

Modelagem térmica dos membros superiores

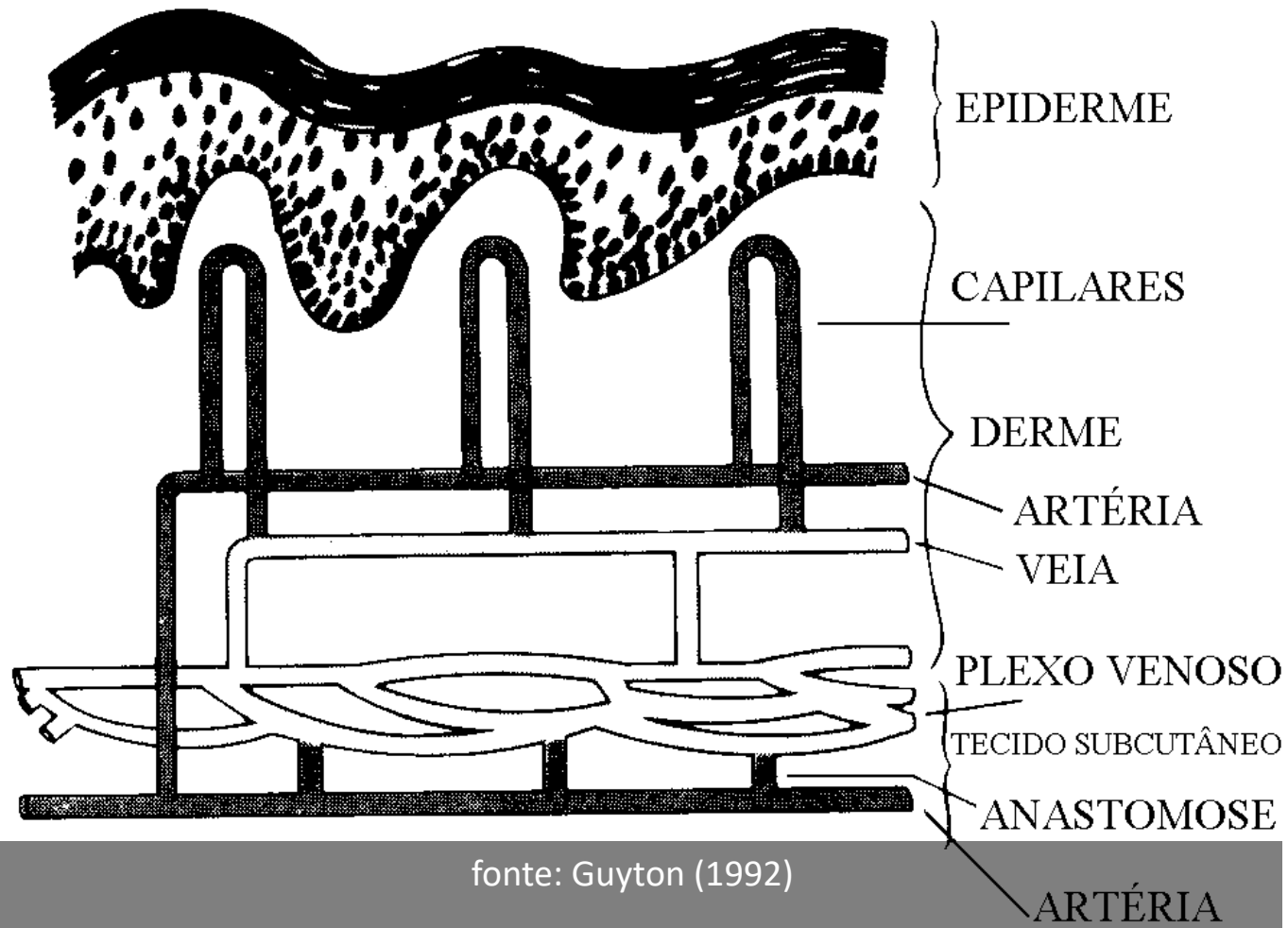
Prof. Maurício Silva Ferreira

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Sala TS – 33

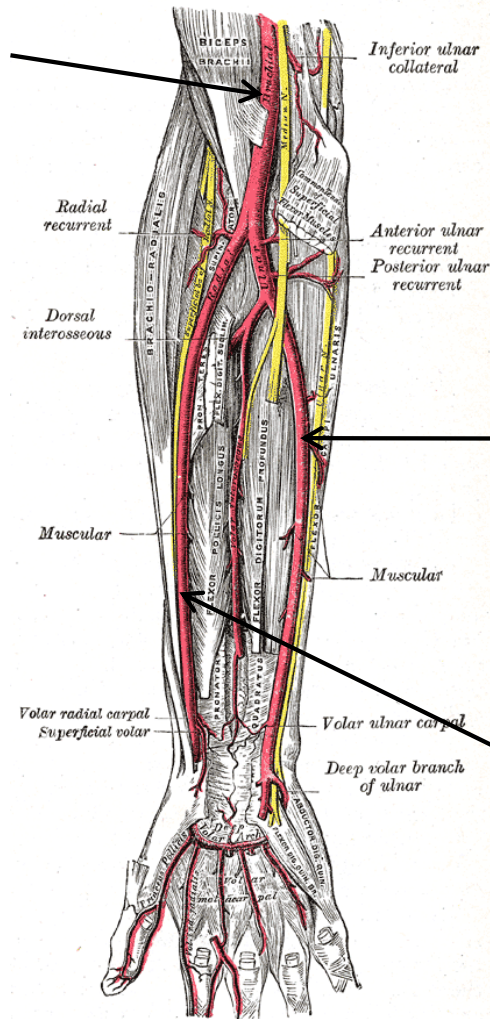
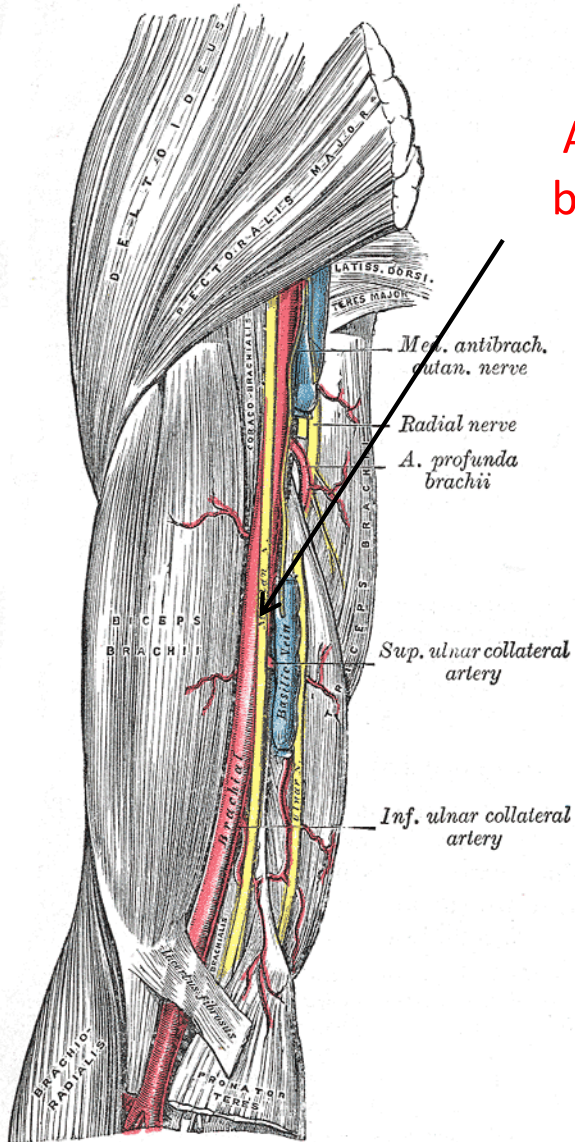
email: mauserreira@usp.com

