidized Fe-S, reduced b-type heme b_L, reduced b-type heme b_H and bound ubisemiquinone at n but not at p side.

There are seven different reversible elementary processes with rate equation:

- P site ubiquinol reacts with oxidized Fe-S to reduced Fe-S and p-site bound ubisemiquinone and release of two protons into the cytosol



$$v_{SQ_p} = V_{max}^{SQ_p} \left((QH_2)_p \cdot x0nxxx - \frac{1}{K_{eq}^{SQ_p}} \cdot x1bxxx \right)$$

$$K_{eq}^{SQ_p} = \exp \left(\frac{f_V^{SQ_p} \cdot V \cdot F}{R \cdot T \cdot 1000} \right) \cdot \frac{h_{cyt}}{h_{ref}}$$

$$f_V^{SQ_p} = 0.1$$

$$h_{ref} = 10^{-7}$$

- Reduction of the low b-type heme and release of ubiquinon at p site:
x1b0xx ↔ x1n1xx + Q_p + h_{in}

$$v_{Q_p} = V_{max}^{Q_p} \left(x1b0xx - \frac{1}{K_{eq}^{Q_p}} \cdot x1n1xx \cdot Q_p \right)$$

$$K_{eq}^{Q_p} = \exp \left(\frac{(E_0^{Q_p} + f_V^{Q_p} \cdot V) \cdot F}{R \cdot T \cdot 1000} \right) \cdot \frac{h_{cyt}}{h_{ref}}$$

$$f_V^{Q_p} = 0.1$$

$$E_0^{Q_p} = 120$$

$$h_{ref} = 10^{-7}$$

- Electrontransfer between the low b-type heme b_L and the high b-type heme b_H:
xxx10x ↔ xxx01x

$$v_{hemes} = V_{max}^{hemes} \left(xxx10x - \frac{1}{K_{eq}^{hemes}} \cdot xxx01x \right)$$

$$K_{eq}^{hemes} = \exp \left(\frac{(E_0^{hemes} + f_V^{hemes} \cdot V) \cdot F}{R \cdot T \cdot 1000} \right)$$

$$f_V^{hemes} = 0.8$$

$$E_0^{hemes} = 80$$

- **N site ubiqinone reacts with reduced high b-type heme to bound semiquinone at n site:**
 $xxxx1n + h_{mito} + Q_n \leftrightarrow xxxx0b$

$$v_{SQ_n} = V_{max}^{SQ_n} \left(Q_n \cdot xxxx1n - \frac{1}{K_{eq}^{SQ_n}} \cdot xxxx0b \right)$$

$$K_{eq}^{SQ_n} = \exp \left(\frac{\left(E_0^{SQ_n} + f_V^{SQ_n} \cdot V \right) \cdot F}{R \cdot T \cdot 1000} \right) \cdot \frac{h_{mito}}{h_{ref}}$$

$$f_V^{SQ_n} = 0.1$$

$$E_0^{SQ_n} = 30$$

- **Reduced high b-type heme reacts with n site bound ubisemiquinone:**
 $xxxx1b + h_{mito} \leftrightarrow xxxx0n + (QH_2)_n$

$$v_{(QH_2)_n} = V_{max}^{(QH_2)_n} \left(\cdot xxxx1b - \frac{1}{K_{eq}^{(QH_2)_n}} \cdot xxxx0n \cdot (QH_2)_n \right)$$

$$K_{eq}^{(QH_2)_n} = \exp \left(\frac{\left(E_0^{(QH_2)_n} + f_V^{(QH_2)_n} \cdot V \right) \cdot F}{R \cdot T \cdot 1000} \right) \cdot \frac{h_{mito}}{h_{ref}}$$

$$f_V^{(QH_2)_n} = 0.1$$

$$E_0^{(QH_2)_n} = 130$$

$$h_{ref} = 10^{-7}$$

- **Reduced Fe-S reacts with oxidized cytochrome c1 :**
 $01xxxx \leftrightarrow 10xxxx$

$$v_{c1} = V_{max}^{c1} \left(01xxxx - \frac{1}{K_{eq}^{c1}} \cdot 10xxxx \right)$$

$$K_{eq}^{c1} = \exp \left(\frac{E_0^{c1} \cdot F}{R \cdot T \cdot 1000} \right)$$

