Index

a
Abdallah, Su, and Hwang system 101
absorption
  of light 155
  MC simulation 158
  spectrophotometry 356
accelerated testing 105–106
acellular hydrogels 596
activation energy barrier 554, 555, 557
activation enthalpy 557
active implantable medical device (AIMD) 224
active implant devices 203
acute radiation dermatitis 525–526
acute thermoregulatory responses
  of behavioral thermoregulation 540–541
  forced hypothermia 538–540
  regulated hypothermia 538–540
  toxic agents 541–542
adenosine diphosphate (ADP) 577
adenosine triphosphate (ATP) 577, 593
adjoint/conjugate gradient method 144–145
adjoint method
  inverse heat conduction problems 139–141
  optimization applications 144
adjunctive therapy
  chemotoxic adjuvants 605–606
  immunologic adjuvants 606–607
  nutraceutical adjuvants 606
  pro-apoptotic adjuvants 606
adrenocorticotrophic hormone (ACTH) 503
Affeld, Walker, and Schichl system 101–103
albumen, denaturation 371
algorithms
  evolutionary 141–142, 146–147
  genetic 141–142, 146–147
  inverse adding-doubling 358–359
  NM 797
pattern search 148
simulated annealing 148
temperature estimation 309–310
allometric association
  characteristics 475–477
  with metabolic heat production 476
ambient temperature 54
  effect of 506, 535
  vs. rectal temperature 537
  systematic analysis of 535
ambient vapour pressure 469
anesthesia-induced vasodilation 16–17
antidiuretic hormone (ADH) 503
apoptosis 601
apparent diffusion coefficient (ADC) 288
Arrhenius kinetic analysis method 554
Arrhenius process
  damage coefficients 560
  parameters 561–564
  relative reaction rate 573
  time delay 580–582
arterio-venous anastomoses (AVA) 504
ASTM gel phantoms 715
autoregressive (AR) model 306
Avogadro’s number 557

© 2018 John Wiley & Sons Ltd. Published 2018 by John Wiley & Sons Ltd.
background electric field induces electric current and charge 206
magnitude and phase of 212
scattering of 203
balanced steady state free precession (bSSFP) sequence 290
Bayesian estimation (BE) 797
Beer’s law 155, 157
Berkow formula 517
Bernoulli differential equation 559
Bessel functions 764
biochemical cell death
cryoimmunology 603–604
osmotic and biochemical stressors 592
PCD 602–603
post-thaw 599
rates of 606
bioheat transfer applications 333
inverse solution methods 143–145
non-gradient methods advantage 145–146
evolutionary algorithms 146–147
pattern search algorithms 148
simulated annealing algorithms 148
bioheat transfer model (BHTM) 15
derivation 3
Pennes’ 4
blood temperature in 8
simplicity and reasonable performance of 8
vs. two-compartment GBHTM 9
in vivo temperatures determination 8
two-compartment GBHTM 3
biological systems 261
biomaterials
bio-heat transfer applications
DSC (see differential scanning calorimetry (DSC))
nanocalorimetry (see nanocalorimetry)
overview 393, 394
biopreservation of 393, 394
cryotherapy of 397
nanoscale calorimetric measurement lipids systems 402–403
protein/DNA systems 401–402
phase change events 393, 395
specific heat capacity 395–396
temperature application to 393
thermal therapy of 397
thermodynamic and kinetic modeling of protein denaturation 399–401
water solidification 396–399
Biot’s modulus 760, 764
Björk system 101
black box modeling 77–79
blood flow
in circulatory systems 33
effect of 716
metabolic heat effects 759
non-thermal factors of 464
rate of 39, 46
and sweating 476–477
typical characteristic of 764
velocity 26, 33
blood perfusion
definition 336–337
effects 762–765
on energy balance 650
impact of 726
and metabolic heat generation rate 679
rate 650
blood temperatures 471
blood vessels 240
diameters 3
network 682
thermal effects
boundary equation 26
elementary control volume 25–26
non-dimensional governing equation 26–27
non-dimensional volume-averaged tissue temperature 27–28
physiologic flow 27
tissue-blood heat transfer rate 28–29
blood volume 6, 76, 441, 443, 489
body cooling
experiments 785, 790–791
phases of 781
body-fluid volumes 489
body heat
- balance 502
- storage 470
body mass 502
- function 476
- vs. SAR 509
- vs. surface area 476, 477, 502
body temperature
- mean 469, 484
- regulation of 463, 466
Boltzmann constant 638, 680
Boltzmann distribution 269–270
boundary conditions
- blood vessels 26
- Dirichlet 670
- discretization 180
- of heat equation 783
- heat transfer problems 133
- in numerical model 758
Brownian motion 640, 641, 649
burn injuries
- calculating 726–731
- classification 514
- deep-partial-thickness 724, 728, 731
- degree of 518
- demographics 514
- depth 516–517
- electric burns 524–525
- first-degree 723
- hospital management 521–524
- hypermetabolic response to 518–519
- major 520
- management 521–524
- minor 521
- moderate 520
- parameters 726
- pathophysiology 516–520
- patient categorization 520–521
- physical basis 515–516
- prehospital management 521
- radiation burns (see radiation burns)
- reduction in 732
- risk factors 513
- rule of nines 724
- scald burns (see scald burns)
- second-degree burns 723
- size 517
- skin anatomy and function 514–515
- skin burns (see skin burns)
- surface area 724
- systemic changes in 517–520
- third-degree burns 723
- burn wound excision 523