Esquema da circulação cutânea

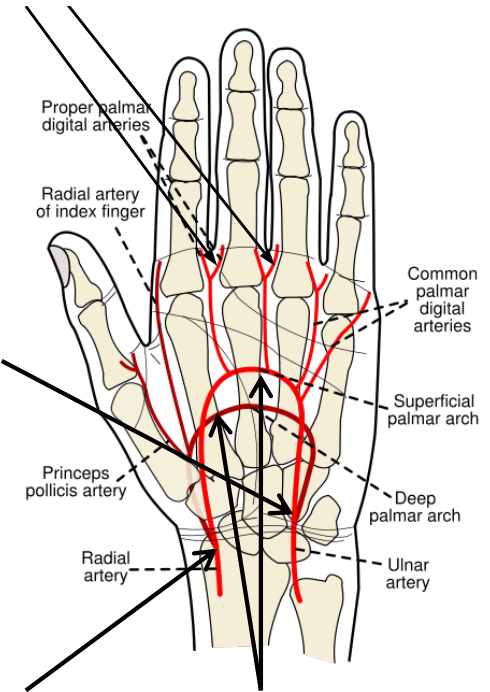


Anatomia dos membros superiores

Artérias



Artérias digitais



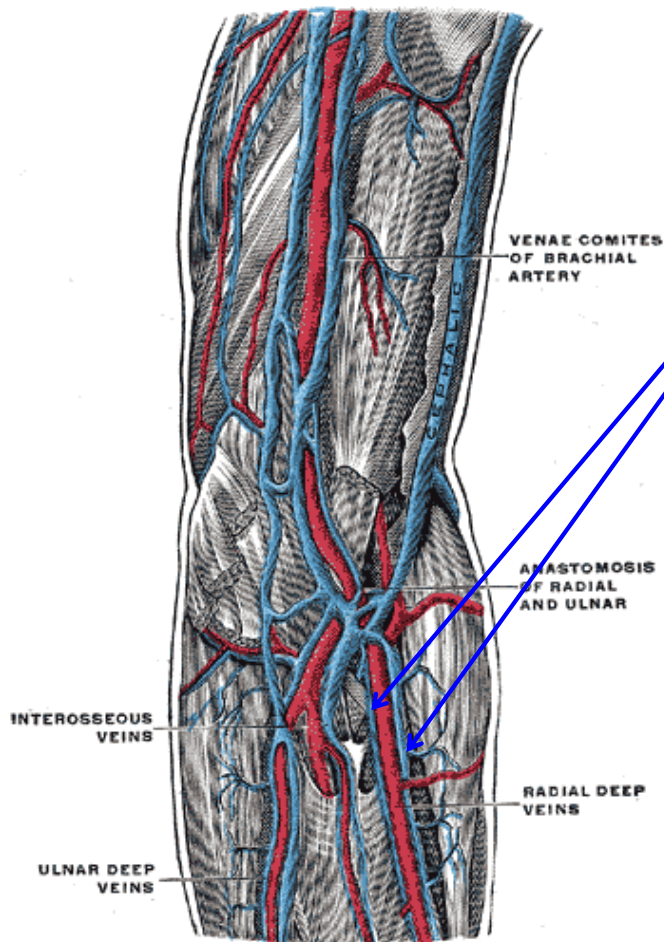
Artéria ulnar

Artéria radial

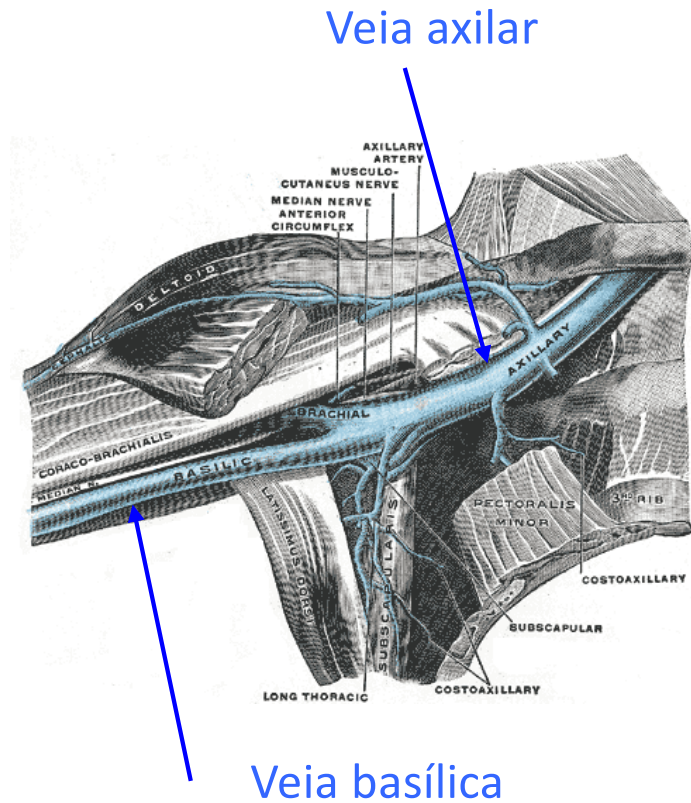
