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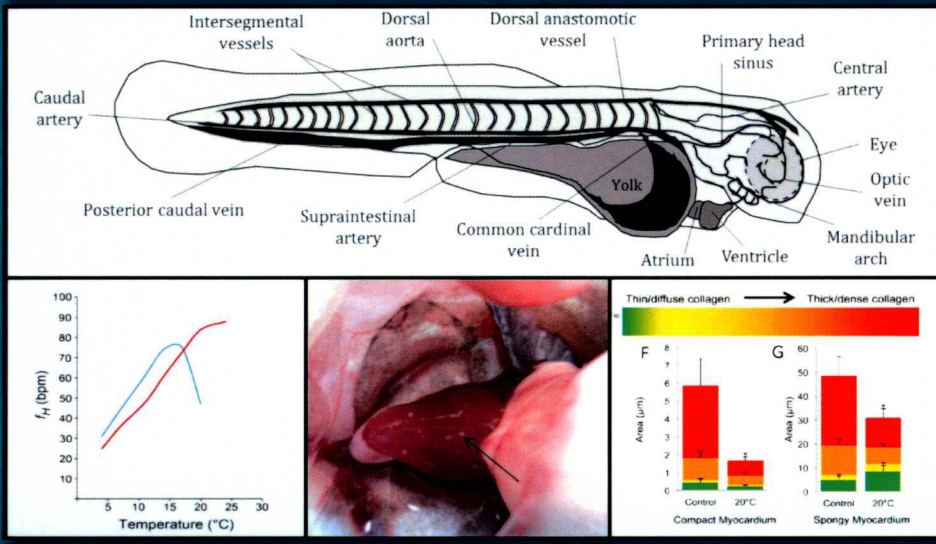
The Cardiovascular System

Development, Plasticity and Physiological Responses



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THE CARDIOVASCULAR SYSTEM: DEVELOPMENT, PLASTICITY AND PHYSIOLOGICAL RESPONSES

Fish Physiology

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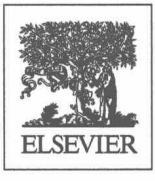

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Cover Images: Starting at top and moving clockwise. Top, Cardiovascular morphology of a 3 day post-fertilization zebrafish embryo (Burggren, Dubansky and Bautista, 2017; Chapter 2); Bottom right, Influence of cold acclimation on collagen content of the zebrafish heart (Gillis and Johnston, 2017; Chapter 3); Bottom middle, Visible xenomas on the surface of an Atlantic cod heart (Powell and Yousaf, 2017; Chapter 7); Bottom left, Effects of acute changes in temperature on the resting heart rate (f_H) of cold- (blue lines) and warm- (red lines) acclimated rainbow trout (Eliason and Anttila, 2017; Chapter 4).

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ABBREVIATIONS

2,3-DPG 2,3-diphosphoglycerate
4-HT 4-hydroxytamoxifen
5-HD sodium 5-hydroxydecanoic acid
5-HT 5-hydroxytryptamine (serotonin)
A atrium
AA arachidonic acid
A_o ventral aorta
ABA afferent branchial arteries
ACE angiotensin-converting enzyme
ACH acetylcholine
ACV anterior cardinal vein
AD adrenaline
ADO adenosine
ADP adenosine diphosphate
ADP_{50} ratio of atrial to ventricular action potential duration
AE anion exchange or Cl^-/HCO_3^- exchanger
AFA afferent filamental arteries
AGD amoebic gill disease
AIP AHR-interacting protein
AKAP A-kinase anchoring protein
AHR aryl hydrocarbon receptor
ALAs afferent lamellar arterioles
AMP adenosine monophosphate
AMPA alpha-amino-3-hydroxy-5-methylisoxazole-4-propionic acid
AMPK AMP-activated protein kinase
AMs adrenomedullins
ANG-1 angiopoietin 1
AngII angiotensin II
ANP atrial natriuretic peptide
ANRT AHR nuclear receptor translocator