$$E_0^{c1} = -35$$

- **Reduced cytochrome c1 reacts with oxidized cytochrom c:**
 $1xxxx + cytc_{ox} \leftrightarrow 0xxxx + cytc_{red}$

$$v_{cyc} = V_{max}^{cyc} \left(1xxxx \cdot cytc_{ox} - \frac{1}{K_{eq}^{cyc}} \cdot 0xxxx \cdot cytc_{red} \right)$$

$$K_{eq}^{cyc} = \exp \left(\frac{E_0^{cyc} \cdot F}{R \cdot T \cdot 1000} \right)$$

$$E_0^{cyc} = -10$$

Complex I : [11], Hirst 2005 Biochemical Society Transaction vol 33, Rouslap 2010 nature (NADH + Q + 4 H_mito <-> NAD + QH2 + 4 H_in)

Similar to complex III the state of complex I is described as an array of integer numbers of length 10, one number for the flavin, eight for the iron sulfur clusters, and one for the semi-ubiquinone. The flavin mononucleotide can be fully reduced (state=2), exist as flavin radical (state=1) or by fully oxidized (state=0). The iron-sulfur clusters of complex I can exist in oxidized form (represented by a zero) or in a reduced form (state=1). The last digit in the array represents the bound semi-ubiquinone, which can be absent (state=0) or bound (state=1).

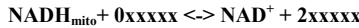
$$\begin{array}{cccccccccc} FMN & N3 & N1a & N1b & N4 & N5 & N6a & N6b & N2 & SQ \\ \frac{2}{1/0} & 1/0 & 1/0 & 1/0 & 1/0 & 1/0 & 1/0 & 1/0 & 1/0 & 1/0 \end{array}$$

This results in 1536 state variables and twelve elementary processes, generating 4480 reactions. This system of complex I was analyzed and reduced to a simplified system containing only six clusters. The iron sulfur clusters N1b, N4, N5, N6a, and N6b were lumped together to N* due to their similar midpoint potentials. The reduced system consists of 96 state variables, eight elementary processes and therewith 184 reactions. The occupation states of the remaining clusters are similar between the full and the reduced system. For the here developed model of the citric acid cycle and respiratory chain the simplified model was used.

$$\begin{array}{cccccc} FMN & N3 & N1a & N^* & N2 & SQ \\ \frac{2}{1/0} & 1/0 & 1/0 & 1/0 & 1/0 & 1/0 \end{array}$$

There are eight different reversible elementary processes:

- Mitochondrial NADH reacts with oxidized FMN to NAD⁺ and frf.

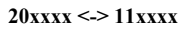


$$v_{frf} = V_{max}^{frf} \left(NADH_{mito} \cdot 0xxxxx - \frac{1}{K_{eq}^{frf}} \cdot NAD_{mito}^+ \cdot 2xxxxx \right)$$

$$K_{eq}^{frf} = \exp \left(\frac{E_0^{frf} \cdot F}{R \cdot T \cdot 1000} \right)$$

$$E_0^{frf} = -32mV$$

- One electron is transferred from the fully reduced flavin mononucleotide to N3.



$$v_{frf-N3} = V_{max}^{frf-N3} \left(20xxxx - \frac{1}{K_{eq}^{frf-N3}} \cdot 11xxxx \right)$$

$$K_{eq}^{frf-N3} = \exp \left(\frac{E_0^{frf-N3} \cdot F}{R \cdot T \cdot 1000} \right)$$

$$E_0^{frf-N3} = 12mV$$

- Transfer from flavine-radical to N3.



$$v_{fr-N3} = V_{max}^{fr-N3} \left(10xxxx - \frac{1}{K_{eq}^{fr-N3}} \cdot 01xxxx \right)$$

$$K_{eq}^{fr-N3} = \exp\left(\frac{E_0^{fr-N3} \cdot F}{R \cdot T \cdot 1000}\right)$$

$$E_0^{fr-N3} = 170mV$$

- **From N3 to N1a.**

x10xxx <-> x01xxx

$$v_{N3-N1a} = V_{\max}^{N3-N1a} \left(x10xxx - \frac{1}{K_{eq}^{N3-N1a}} \cdot x01xxx \right)$$

$$K_{eq}^{N3-N1a} = \exp\left(\frac{E_0^{N3-N1a} \cdot F}{R \cdot T \cdot 1000}\right)$$