Arcos palmares

Anatomia dos membros superiores

Veias profundas

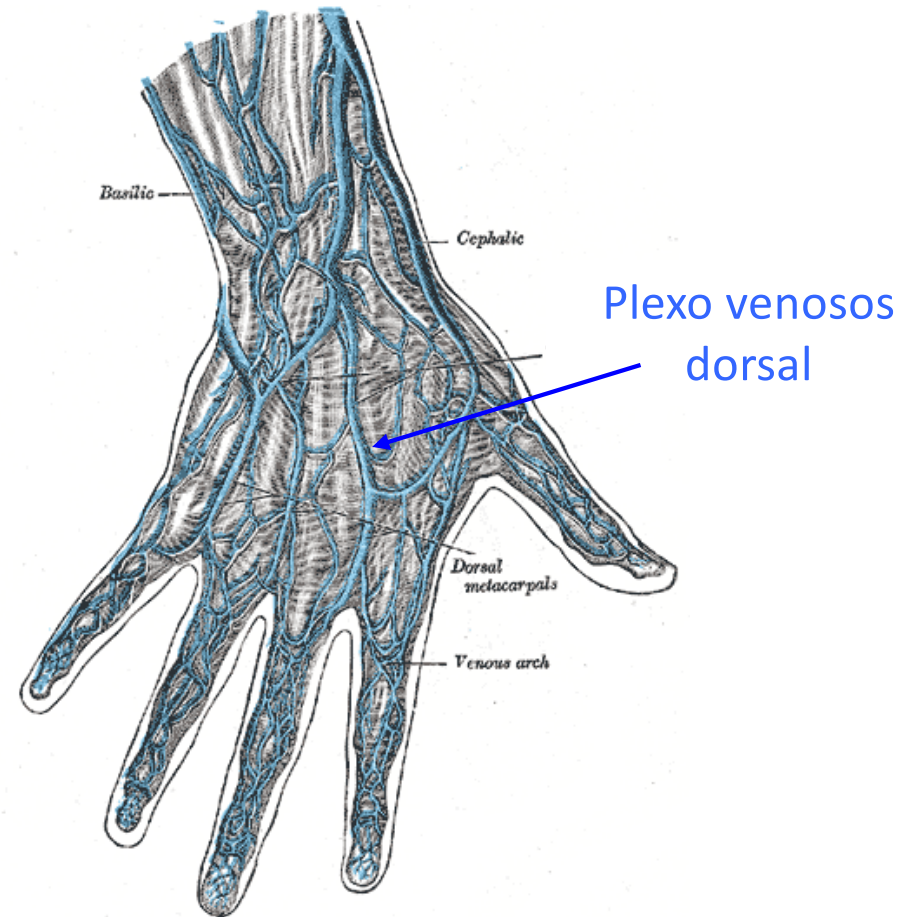
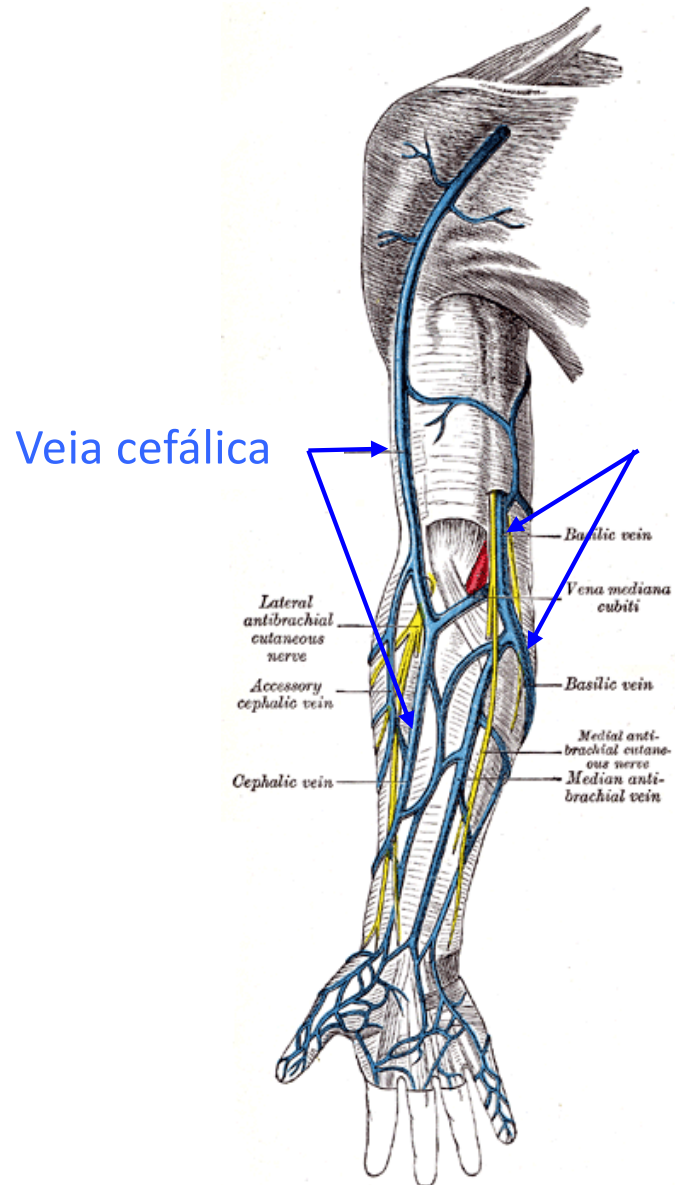


Venae
comitantes

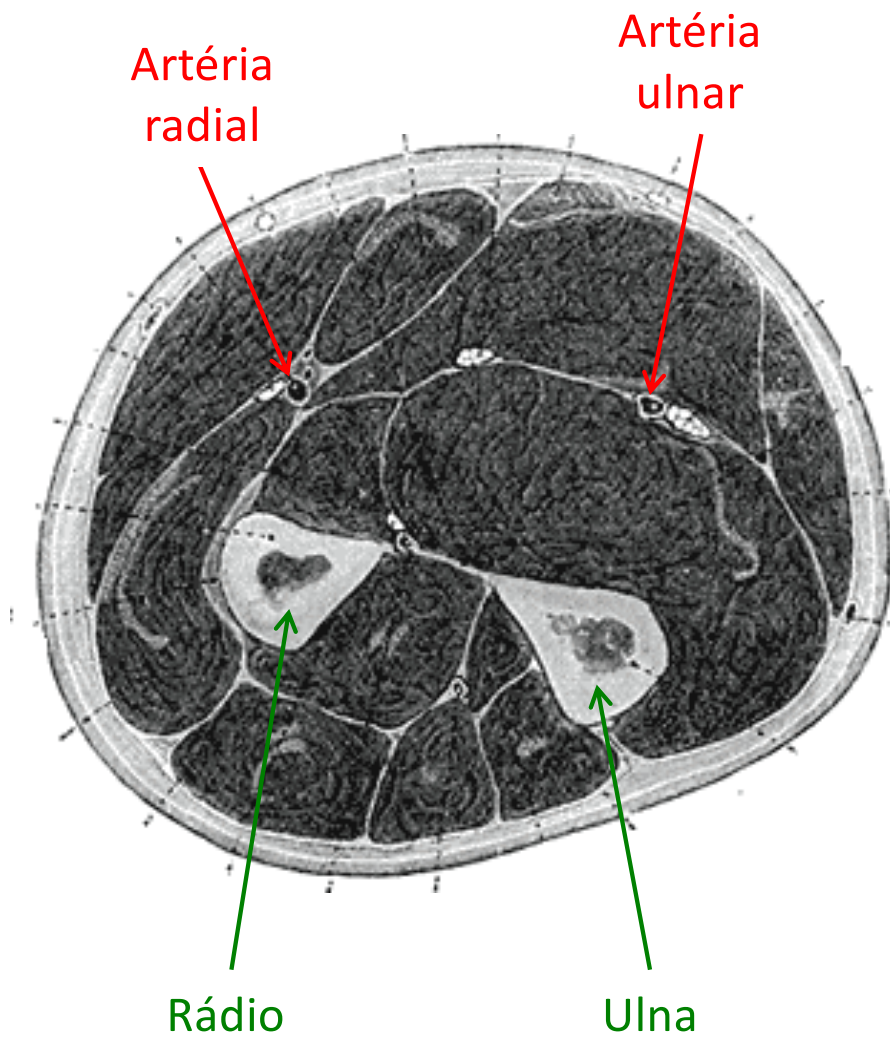
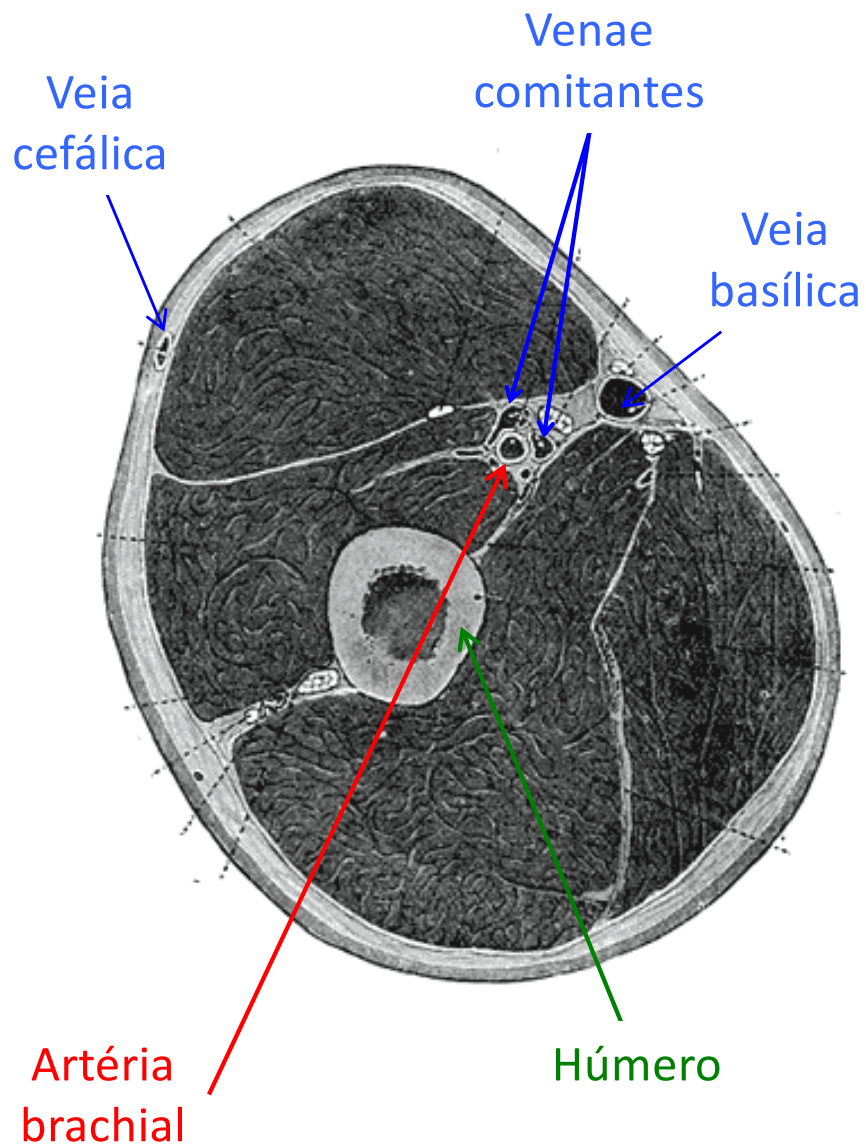