AOP adverse outcome pathway
APC antigen-presenting cells
AP action potential
AR adrenoreceptor
ARC activity-regulated cytoskeleton-associated protein
ASCV Atlantic salmon calcivirus
ASN anterior spinal nerve
ASR aquatic surface respiration
AT_1 angiotensin 1 receptor
AT_2 angiotensin 2 receptor
ATP adenosine triphosphate
A.U. arbitrary units
A-VO_2 difference between the oxygen content of arterial and venous blood, also known as tissue oxygen extraction
AV atrioventricular
AVP atrioventricular plexus
AVR atrioventricular region
AVT arginine vasotocin
Ax axillary body
AZ acetazolamide
α-AR alpha adrenoreceptor
β_2-AR β_2-type adrenoreceptor
BA bulbus arteriosus
β_b capacitance of blood for O_2
BCR branchial cardiac ramus
BCT branchiocardiac nerve trunk
BKs bradykinins
$BL\,s^{-1}$ swimming speed expressed as body lengths per second
B_{max} receptor density
BMP bone morphogenic protein
BN branchial nerve
β-NHE β-adrenergic Na^+–H^+ exchanger
BNP brain natriuretic peptide
bpm beats per minute
BV branchial vein
BZ benzolamide
C conus or compliance
CA carbonic anhydrase
Ca^{2+} calcium
$[Ca^{2+}]_i$ intracellular free Ca^{2+} concentration
CAM chorioallantoic membranes
cAMP cyclic adenosine monophosphate
CaN calcineurin

C_aO_2 arterial O_2 content
CASQ2 calsequestrin 2
CAT catecholamines
CaTF Ca^{2+} sensitive transcription factors
CBF coronary blood flow
CBS cystathionine beta-synthase
CCO cytochrome *c* oxidase
CCK cholecystokinin
CD73 ecto-5′-nucleotidase
CdA caudal artery
CDβ β COMMA-D cell line engineered to express β-galactosidase
CdV caudal vein
CgA chromogranin A
cGMP cyclic guanosine monophosphate
CGRP calcitonin gene-related peptide
ChAT choline acetyltransferase
CICR Ca^{2+}-induced Ca^{2+}-release
CK creatine kinase
cKit receptor tyrosine kinase
cmlc myosin light chain polypeptide
CMA coeliacomesenteric artery
CMS cardiomyopathy syndrome
cNOS constitutive nitric oxide synthase
CNP C-type natriuretic peptide
CNS central nervous system
CO carbon monoxide
CO_2 carbon dioxide
C_{O_2} content of O_2 in blood
CoA coenzyme A
COL1A1 collagen Type I alpha 1 chain gene
COX cyclooxygenase
CP creatine phosphate
CPCs cardiac progenitor cells
CPO cardiac power output
CPO_{max} maximum cardiac power output
CPO_{sys} systemic cardiac power output
CPT carnitine palmitoyltransferase
Cr creatine
CR cagal cardiac ramus
CrA carotid arteries
CS citrate synthase
C_s the slope of the capacitance curve
CSE cystathionine gamma-lyase

CSPN cardiac spinal pre-ganglionic neuron
CSQ calsequestrin
CSQ2 cardiac isoform of calsequestrin
CST catestatin
CTGF connective tissue growth factor
CT_{max} critical thermal maximum
cTnC cardiac troponin C
cTnI cardiac troponin I
cTnT cardiac troponin T
CV conal valves
C_vO_2 venous O_2 content
CVS central venous sinus
CVPN cardiac vagal pre-ganglionic neuron
CYP1A cytochrome P450 1A
CYS cysteine
d day
DA dorsal aorta
DC ductus of Cuvier
DDT dichlorodiphenyltrichloroethane
DIDS 4,4′-diisothiocyano-2,2′-stilbenedisulfonic acid
DLCs dioxin-like compounds
DMO 5,5-dimethyl-2,4-oxazolidinedione
DNA deoxyribonucleic acid
DPI days post-injury
DPF days post-fertilization
DPT days post-treatment
dsRNA double-stranded RNA
ΔG_{ATP} Gibbs free energy per mole of hydrolyzed ATP
ΔP change in pressure (pressure difference)
ΔpH_{a-v} arterial–venous pH difference
ΔP_V pressure gradient that drives venous return
$\Delta S_{a-v}O_2$ change in arterial–venous Hb–O_2 saturation (see below)
ΔV change in volume
$E_{a-v}O_2$ extraction of O_2 at the tissues
EBA efferent branchial arteries
E–C excitation–contraction
ECG electrocardiogram
ECM extracellular matrix
ECs endocardial cushions
EDCF endothelium-derived contracting factors
EDRF endothelium-derived relaxing factors
EE endocardial endothelium
EFAs efferent filamental arteries