C
- calorimeter 754
- cardiovascular system
  - Akaike information criterion 87–88
  - balance of impedance 79–80
  - changes 519
  - compliance, definition 80
  - effect of measurement accuracy 88–89
  - four-element R-L-RC model 85–86
  - least-squares matching 86–87
  - RC Windkessel model 80–82
  - R-RC modified Windkessel model 83–85
- cavity measurement technique
  - circular waveguide cavity 387
  - coaxial cavity 387
  - geometries types 387
  - narrow band measurement 387
  - permittivity and permeability of specimen 389
  - quality factor
    - definition 390
    - measurement 389
  - rectangular waveguide cavity 387, 390, 391
    - in reflection mode 388
    - resonance frequency 388
    - in transmission mode 388
- CEE see convective energy equation (CEE)
- cell biology 601
- cell–cell/matrix signaling 597
- cell culture 652
- cell damage 697
- cell death 553 see also biochemical cell death; programmed cell death (PCD)
  - autophagy 577
  - biochemistry of apoptosis 578–580
  - biology of apoptosis 576–577
  - cryo-induced 598, 601
  - by ice formation 697
cell death (contd.)
   mechanism of 602, 708
   necroptosis 577
   processes 575–580
   and pyroptosis 577
   quantitative markers of 570–571
   cell dehydration 696, 697
   cell injury 697
   cell survival curves
      Arrhenius model, failure of 574–575
      CEM 573–574
      fundamental relations 572–573
   cellular immune response 604
   cellular metabolism 593
   central processing unit (CPU) 234, 240
   central venous pressure 489
   change in backscatter energy (CBE) 305
   chemical burns 514
   chemical energy 468
   chemical reaction kinetics
      two-component reactions 555–557
      uni-molecular process descriptions 557–559
   chromel-alumel thermocouple sensors 313
   chronic radiation dermatitis 526
   circulatory systems 33–34
   clothing design 53
   coaxial probe measurement technique 385–387
   cold-induced vasodilation (CIVD) 439, 530
   cold stress
      focal 450–451
      local heat-induced
         vasoconstriction 438–439
         vasodilation 439
      physiological response 435
      systemic 445–447
   collagen birefringence loss 566–567
   collagen shrinkage 565–566
   compliance
      calculation of 124
      definition 80
      physical systems 92
   compressed sensing theory 291
   computational fluid dynamics (CFD)
      246
   computational model test case
      hardware specifications 240–241
      numerical method and code description
         bioheat model parameters and
         variables 237
   FORTRAN 237–238
      hardware specifications 240–241
      iterative first-order finite difference
         scheme 236–237
      output 238–240
      simple bioheat model 235
   computed tomography (CT)
      nanoparticle distribution 633
      noninvasive imaging modalities 304
      tissue injury in 591
      of tumor 673
   computer-generated vasculatures
      bioheat equation 34
      examples
         geometry and flow parameters 42–45
         geometry of finger 49
         network growth 45–46