Anatomia dos membros superiores

Veias superficiais



Anatomia dos membros superiores



Transferência de calor nos membros superiores

- FERREIRA; YANAGIHARA (2011):
- Regime permanente;
- Oito cilindros de seção circular (braço, antebraço, mão e dedos);
- Duas camadas concêntricas (núcleo e pele);
- Macro e micro circulação.

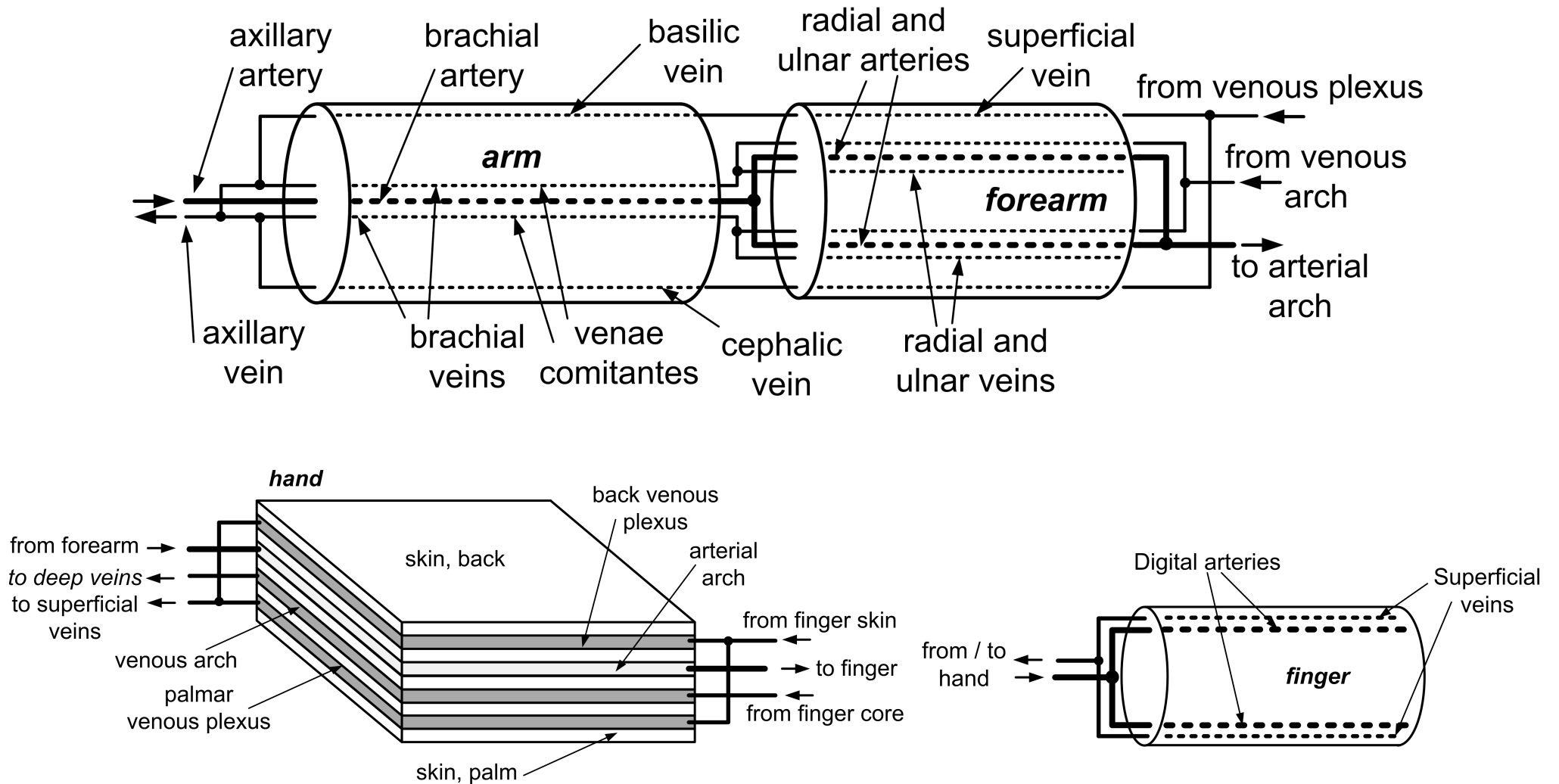
Modelo de Ferreira e Yanagihara

Parâmetros geométricos dos vasos

Vessel	Number	L / m	D / mm	D^* / mm	x / mm
Brachial artery	1	0.31	4.0	3.5-4.4	24
Ulnar artery	1	0.28	2.6	1.8-4.3	17
Radial artery	1	0.28	2.6	1.9-3.1	17
Arterial palmar arch	10	-----	1.6	1.4-1.8	---
Proper palmar digital artery	2 ⁺	0.08	1.0	0.5-1.3	7.5
Brachial vein	2	0.31	2.9	2.9-3.8	21
Radial vein	2	0.28	2.0	1.6	15
Ulnar vein	2	0.28	2.0	2.3	15
Venous arch	10	-----	1.6	-----	---
Cephalic vein	1	0.31	3.3	1.9-3.8	8
Basilic vein	1	0.31	3.3	1.9-5.1	8
Superficial vein	6	0.28	1.8	1.8	4
Venous palmar plexus	10	-----	1.0	-----	---
Venous back plexus	5	-----	1.8	-----	---
Palmar digital vein	4 ⁺	0.08	1.0	0.8-1.3	8.5