EGCs eosinophilic granular cells
E_{ion} equilibrium potential
EIPA ethyl isopropyl amiloride
E_{K+} equilibrium potential for K^+
ELAs efferent lamellar arterioles
EM electron microscopy
E_m membrane potential
EMT epithelial-to-mesenchymal transition
E_{Na+} equilibrium potential for Na^+
eNOS endothelial nitric oxide synthase
EPA eicosapentanoic acid
EPDCs epicardial-derived cells
EPO erythropoietin
EPOR EPO receptor
ERG erythroblast transformation-specific -related gene
ERG channel ether-à-go-go-related gene K^+ channel
ERK extracellular signal-regulated kinase
ET endothelins
E–T excitation–transcription
ET-1 endothelin-1
ETA eicosatetranoic acid
F Faraday's constant
F_C flow rate through chamber
FGF fibroblast growth factor
f_H frequency of the heartbeat, or heart rate
f_{Hmax} maximum cardiac frequency or maximum heart rate
FP flow probe
FKBP12 12-kDa FK506-binding protein
f_R respiratory frequency
Fs Furans
G6P glucose-6-phosphate
Gα13 G protein subunit Gα13
GA gill arch
GBF gonad blood flow
GC guanylate cyclase
GF gill filaments
G_i inhibitory G protein
G_o gonad
GLUTs glucose transporter proteins
GPCR G protein-coupled receptor
GPI glycophosphatidylinositol
G_s stimulatory G protein
GTP guanosine triphosphate

G_u gut
H heart
h hour
H^+ hydrogen ion
Hb hemoglobin
[Hb] hemoglobin concentration
Hct hematocrit
HCN channel family of hyperpolarization-activated, cyclic nucleotide-gated, ion channels involved in controlling the pacemaker
HEK cells human embryonic kidney cells
HEP high energy phosphate
HH hedgehog
HIF-1 hypoxia inducible factor 1
HIF 1-α hypoxia inducible factor 1-α
HK hexokinase
HO heme oxygenase.
HOAD β-hydroxyacyl CoA dehydrogenase
hpf hours post-fertilization
HPV hepatic portal vein
HSMI heart and skeletal muscle inflammation
HSP heat shock proteins
H_2S hydrogen sulfide
HV hepatic vein
I_{Ca} Ca^{2+} current
I_{CaL} L-type Ca^{2+} current
I_{CaT} T-type Ca^{2+} current
ICN intracardiac neuron
ICNS intracardiac nervous system
I_f pacemaker current, "funny" current
IFNα interferon alpha
IFNγ interferon gamma
IGF-1 insulin-like growth factor 1
IgM immumoglobulin
I_{KACH} acetylcholine-activated inward rectifier current
I_{KATP} ATP-sensitive inward rectifier current
I_{K1} inward-rectifier K^+ current
I_{Kr} delayed-rectifier K^+ current
I_{Na} Na^+ current
I_{NCX} Na^+–Ca^{2+} exchange current
iNOS inducible NO synthase
ION_i intracellular "free" ion concentration
ION_e extracellular "free" ion concentration
IP_2 inositol diphosphate

IP_5 inositol pentaphosphate
IRK2 inwardly rectifying K^+ channel 2
I/R ischemia–reperfusion
ISA infectious salmon anemia
ISG15 interferon-stimulated gene 15
ISL1 transcription factor islet 1
ISO isoproterenol
JAK1 janus kinase 1
JNK C-jun NH_2 terminal kinase
JV jugular vein
K_{ATP} ATP-sensitive K^+ channels
K_{Ca} Ca^{2+}-activated K^+ channels
K_{cat} turnover number
K_d receptor binding affinity
kDa kilo Dalton
K_{eq} equilibrium constant
K^+ potassium ion
K^+/Cl^- potassium chloride co-transport
$[K^+]_e$ extracellular K^+ concentration
$[K^+]_i$ intracellular K^+ concentration
K_H hydration rate constant
KH7 blocker of soluble guanylate cyclase
k_i inhibition constant
Kir inward rectifier K^+ channels
L vessel length
La lamella
L-AA L-ascorbic acid
L-ARG L-arginine
LCV lateral cutaneous vein
LDA length-dependent activation
LDH lactate dehydrogenase
L-NMMA L-N^G-monomethyl-L-arginine
LTCC L-type Ca^{2+} channels
M_2R muscarinic type-2 receptor
MAPK mitogen-activated protein kinase
max dP/dt_{sys} maximal rate of pressure change during systole
max dP/dt_{dia} minimum rate of pressure change during diastole
M_b body mass
MCFP mean circulatory filling pressure
MCT monocarboxylate transporters
MD medulla
MHC major histocompatibility complex
min minute