         obstructions 47–49
         3D capillary bed 46–47
      method
         assumptions and framework 35
         constrains and criteria 38–40
         input parameters 35–37
         iterative generation 40–42
         output parameters 37–38
      tree-based synthetic vasculatures 42
   COMSOL 651
   conditional probability distribution (CPD)
      method 797–803
   confocal laser scanning microscopy images 160, 161
   conjugate gradient method 140
   constant temperature heating 339–343
   constant volume gas thermometer 262
   contact burns 514
   convection-diffusion equation 648
   convective energy equation (CEE) 3, 15, 16, 22, 25, 715
   cooler temperatures, TH 743
   COPASI 580
core temperature
  anesthetics effect on 16–19
  baseline 538
  cardiotoxic effects 536
  external source terms 15
  internal 15, 530
  level 530
  normal 531, 535
  telemetric monitoring of 530
  thermal model 16
  transient reduction in 548
Cornhill system 101
countercurrent artery–vein pair 672
Courant–Friedrichs–Lewy (CFL) condition 181
cover burn wound age 523
CPD see conditional probability distribution (CPD) method
critical temperature 560
cryoablation see also cryosurgery
  solid cancers treatment see solid cancers, cryoablation for
technology 689
cryoimmunity 598
cryo-induced cell death 598, 601
cryoinjury
  functions 599
  principal method of 595
cryolesion
  culture models 596–598
  freezing injury 593–594
  hypothermic injury 593
  post-thaw injury 595
  thawing injury 594–595
cryomicroscopy 399
cryoneurolysis 707
cryoprotective agents (CPAs) 397
cryosurgery
  cooling rate 599
  duration of exposure 600
  freeze/thaw cycles 600–601
  IIF 681–682
  nadir temperature 599–600
  parameters 598–601
  thawing rate 600
  tissue type 598–599
cryotherapeutic procedures 596
cryotherapy see also cryosurgery
  effects of 595
  intracellular ice 599
CT see computed tomography (CT)
culture models
  acellular hydrogels 596
  animal models 597
  clinical models 598
  monolayer (2D) cultures 596–597
  tissue-engineered (3D) models 597
cumulative equivalent minutes at 43 °C (CEM43) 554, 570, 573–574, 727
d
Darcy’s law 648
Davila system 99–100
death-inducing signaling complex 601
death time 777, 799 see also time of death estimation (TDE)
deep-body temperature 467, 469
deep-partial-thickness burns 724, 728, 731
dehydrated hemoglobin (HHb) 366
device–bias substitution 800
dielectric materials
  dielectric constant 380
electronic polarization 379
  frequency conductivity 382, 383
  Kramers–Kronig relationship 383
measurement techniques
  cavity measurement technique (see
  cavity measurement technique)
  coaxial probe measurement technique 385–387
  parallel plate capacitor 384
  transmission line system 384–385
parameters, Cole–Cole plot of 381–382
relaxation times 381, 382
differential scanning calorimetry (DSC)
  applications 407–411
calibration
  baseline 405
  heat flow 406
  temperature 405–406
commercial availability 403, 404
definition 403
latent heat evolution in CPA 399
Index