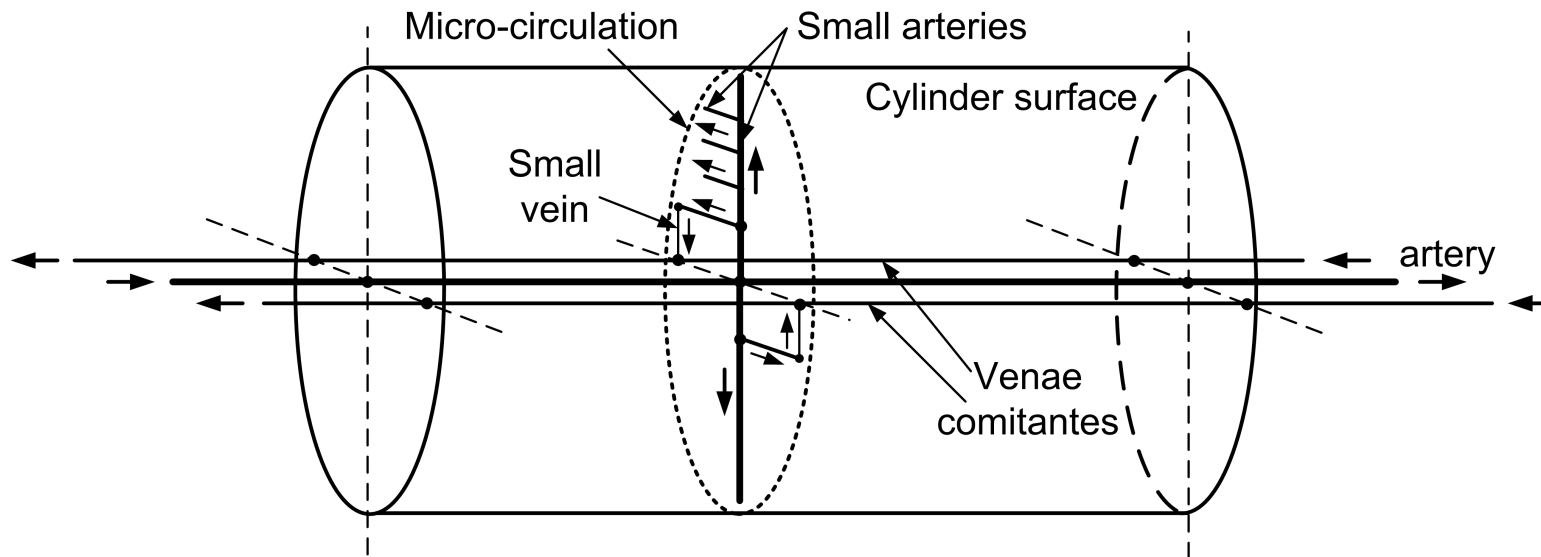
Modelo de Ferreira e Yanagihara

Arranjo da macro-circulação (vasos com $D > 1000\mu\text{m}$):



Modelo de Ferreira e Yanagihara

Arranjo da micro-circulação ($D < 1000\mu\text{m}$ vasos com $D > 1000\mu\text{m}$):



Arteries:

$$\text{Brachial Artery BF in} = \text{Arm BF} + \text{Forearm BF} + \text{Hand BF} + 5 \times \text{Finger BF} \quad (1)$$

$$\text{Brachial Artery BF out} = \text{Forearm BF} + \text{Hand BF} + 5 \times \text{Finger BF} \quad (2)$$

$$\text{Ulnar Artery BF in} = \text{Radial Artery BF in} = \text{Brachial Artery BF out} \div 2 \quad (3)$$

$$\text{Ulnar Artery BF out} = \text{Radial Artery BF out} = (\text{Hand BF} + 5 \times \text{Finger BF}) \div 2 \quad (4)$$

$$\text{Arterial Arch in} = \text{Hand BF} + 5 \times \text{Finger BF} \quad (5)$$

$$\text{Arterial Arch out} = 5 \times \text{Finger BF} \quad (6)$$

$$\text{Palmar Digital Artery BF in} = \text{Finger BF} \div 2 \quad (7)$$

$$\text{Palmar Digital Artery BF out} = 0 \quad (8)$$

Veins:

$$\text{Brachial Vein BF in} = (\text{Forearm BF} + \text{Hand cr BF} + 5 \times \text{Finger cr BF} + \beta) \div 2 \quad (9)$$

$$\text{Brachial Vein BF out} = (\text{Arm BF} + \text{Forearm BF} + \text{Hand cr BF} + 5 \times \text{Finger cr BF} + \beta) \div 2 \quad (10)$$

$$\text{Ulnar Vein BF in} = \text{Radial Vein BF in} = (\text{Hand cr BF} + 5 \times \text{Finger cr BF} + \beta) \div 4 \quad (11)$$

$$\text{Ulnar Vein BF out} = \text{Radial Vein BF out} = (\text{Forearm BF} + \text{Hand cr BF} + 5 \times \text{Finger cr BF} + \beta) \div 4 \quad (12)$$

$$\text{Venous Arch BF in} = 5 \times \text{Finger cr BF} + \gamma \quad (13)$$

$$\text{Venous Arch BF out} = \text{Hand BF} + 5 \times \text{Finger cr BF} + \beta \quad (14)$$

$$\text{Cephalic Vein BF in} = \text{Basilic Vein BF in} = (\text{Hand sk BF} + 5 \times \text{Finger sk BF}) \times \alpha \div 2 \quad (15)$$

$$\text{Cephalic Vein BF out} = \text{Basilic Vein BF out} = \text{Cephalic Vein BF in} \quad (16)$$

$$\text{Superficial Vein BF in} = (\text{Hand sk BF} + \text{Finger sk BF}) \times \alpha \div 6 \quad (17)$$

$$\text{Superficial Vein BF out} = \text{Superficial Vein BF in} \quad (18)$$

$$\text{Palmar Venous Plexus BF in} = 5 \times \text{Finger sk BF} \times \delta \quad (19)$$

$$\text{Palmar Venous Plexus BF out} = \text{Palmar Venous Plexus BF in} \quad (20)$$

$$\text{Back Venous Plexus BF in} = 5 \times \text{Finger sk BF} \times (1 - \delta) \quad (21)$$

$$\text{Back Venous Plexus BF out} = \text{Back Venous Plexus BF in} \quad (22)$$

$$\text{Digital Vein BF in} = 0 \quad (23)$$

$$\text{Digital Vein BF out} = \text{Finger BF} \div 4 \quad (24)$$

$$\beta = \text{Hand sk BF} + 5 \times \text{Finger sk BF} * (1 - \alpha) \quad (25)$$

$$\gamma = 5 \times \text{Finger sk BF} * (1 - \alpha) \quad (26)$$

Balanço de massa:

Modelo de Ferreira e Yanagihara

Transferência de calor no tecido:

$$\left[\frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) + k \frac{\partial^2 T}{\partial x^2} \right] + \underbrace{w_{bl} \rho_{bl} c_{bl} [T_{ar} - T]}_{\text{T.C. com o tecido - micro-circulação}} + \underbrace{q}_{\text{Met.}} + \underbrace{u_{at} [T_{ar} - T]}_{\text{T.C. c/ o tecido - macro-circulação}} + \underbrace{u_{vt} [T_{ve} - T]}_{\text{T.C. Entre veia e tecido}} + \underbrace{u_{st} [T_{vs} - T]}_{\text{T.C. Entre veia superficial e tecido}} = 0$$

Condução de calor no tecido
T.C. com o tecido – micro-circulação
Met.
T.C. c/ o tecido – macro-circulação
T.C. Entre veia e tecido
T.C. Entre veia superficial e tecido

Condições de contorno:

$$-k_{sk} \frac{\partial T}{\partial r} \Big|_{r=R} = h(T - T_{op}) + q_{ev} \quad \text{Convecção, radiação e evaporação}$$

$$\frac{\partial T}{\partial r} \Big|_{r=0} = 0 \quad \text{Simetria}$$

Tampas adiabáticas

Modelo de Ferreira e Yanagihara

Equações diferenciais do sangue

Arterial: $\rho_{bl} Q_{ar} c_{bl} \frac{dT_{ar}}{dx} + h_{at} \pi D_{ar} (T_{ar} - T) = 0$

$$T_{ar} = T_{ar,in} \text{ em } x = 0$$

Venoso: $\rho_{bl} Q_{ve} c_{bl} \frac{dT_{ve}}{dx} + h_{vt} \pi D_{ve} (T_{ve} - T) + 2\pi \rho_{bl} c_{bl} \int_0^{D/2} w_{bl} (T_{ve} - T) r dr = 0$

$$T_{ve} = T_{ve,in} \text{ em } x = L$$

Venoso superficial: $\rho_{bl} Q_{vs} c_{bl} \frac{dT_{vs}}{dx} + h_{st} \pi \cdot D_{vs} \cdot (T_{vs} - T) = 0$ $Nu_D = 4 + 0.155 e^{1.58 \log Gz_x}$

$$Gz_x < 1000$$

$$T_{vs} = T_{vs,in} \text{ em } x = L$$

Modelo de Ferreira e Yanagihara

Table 1

Geometrical parameters

Body segment	L / m	D / m	th / m	A / m^2	V / m^3	e / mm
<i>Arm</i>	0.31	0.085	-----	828×10^{-4}	$1,759 \times 10^{-6}$	4.5
<i>Forearm</i>	0.28	0.067	-----	589×10^{-4}	987×10^{-6}	4.5
<i>Hand</i>	0.10	0.085	0.044	214×10^{-4}	374×10^{-6}	----
<i>Finger</i>	0.07	0.021	-----	46.2×10^{-4}	24.3×10^{-6}	2.0

where L is the cylinder length, D is the cylinder diameter (in the hand D means width), th is the segment thickness, A is the segment superficial area, V is the segment volume, and e is the skin layer thickness.

Table 2

Heat transfer parameters

		Cold ($T_{op} = 10 \text{ }^\circ\text{C}$)	Neutral ($T_{op} = 30 \text{ }^\circ\text{C}$)	Hot ($T_{op} = 40 \text{ }^\circ\text{C}$)
Body segment	$h / (\text{W}/\text{m}^2 \cdot \text{K})$	$q_{ev} / (\text{W}/\text{m}^2)$	$q_{ev} / (\text{W}/\text{m}^2)$	$q_{ev} / (\text{W}/\text{m}^2)$
<i>Arm</i>	8.1	5	4	75
<i>Forearm</i>	8.6	5	4	75
<i>Hand</i>	8.2	10	43	70
<i>Finger</i>	11.0	5	4	75

Modelo de Ferreira e Yanagihara

Transferência de calor na mão:

Dorso da mão:

$$\frac{(hA)_{vbt}}{2} (T_{vb} - T_{sk,b}) - \frac{(hA)_{hd}}{2} [(T_{sk,b} - T_{op}) - q_{ev,hd}] + \rho_{bl} c_{bl} Q_{sk,b} (T_{ar} - T_{sk,b}) + \frac{M_{sk}}{2} = 0$$

Arco arterial:

$$\rho_{bl} c_{bl} Q_{ar,in} (T_{ar,in} - T_{ar}) - (hA)_{art} (T_{ar} - T_{cr}) = 0$$

Arco venoso:

$$\rho_{bl} c_{bl} Q_{vs,in} \delta (T_{vs,in} - T_{vp}) - \frac{(hA)_{vbt}}{2} (T_{vp} - T_{sk,p}) - \frac{(hA)_{vbt}}{2} (T_{vp} - T_{cr}) = 0$$

Modelo de Ferreira e Yanagihara

Primeiro conjunto de dados (Salloum et al., 2007)

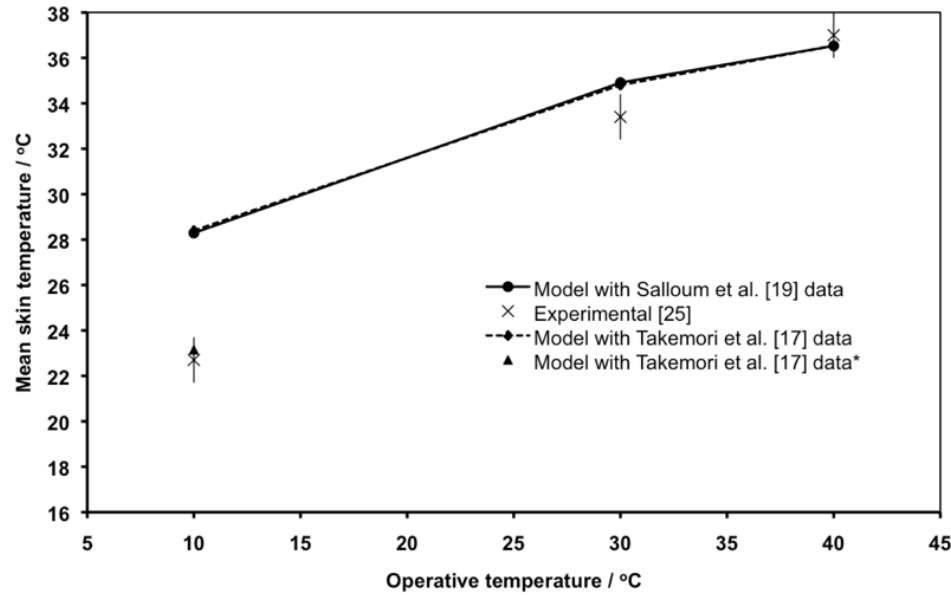
Body segment	Minimum <i>sk BF</i> / (cm ³ /h)	Basal <i>sk BF</i> / (cm ³ /h)	Maximum <i>sk BF</i> / (cm ³ /h)	<i>cr BF</i> / (cm ³ /h)
<i>Arm</i>	0	910	8,319	2,667
<i>Forearm</i>	0	508	5,553	1,758
<i>Hand + Fingers</i>	627	1,114	4,454	388
<i>Hand</i>	473	840	3,362	293
<i>Finger</i>	30.7	54.6	218	19.0