miRNAs microRNAs
miR-133 microRNA 133
MLP muscle LIM protein
MMPs matrix metalloproteinases
$\dot{M}O_2$ rate of oxygen consumption
$\dot{M}O_{2max}$ maximum rate of oxygen consumption
MPP5 membrane palmitoylated protein 5
mRNA messenger RNA
ms milliseconds
M_V mass of ventricle
MY million years
Na^+ sodium
NAD noradrenaline
NANC non-adrenergic non-cholinergic
NCX Na^+/Ca^{2+}-exchanger
NECs neuroepithelial cells
NeKA neurokinin A
NF-κB nuclear factor kappa light chain enhancer of activated B cells
η_H hill coefficient
NHE Na^+–H^+ exchanger
NKA Na^+–K^+–ATPase
NMDA *N*-methyl-D-aspartate
NPs natriuretic peptides (ANP, BNP, CNP, CNP, VNP)
NPR natriuretic peptide receptor (A, B, C, D, V)
NO nitric oxide
NO_2^- nitrite
NOAA National Oceanic and Atmospheric Association
NOK novel oncogene with kinase domain
NOS nitric oxide synthase
NPY neuropeptide Y
NTP nucleotide triphosphate
O ostium of sinoatrial valve
O_2 oxygen
OEC O_2 equilibrium curve
OFT outflow tract
P atrioventricular plug
P_{50} partial pressure of O_2 at which 50% of hemoglobin is bound to oxygen
P_A arterial blood pressure
Pa_{50} arterial P_{50}
PACs polycyclic aromatic compounds
PACA plasma-accessible carbonic anhydrase
P_aCO_2 arterial partial pressure of carbon dioxide

PAF1 polymerase-associated factor 1
PAHs polycyclic aromatic hydrocarbons
PAK p21-activated kinase
P_aO_2 arterial partial pressure of O_2
pCa calcium concentration, expressed as −log
pCa_{50} P_{Ca} for half maximal activation
PCBs polychlorinated biphenyls
PCDD polychlorinated dibenzo-*p*-dioxins
PCNA proliferating cell nuclear antigen
PCO_2 partial pressure of CO_2
PCR polymerase chain reaction
PCS posterior cardinal sinus
PCV posterior cardinal veins
P_{CV} central venous blood pressure
PD pancreas disease
P_{DA} dorsal aortic pressure
PDH pyruvate dehydrogenase
PE phenylephrine
PFK 6-phosphofructokinase
PGE2 prostaglandin E2
pH_a arterial pH
pH_e extracellular pH
pH_i intracellular pH
PHZ phenylhydrazine
P_i inorganic phosphate
PICA plasma inhibitors of carbonic anhydrase
PI–PLC phosphatidylinositol specific phospholipase C
P_{in} input pressure
PK pyruvate kinase
PKC protein kinase C
PKG protein kinase G
PLB phospholamban
PMCA plasma membrane Ca^{2+}–ATPase
PMCV piscine myocarditis virus
PO_2 partial pressure of O_2
P_{out} output pressure
proANF atrial natriuretic factor prohormone
PRV piscine reovirus
PTx pertussis toxin
PUFA polyunsaturated fatty acids
PV pulmonary vein
P_V plasma volume