differential scanning calorimetry (DSC) (contd.)
  modulated 406–407
  schematic of 399, 400
  standard
    heat flux DSC 404
    power compensated DSC 404–405
diffuse optical tomography (DOT) 160, 162, 360
diffuse reflectance spectroscopy (DRS) 360
diffusion theory 157
diffusion time 336
dimensional analysis 75–77
Dirichlet boundary conditions 670
discretization
  boundary conditions 180
  evolution variable 180–181
  software packages 181
  spatial 179
Donovan mock circulation system 93–94
Doppler ultrasound 521
dry-heat transfer 472
dry thermometer 754
DSC see differential scanning calorimetry (DSC)
dual-mode ultrasound array (DMUA) system 321
dynamic similitude 75
dynatek MP3 valve testing system 104–105

eccrine sweat gland distributions 479
echo planar imaging (EPI) 286
echo-shift method
  echo spectrum estimation 306
  filter design 311
  and imaging equations 307–308
  infinitesimal echostrain imaging equation 308
  mathematical model 307–308
  MSS estimation 307
  recursive echo strain imaging equation 309
  temperature estimation algorithm 309–310
  time-shift estimation 310–311
  edge wave 171
electromagnetic distribution
  active implant 212–214
  electric field scattering 211
  passive implants
    FDTD model 208
    measured temperature rises 207–210
    orthopedic implant 208–210
    phantom test hazards 210
    SAR distribution 208–209
    scattering mechanism 206
    set-up for ASTM F2182-11a heating test 207
    thermoregulation in body 207
    US FDA guidance 210
in vivo temperature rise during MRI 209
RF heating during MRI 212–214
wave propagation 204–205
electromagnetic field 647, 715
electromagnetic radiations 514
electromagnetic wave
finite-difference-time domain
  advantages 193
  calculation 193
  characteristic of 193
  discovery 191
  Maxwell equations 190–192
  numerical simulation 190
  operations in 192
  simulation steps and setup 193–196
  time-domain numerical method 192, 193
  two curl equations 191
  XFDTD 193
  propagation 204–205
radiofrequency
  fields inside human body 196–200
  waves (see radiofrequency (RF) waves)
electromotive force (EMF) 261, 263
electronic polarization 379
electron transport chain (ETC) 577
endothermy 463
endovascular cooling, TH
blood vessel or body cavity 745
measurements 746–749
methods 745–746
energy balance 767
enhanced permeability and retention (EPR) 644
escharotomies 523–524
evolutionary algorithms 141–142, 146–147
evolution variable discretization 179–181
extracorporeal membrane oxygenation (ECMO) 95–96
Eyring–Polanyi equation 559

f

face wave 171
Fast computation techniques
  cache re-use 234, 258
  computational model test case (see computational model test case)
  issues
    distributed memory parallel 253–257
    thread parallel 249–253
    vectorization and data streams 244–246
    X15 code performance 241–244
    memory hierarchy 246–249
  Fast Fourier Transform (FFT) 196
  FDTD see finite difference time domain (FDTD)
  Fenwal 121-102E AJ-Q01 glass probe 343
  ferro- and ferrimagnetic materials 637, 639
  ferrofluid 645, 646, 653
  fiber-optic temperature sensors 265
  Fick’s law 157, 763
  finite difference method (FDM) 163
  finite difference time domain (FDTD)
    advantages 193
    calculation 193
    characteristic of 193
    discovery 191
    electromagnetic waves and fields 183
    Maxwell equations 190–192
    method 208, 224
    numerical simulation 190
    operations in 192
    simulation steps and setup

boundary and space 195
  cell size 193–194
  FFT 196
  and frequency resolution 196
  time step size 194–195
  time-domain numerical method 192, 193
  two curl equations 191
  XFDTD 193
  finite element analysis (FEA) 163
  finite element method (FEM) 208, 676, 795–797
fire burns 514
firefighter protective clothing
  heat stress effect 57–58, 66–67
  human thermal model
    ambient conditions 64
    finite-element programs 59–60
    physiological variables 60–61
    twenty-one element 58
    uses 68
    validation 61–64
    individuals heat by fire 64
    metabolic rates during firefighting 55–56
    thermal injury 64–66
  thermal properties
    and evaporative resistance 54–55
    MIL outfit 55
    RB90 outfit 55
    thermal insulation 54
    thermal resistance 54–55
    types of material layers 54
    UW outfit 55
first-degree burns 723
First law of thermodynamics 467
floating point operations (FLOP) 233, 241
fluorescein isothiocyanate-conjugated dextran (FITC-dextran) 570
FOCUS (Matlab-based package) 181
focused ultrasound (FUS) 301
forced hypothermia 538–540
FORTRAN (FORmula TRANslator) 237, 238
four-element R-L-RC model 85–86
four-region mock circulation system 107, 109
fractal vascular network 675–676
Frank–Starling relations, thermal stress on 441, 442
freeze/thaw cycles 598, 600–601, 690, 695, 698, 700, 702
freezing injury 593–594
frequency encoding (FE) 274
frequency factor 554
functional near-infrared spectroscopy (fNIRS) 360
function specification methods 137–138