Segundo conjunto de dados (Takemori et al., 1995)

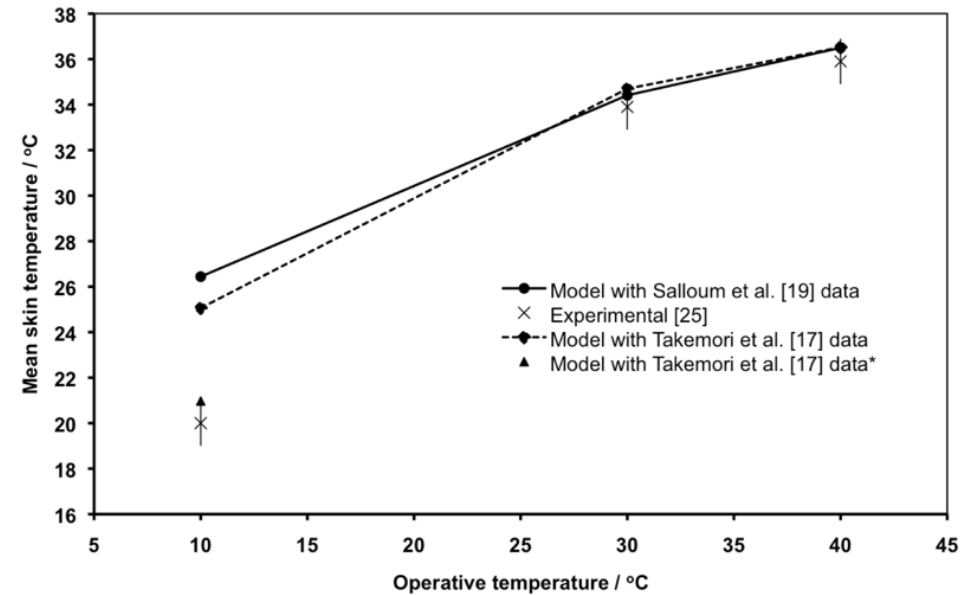
Body segment	Minimum <i>sk BF</i> / (cm ³ /h)	Basal <i>sk BF</i> / (cm ³ /h)	Maximum <i>sk BF</i> / (cm ³ /h)	<i>cr BF</i> / (cm ³ /h)
<i>Arm</i>	0	488	8,319	2,941
<i>Forearm</i>	0	272	5,553	1,643
<i>Hand + Fingers</i>	0	4,699	5,723	264
<i>Hand</i>	0	3,547	4,320	199
<i>Finger</i>	0	230	281	12.9