$$E_0^{N3-N1a} = -135mV$$

- **From N1a to N*.**

xx10xx <-> xx01xx

$$v_{N1a-N^*} = V_{\max}^{N1a-N^*} \left(xx10xx - \frac{1}{K_{eq}^{N1a-N^*}} \cdot xx01xx \right)$$

$$K_{eq}^{N1a-N^*} = \exp\left(\frac{E_0^{N1a-N^*} \cdot F}{R \cdot T \cdot 1000}\right)$$

$$E_0^{N1a-N^*} = 130mV$$

- **From N* to N2, thereby exporting one proton from the mitochondrial matrix.**

xxx10x + h_{mito} <-> xxx01x + h_{in}

$$v_{N^*-N2} = V_{\max}^{N^*-N2} \left(xxx10x - \frac{1}{K_{eq}^{N^*-N2}} \cdot xxx01x \right)$$

$$K_{eq}^{N^*-N2} = \exp\left(\frac{(V_{mm} + E_0^{N^*-N2}) \cdot F}{R \cdot T \cdot 1000}\right) \cdot \frac{h_{mito}}{h_{in}}$$

$$E_0^{N^*-N2} = 150mV$$

$$h_{ref} = 10^{-7}$$

- **Binding of ubiquinon to complex I and transfer of one electron from N2 forming bound semi-ubiquinon and exporting one proton from the mitochondrial matrix.**

xxxx10 + Q + h_{mito} <-> xxxx01 + h_{in}

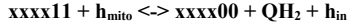
$$v_{N2-SQ} = V_{\max}^{N2-SQ} \left(Q \cdot xxxx10 - \frac{1}{K_{eq}^{N2-SQ}} \cdot xxxx01 \right)$$

$$K_{eq}^{N2-SQ} = \exp\left(\frac{(V_{mm} + E_0^{N2-SQ}) \cdot F}{R \cdot T \cdot 1000}\right) \cdot \frac{(h_{mito})^2}{h_{in} \cdot h_{ref}}$$

$$E_0^{N2-SQ} = 185mV$$

$$h_{ref} = 10^{-7}$$

- Transfer of one electron from N2 to bound semi-ubichinon forming and releasing ubichinol, thereby exporting one proton from the mitochondrial matrix.



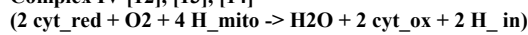
$$v_{N2-QH_2} = V_{max}^{N2-QH_2} \left(xxxx11 - \frac{1}{K_{eq}^{N2-QH_2}} \cdot xxxx00 \cdot QH_2 \right)$$

$$K_{eq}^{N2-QH_2} = \exp \left(\frac{(V_{mm} + E_0^{N2-QH_2}) \cdot F}{R \cdot T \cdot 1000} \right) \cdot \frac{(h_{mito})^2}{h_{in} \cdot h_{ref}}$$

$$E_0^{N2-SQ} = 225mV$$

$$h_{ref} = 10^{-7}$$

Complex IV [12], [13], [14]



$$v_{C_4} = V_{max}^{C_4} \cdot \frac{\text{cyt}_{red}^n}{\text{cyt}_{red}^n + (K_m^{\text{cyt}_{red}})^n} \cdot \frac{O_{2mito}}{O_{2mito} + K_m^{O_2}} \left(\frac{h_{mito}}{h_{in}} \right)^6$$

$$K_m^{O_2} = 0.001$$

$$n = A + B \frac{\left(\frac{ATP_{mito}}{ADP_{mito}} \right)^k}{\left(\frac{ADP_{mito}}{ADP_{mito}} \right)^k + \left(K_n^{\frac{ATP}{ADP}} \right)^k}$$

$$A = 1.1$$

$$B = 0.8$$

$$K_n^{\frac{ATP}{ADP}} = 24$$

$$k = 2.3$$

The factor $\left(\frac{h_{mito}}{h_{in}} \right)^6$ was included to ensure proper activation of complex IV with increased demand, but complex IV activity might actually be regulated by the intra- and/or extramitochondrial ATP/ADP ratio.