G
galium arsenide (GaAs) 265
gastrointestinal tract (GIT) changes 519–520
Gaußian probability distribution 794, 797
Gauss-based methods 143–144
Gaussian distribution 650
Gauss-Newton method 139
GEBR42KA102M bead thermistors 343
generic bioheat transfer model (GBHTM) 3, 622
derivation of ‘N + 1’ compartments 7–8
simplifications 6–7
three-compartment 7
two-compartment 4–5
thermal model 20–22
genetic algorithms 141–142, 146–147
geometric similitude 74–75
GE P60BA102M glass probe 343
Gibbs free energy 556, 557, 680
glioblastoma multiforme (GBM) 655
Godunov method 180
gradient-based methods
adjoint methods 139–141
bioheat transfer applications
adjoint method 144–145
Gauss-based methods 143–144
definition 137
function specification 137–138
Gauss-Newton method 139
regularization 138
graphic processing unit (GPU) 234
ground temperature 64

h
Hales, Stephen 71
heat balance equation 467, 502, 504, 506
heat capacity 468
heat conduction equation 468
heat flux
behavior 746
rates 475
thermal conductivity 473
heat flux DSC (HC DSC) 404
heat gain 502
heat generation rate 162, 633, 642, 645, 646
heat-induced
vasoconstriction 438–439
vasodilation 436–439
heat loss
allometric characteristics 475–477
anatomical considerations 477–479
blood flow and sweating 476–477
body-fluid volumes 489
central venous pressure 489
deep-body to skin thermal gradient 469–471
eccrine sweat gland distributions 479
evaporative 724
first principles of 465–475
going with, and against, the flow 467–469
heterogeneous tissue compositions 477–479
homeostasis 480
from inanimate 473–475
interpreting (and misinterpreting) tissue temperatures 467
isometric objects 473–475
known and unknown unknowns 487–489
with metabolic heat production 476
physiological considerations 480–487
plasma osmolality 489
shape dependency 476
and specific surface area dependency 475
sudomotor responses 485–487
temperature and thermal gradients 467–471
temperature regulation and components 464
thermal physiology models 465
thermal properties 473–475
thermoeffectors activity for 544
thermosensitivity 482–484
unknown interactions with blood pressure regulation 488
and vapour-pressure gradient 471–472
vascular responses 484–485
volume 475
water vapour 471–472
zones of thermoregulation 480–482
heat measurements
dielectric properties, tissue
cavity measurement technique (see cavity measurement technique)
coaxial probe measurement technique 385–387
parallel plate capacitor 384
transmission line system 384–385
of internal state 135–136
temperature
fiber-optic temperature sensors 265
radiation thermometry 264–265
thermistors 263
thermocouples (see thermocouples)
thermometers 262
thermal properties
calibration 343–344
complexities 338–339
constant temperature heating technique 339–343
electronic controller 339
probe design 343
reviews of 337–338
self-heated thermistors 339
heat production
allometric association with 476
endogenous metabolic 502
rate of tissue 670
and removal 469
heat shock proteins 570
heat stress
characteristics 435
focal 450
local heat-induced
vasoconstriction 438
vasodilation 436–438
systemic
cardiac pump 440
cardiac responses 440–442
non-painful research protocol 440
passive 444
vascular responses 443–444
heat transfer
in biological tissue 676–677
characterization problems 133, 134
coefficients 516, 745, 754
direct problems 133, 134
inverse problems
definition 133
external source 136
internal state measurement 135–136
physics-based mathematical models 134–135
solution methods 136–149
source/boundary condition, determination of 133
and thermophysical characteristics 136
modeling 782–789, 803–804
principles of 715
rates vessel-to-tissue 670
source problems 133, 134
WCET 759–762
hemolysis testing 98
heterogeneous tissue compositions 477–479
HIFU_Simulator (Matlab-based package) 181
high-intensity focused ultrasound (HIFU)
adjoint method 144
clinical usage 303
spatial and temporal control features 302–303
high-intensity therapeutic ultrasound (HITU) 167, 178
high temperature surgery
birefringence loss in collagen 566–567
collagen shrinkage 565–566
lower temperature coagulation 568–569
processes 569
homeostatic response 506–508
hospital management
  attenuation of hypermetabolic response 523
burn wound excision 523
cover burn wound age 523
escharotomies 523–524
inhalational injury management 524
initial assessment 521–522
resuscitation 522
wound care 522
Hugo model 224, 226
human thermal models
  ambient conditions 64
  finite-element programs 59–60
  physiological variables 60–61
RB90 outfit
  metabolic rates measured 61–62
  rectal and mean skin temperatures 62–63
thermal resistances measured 62, 64
twenty-one element 58
uses 68
UW outfit
  metabolic rates measured 61–62
  rectal and mean skin temperatures 62–63
hybrid theory 159–160
hybrid transmission line model, lead heating
  calculated electric field 224, 226
FDTD calculation 224–225, 227
Hugo model 224, 226
open circuit voltage calculation 224, 225
phantom heating test 226–227
Saluda lead 229
SAR distribution 228
simulation of heating with 224
source impedance 224
in vivo temperature rise 225–228
hybrid vascular models 111
hybrid ventricular models 110–111
hypermetabolic response
  attenuation of 523
burn injury 518–519
hyperthermia therapy 302, 675
hyperthermic temperatures
Arrhenius coefficients from cell survival curves 571–575
cell death processes 575–580
quantitative markers of cell death 570–571
thermal damage predictions 582–584
time delay 580–582
hypothermic injury 593
hysteresis/eddy currents 638