P_{ven} venous pressure
Pv_{50} venous P_{50}
P_VO_2 venous partial pressure of oxygen
P_{VA} blood pressure in the ventral aorta
$\dot{Q}$ cardiac output
$\dot{Q}_{max}$ maximum cardiac output
Q_{10} temperature quotient; the ratio of a rate function over a 10°C temperature difference
qPCR quantitative polymerase chain reaction
r vessel radius
R vascular resistance
RA retinoic acid
RAS renin–angiotensin system
RBC red blood cell
R_{cor} vascular resistance of the coronary circulation
RD2 retinaldehyde dehydrogenase 2
ReA renal artery
R_{gill} vascular resistance of the gill circulation
RMP resting membrane potential
RNA-Seq high-throughput RNA sequencing
ROS reactive oxygen species
RQ respiratory quotient
R_{sys} vascular resistance of the systemic circulation
rTNF-α recombinant tumor necrosis factor-α
R_{tot} total peripheral vascular resistance
RyR ryanodine receptor
R_v resistance to venous return
RVM relative ventricular mass (mass of the ventricle relative to body mass, expressed as a percentage)
RVR resistance to venous return
S1P lysosphingolipid siphogosin-1-phosphate
S1Pr2 lysosphingolipid siphogosin-1-phosphate receptor 2
SA sinoatrial
sAC soluble adenylyl cyclase
SA node sinoatrial node
SAP sinoatrial plexus
SAR sinoatrial region
SAV salmonid alphavirus
$S_{a-v}O_2$ difference in arterial–venous Hb–O_2 saturation
SBV stressed blood volume
SC spinal cord
SCA subclavian artery

SCP salmon cardiac peptide
SCV subclavian vein
SD sleeping disease
SDS sodium dodecyl sulfate
SEM scanning electron microscope
SERCA sarco–endoplasmic reticulum Ca^{2+}-ATPase
SeV subepithelial vein
SG sympathetic ganglia
SGC soluble guanylate cyclase
SIV supraintestinal vein
SL sarcolemma or sarcolemmal
SL_n sarcomere length
SMLC2 slow myosin light chain 2
SN spinal nerve
SNP sodium nitroprusside
SNS sympathetic nervous system
SPN spinal pre-ganglionic neurons
SO_2 Hb-O_2 saturation (arterial S_aO_2 and venous S_vO_2)
SP substance P
SR sarcoplasmic reticulum
SUR sulfonylurea receptor
SV sinus venosus
$t_{1/2}$ half-time
TBX T-box transcription factor
TCA cycle tricarboxylic acid cycle
TCDD 2,3,7,8-tetrachlorodibenzo-*p*-dioxin
TCR T-cell receptor
TDEE temperature-dependent deterioration of electrical excitation
TdT dUTP nick-end labeling
TEFs toxicity equivalence factors
TGF-β_1 transforming growth factor-beta 1
TIMP tissue inhibitor of metalloproteinase
TM tropomyosin
TMAC transmembrane adenylyl cyclase
TnC troponin C
TnI troponin I
TNF-α tumor necrosis factor-alpha
$\dot{T}O_{2max}$ maximum arterial O_2 transport
T_{optAS} optimal temperature for aerobic scope
TUNEL terminal deoxynucleotidyl transferase
UI urotensin I
UII urotensin II

U_{crit} critical swimming speed of a fish
UDP uridine diphosphate
UK United Kingdom
Us urotensins
USBV unstressed blood volume
UTP uridine triphosphate
UTR 3′-untranslated region
V ventricle
V_b blood volume
$\dot{V}_b$ blood flow
VC vena cava
VCR visceral cardiac ramus of vegas
VEGF vascular endothelial growth factor
VIP vasoactive intestinal peptide
V_m resting membrane potential
VMHC ventricular myosin heavy chain
VNP ventricular natriuretic peptide
VO vascular occluder
$\dot{V}O_2$ O_2 uptake per unit time
V_R total ventilation volume
VS vasostatin
V_s stroke volume, volume of blood pumped with each heartbeat
V_{smax} maximum stroke volume
VS-1 vasostatin 1
VS-2 vasostatin 2
VST vagosympathetic trunk
WAF water accommodated fraction
W_S stroke work
WT1 Wilms' tumor protein 1
X cardiac vagus rami
$X1$ lateral vagal motor neuron group
X_{br} vagal ramus interconnecting gill arches
X_m medial vagal motor neuron group
X_{mr} rostral components of the medial vagal motor neuron group
X_{mc} caudal components of the medial vagal motor neuron group
X_r vagal root
Φ Bohr-coefficient
η fluid viscosity