CAC

Pyruvate exchanger [15]

(Pyr_in + H_mito <-> Pyr_mito + H_in)

$$v_{pyr-exchanger} = V_{\max}^{Pyr-exchanger} \cdot \frac{(Pyr_{in} \cdot H_{in} - Pyr_{mito} \cdot H_{mito})}{\left(1 + \frac{Pyr_{in}}{K_m^{Pyr_{in}}}\right) \left(1 + \frac{Pyr_{mito}}{K_m^{Pyr_{mito}}}\right)}$$

$$K_m^{Pyr_{in}} = 0.15$$

$$K_m^{Pyr_{mito}} = 0.15$$

Pyruvatedehydrogenase complex [16], [17]

(Pyr_mito + CoA + NAD -> AcCoA + Co2 + NADH)

$$v_{pdhc} = V_{\max}^{pdhc} \left(1 + A_{\max}^{Ca_{mito}} \frac{Ca_{mito}}{Ca_{mito} + K_a^{Ca_{mito}}}\right) \left(\frac{Pyr_{mito}}{Pyr_{mito} + K_m^{Pyr}}\right) \left(\frac{NAD_{mito}}{NAD_{mito} + K_m^{NAD_{mito}}}\right) \left(\frac{CoA_{mito}}{CoA_{mito} + K_m^{CoA_{mito}}}\right)$$

$$A_{\max}^{Ca_{mito}} = 1.7$$

$$K_a^{Ca_{mito}} = 10^{-3}$$

$$K_m^{Pyr} = 0.090$$

$$K_m^{NAD_{mito}} = 0.036$$

$$K_m^{CoA_{mito}} = 0.0047$$

Citrate synthase [18],

(Oxa + AcCoA -> Cit)

$$v_{cs} = V_{\max}^{cs} \left(\frac{Oxa_{mito}}{Oxa_{mito} + K_m^{Oxa} \left(1 + \frac{Cit_{mito}}{3.7}\right)}\right) \left(\frac{AcCoA_{mito}}{AcCoA_{mito} + K_m^{AcCoA} \cdot \left(1 + \frac{CoA_{mito}}{0.025}\right)}\right)$$

$$K_m^{Oxa} = 0.0045$$

$$K_m^{AcCoA} = 0.005$$

$$K_i^{Cit} = 3.7$$

$$K_i^{CoA} = 0.025$$

Aconitase [19],

(Cit <-> IsoCit)

$$v_{Aco} = V_{\max}^{Aco} \frac{Cit_{mito} - \frac{IsoCit_{mito}}{K_{eq}^{Aco}}}{1 + \frac{Cit_{mito}}{K_m^{Cit}} + \frac{IsoCit_{mito}}{K_m^{IsoCit}}}$$

$$K_{eq}^{Aco} = 0.067$$

$$K_m^{Cit} = 0.48$$

$$K_m^{IsoCit} = 0.12$$

NAD-dependent isocitrate dehydrogenase [20] [21] [22] [23] [24]

(IsoCit + NAD -> akg + NADH)

$$v_{icdh} = V_{\max}^{icdh} \left(\frac{IsoCit_{mito}^{n^{IsoCit}}}{IsoCit_{mito}^{n^{IsoCit}} + (K_m^{IsoCit})^{n^{IsoCit}}} \right) \left(\frac{NAD_{mito}}{NAD_{mito} + K_m^{NAD} \cdot \left(1 + \frac{NADH_{mito}}{K_i^{NADH}} \right)} \right)$$

$$n^{IsoCit} = 1.9$$

$$K_m^{IsoCit} = \frac{K_{m1}^{IsoCit}}{\left(1 + \left(\frac{Ca_{mito}}{K_a^{Ca}} \right)^{n^{Ca}} \right)} + K_{m2}^{IsoCit}$$

$$K_{m1}^{IsoCit} = 0.11$$

$$K_{m2}^{IsoCit} = 0.06$$

$$K_a^{Ca} = 0.0074$$

$$n^{Ca} = 2$$

$$K_m^{NAD} = 0.091$$

$$K_i^{NADH} = 0.0041$$

α -ketoglutarate dehydrogenase [25-29], [27], [28], [26],

(akg + NAD + CoA -> SucCoA + NADH)

$$v_{akdhc} = V_{\max}^{akdhc} \left(1 - \frac{Ca_{mito}}{Ca_{mito} + K_i^{Ca}} \right) \left(\frac{akg_{mito}}{akg_{mito} + K_m^{akdhc}} \right) \left(\frac{NAD_{mito}}{NAD_{mito} + K_m^{NAD} \cdot \left(1 + \frac{NADH_{mito}}{K_i^{NADH}} \right)} \right) \left(\frac{CoA}{CoA + K_m^{CoA} \cdot \left(1 + \frac{SucCoA}{K_i^{SucCoA}} \right)} \right)$$