i
ice nucleation 593
ice propagation 595
image-guided minimally invasive thermotherapy
  noninvasive thermometry
    MR temperature sensitivity 304–305
    ultrasound temperature sensitivity 305–306
    spatial and temporal control features 302–303
temperature feedback 302
immune system changes 520
indocyanine green (ICG) 571
inertance
  calculation of 124
  definition 92
inertial cavitation 177
inflammation/edema 519
inhalational injury management 524
input impedance 78, 79
Intel Haswell-EP processors 240, 243
International Confederation for Thermal Analysis and Calorimetry (ICTAC) 403
International Electrotechnical Commission (IEC) 19
interpreting (and misinterpreting) tissue temperatures 467
intra-aortic balloon pump (IABP) systems 97
intracellular ice formation (IIF)
  during cryosurgery 681–682
  experiments and modeling 397–398
  probability of 679–680
inverse adding-doubling (IAD) algorithm 358–359
inverse heat transfer problems
  definition 133
  external source 136
  internal state measurement 135–136
  physics-based mathematical models 134–135
solution methods
  bioheat medical applications 143–149
  comparison studies 148–149
  genetic algorithms 141–142
  gradient-based methods (see
   gradient-based methods)  
other non-gradient-based methods 142–143
  source/boundary condition 133
  and thermophysical characteristics 136
inverse magnetostrictive effect 640
in vivo cryotherapy 595
in vivo temperature
  change
   due to local source term 22
  worst-case tissue 19–22
  core temperature estimation
   anesthetics effect on 16–19
  external source terms 15
  internal source terms 15
  thermal model 16
  irreversible Arrhenius kinetics 553
  isoflurane 16
  isometric objects 473–475

j
  Joule–Thomson cryoprobes 592,
   689–695
  jugular vein bulb temperature (JVBT) 749