Modelo de Ferreira e Yanagihara - Validação

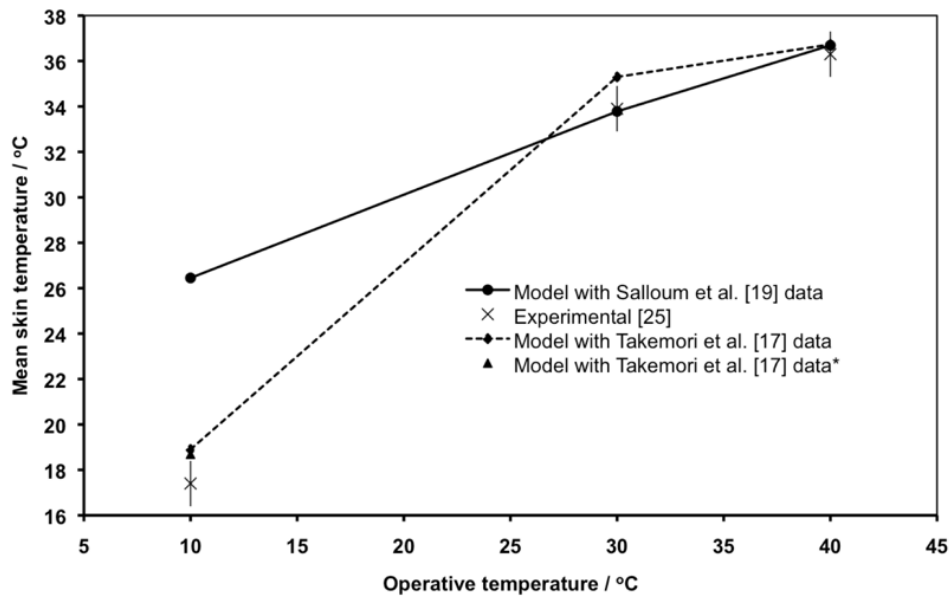
Braço



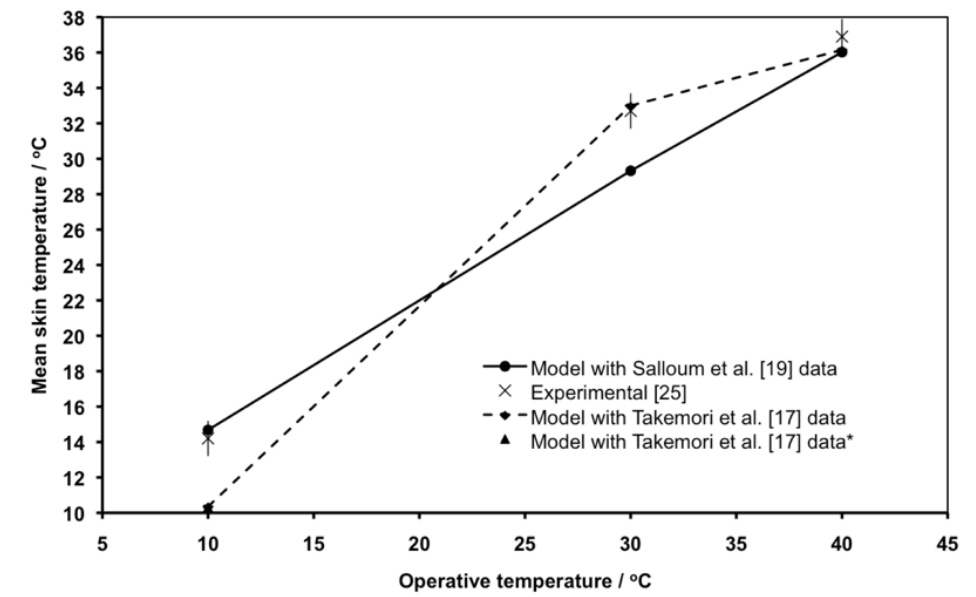
Antebraço



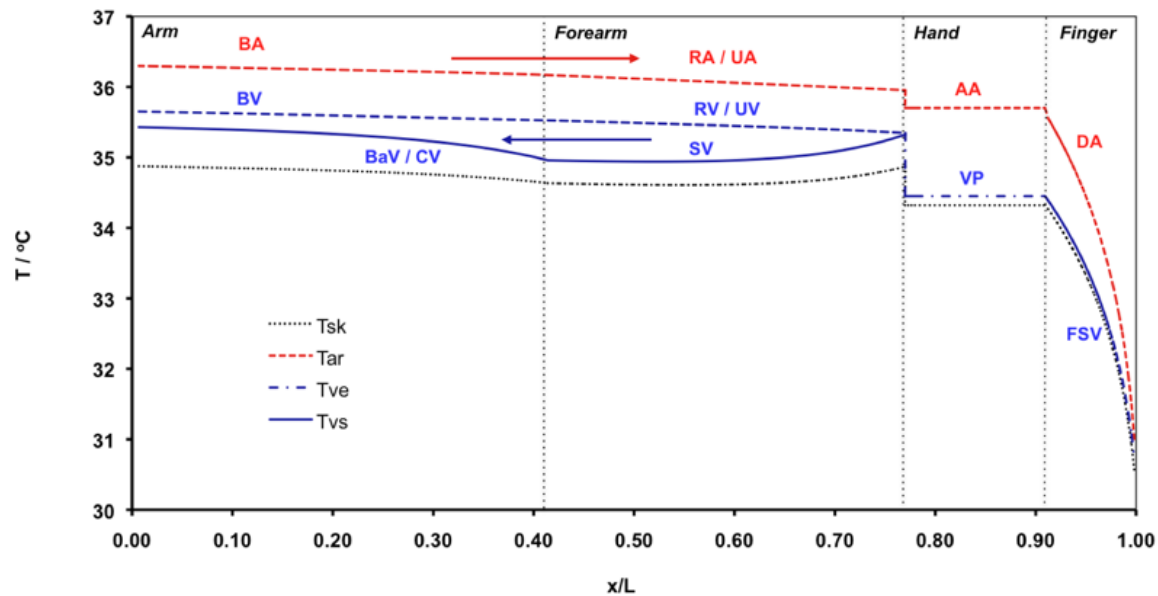
Mão



Dedo

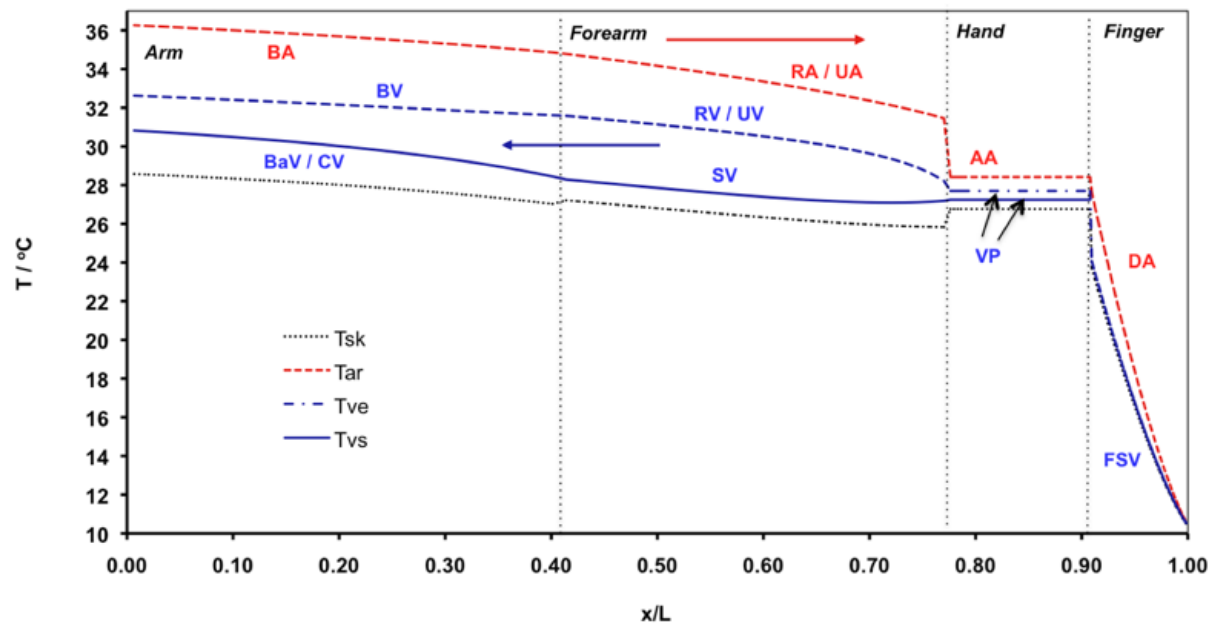


Modelo de Ferreira e Yanagihara - Resultados



$T_{op} = 30^\circ\text{C}$

$T_{op} = 10^\circ\text{C}$



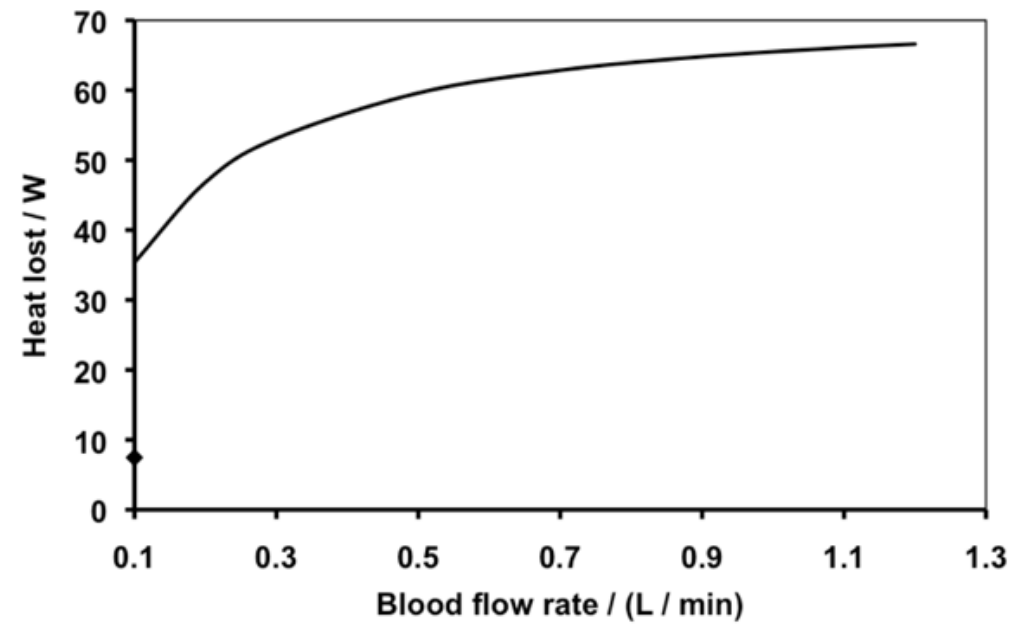
Modelo de Ferreira e Yanagihara - Resultados

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www.avacen.com

Calor rejeitado para o ambiente por um membro superior



Referências

- Ferreira, M.S. and Yanagihara, J.I., 2011, “A New Heat Transfer Model of the Human Upper Limbs,” ASME Journal of Biomechanical Engineering?
- Takemori, T., Nakajima, T., and Shoji, Y., 1995, “A Fundamental Model of the Human Thermal System for the Prediction Comfort,” Heat Transfer – Japanese Research, 24, pp. 147-165.
- Salloum, M., Ghaddar, N., and Ghali, K., 2007, “A New Transient Bioheat Model of the Human Body and its Integration to Clothing Models,” International Journal of Thermal Sciences, 46, pp. 371–384.