$$K_m^{akdhc} = \left(\frac{K_{m1}^{akdhc}}{\left(1 + \frac{Ca_{mito}}{K_{i-akg}^{Ca}}\right)} + K_{m2}^{akgh} \right) \left(1 + \frac{NADH_{mito}}{K_{i-akg}^{NADH}} \right)$$

$$K_{m1}^{akdhc} = 2.5$$

$$K_m^{NAD} = 0.021$$

$$K_i^{NADH} = 0.0045$$

$$K_m^{CoA} = 0.0013$$

$$K_i^{SucCoA} = 0.0045$$

Succinyl-CoA Synthetase [30], [31], [32],[33]

(SucCoA + ADP + P <-> Succ + CoA + ATP)

$$K_{eq-succoas} = 3.63$$

$$v_{succoas-atp} = V_{max-succoas-atp} \left(1 + A_{max}^P \cdot \left(\frac{P_{mito}^{n^P}}{P_{mito}^{n^P} + (K_m^P)^{n^P}} \right) \right) \left(\frac{SucCoA_{mito} \cdot ADP_{mito} \cdot P_{mito} - \frac{Succ_{mito} \cdot CoA_{mito} \cdot ATP_{mito}}{K_{eq-succoas}}}{\left(1 + \frac{SucCoA_{mito}}{K_m^{SucCoA}} \right) \left(1 + \frac{ADP_{mito}}{K_m^{ADP}} \right) \left(1 + \frac{P_{mito}}{K_m^P} \right) + \left(1 + \frac{Succ_{mito}}{K_m^{Succ}} \right) \left(1 + \frac{CoA_{mito}}{K_m^{CoA}} \right) \left(1 + \frac{ATP_{mito}}{K_m^{ATP}} \right) - 1} \right)$$

$$A_{max}^P = 1.2$$

$$K_m^P = 2.5$$

$$n^P = 3$$

$$K_m^{SucCoA} = 0.041$$

$$K_m^{ADP} = 0.25$$

$$K_m^P = 0.72$$

$$K_m^{Succ} = 1.6$$

$$K_m^{CoA} = 0.056$$

$$K_m^{ATP} = 0.017$$

Succinatedehydrogenase [34], [35]

(Succ + Q <-> Fum + QH₂)

$$v_{succdh} = V_{max-succdh} \left(\frac{Succ_{mito} \cdot Q_n - \frac{Fum_{mito} \cdot (QH_2)_n}{K_{eq-succdh}}}{Succ_{mito} + K_m^{Succ} \left(1 + \frac{Mal_{mito}}{K_i^{Mal}} \right)} \right)$$

$$K_{eq-succdh} = \exp\left(\frac{25 \cdot F}{R \cdot T}\right)$$

$$K_m^{Succ} = 1.6$$

$$K_i^{Mal} = 2.2$$

Fumerase [36, 37]

(Fum <-> Mal)

$$v_{fum} = V_{\max-fum} \left(\frac{Fum_{mito} - \frac{Mal_{mito}}{K_{eq-fum}}}{1 + \frac{Fum_{mito}}{K_m^{Fum}} + \frac{Mal_{mito}}{K_m^{Mal}}} \right)$$

$$K_{eq-fum} = 4.4$$

$$K_m^{Fum} = 0.14$$

$$K_m^{Mal} = 0.3$$

Malatedehydrogenase [24], [38], [39]

(Mal + NAD <-> Oxa + NADH)

$$v_{mdh} = V_{\max-mdh} \left(\frac{Mal_{mito} \cdot NAD_{mito} - \frac{Oxa_{mito} \cdot NADH_{mito}}{K_{eq-mdh}}}{\left(1 + \frac{Mal_{mito}}{K_m^{Mal}}\right) \left(1 + \frac{NAD_{mito}}{K_m^{NAD}}\right) + \left(1 + \frac{Oxa_{mito}}{K_m^{Oxa}}\right) \left(1 + \frac{NADH_{mito}}{K_m^{NADH}}\right) - 1} \right)$$

$$K_{eq-mdh} = 1.2 \cdot 10^{-3}$$

$$K_m^{Mal} = 0.145$$

$$K_m^{NAD} = 0.06$$

$$K_m^{Oxa} = 0.017$$

$$K_m^{NADH} = 0.044$$

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