k
  kata-thermometer 754
  kinematic similitude 75
  kinetic coefficients 556
  kinetic energy 472, 593
  Kolf model 72, 74
  Kramers–Kronig relationship 383
  Kubelka–Munk theory 157
  k-Wave (Matlab-based package) 181
  KZK Texas (time-domain solver) 181
  Lagrangian technique 139–140
  Lambert’s law 155
  Lamé constants 648
  laminar flows 716
  Laplace transform 341
  Larmor frequency 623
  laser chromophore 571
  laser therapy 635
  laws of thermodynamics 465
  lead
   characteristics 215
   features 215
  hybrid transmission line model
   calculated electric field 224, 226
   FDTD calculation 224–225, 227
   heating simulation 224
   Hugo model 224, 226
   open circuit voltage calculation 224,
    225
   phantom heating test 226–227
   Saluda lead 229
   SAR distribution 228
   source impedance 224
   in vivo temperature rise 225–228
transmission line (wave) model
   characteristic impedance 216
   discretization 216
   electric field transfer function
    219–222
   header current transfer function
    222–224
   heating process 214–215
   parameters 215
   propagation constant 215–216
   transfer function measurements
    217–219
Leishmania amazonensis 411
  Levenberg–Marquardt method 139
light propagation
   application to biomedical research
    ballistic regime 160
    confocal laser scanning microscopy
     160, 161
diffuse optical tomography 160, 162
  ex vivo two-photon imagining
    160, 161
light propagation (contd.)

gyration between tissue and absorption 155
reflection and refraction 153–155
scattering 155–156
photothermal effect, safety considerations
Arrhenius integral 163
finite difference method 163
finite element analysis 163
melanin granule mode 163–164
optical energy distribution 162–163
in turbid media
diffusion theory 157
hybrid theory 159–160
Kubelka–Munk theory 157
Monte Carlo simulation 157–159
scattering and absorption 156
Linde–Hampson process 687
linear ultrasound modeling
paraxial approximation 172–173
Rayleigh–Sommerfeld integral 170–172
temperature elevation 173–174
liquid-in-glass thermometer 262
liquid-nitrogen cryoablation console 688
localized cooling, TH 743
localized heating 506–508
Louisville system 96–97
lower temperature coagulation
birefringence loss in myocardium 568–569
retinal damage 568
skin burns 569
lumped-parameter models
physical models, cardiovascular system
Akaike information criterion 87–88
balance of impedance 79–80
compliance, definition 80
effect of measurement accuracy 88–89
four-element R-L-RC model 85–86
least-squares matching 86–87
RC Windkessel model 80–82
R-RC modified Windkessel model 83–85
respiratory system
calculation 124
clinical applications 127–129
construction 120–121
four candidate models 123
identification 125–126
inverse modeling 127
mechanical properties 119–120, 124
model selection 121–123
optimization method 126–127
vs. RLCRC model 125
speculation of 129
upper and lower generation 125
validation 129
viscous forces 124
Zm estimation 126
magnetic anisotropy 639
magnetic dipole 638
magnetic nanoparticle hyperthermia
animal and clinical studies 653–655
cancer treatment 654
history and development of 634–636
modeling heat transfer process 649–653
multi-scale modeling 648–649
nanoparticles delivery 644–647
physical mechanisms of 636–643
side effects of 632
therapies 651, 655
tissue quantification 644–647
magnetic resonance imaging (MRI) 506
basic principles 267–269
Boltzmann distribution 269–270
computer-generated vasculatures 34
electromagnetic field (see electromagnetic field)
electromagnetic scattering 203
electromagnetic wave (see electromagnetic wave)
noninvasive imaging modalities 304
procedure spanning hours 233
radiofrequency excitation 270–271
relaxation phenomenon 271–272
signal detection 272–273
signal generation 270–271
signal localization 273–274
temperature dependence
contrast agents 286–287
diffusion 284–286
longitudinal relaxation time 280–282
magnetization transfer method 287
PRFS 277–280
proton density 275
repetition time 276
signal intensity 275–277
spectroscopy 286
transverse relaxation time 282–284

temperature measurement
fast imaging 290–291
motion 288–289
phase drift 288
resolution vs. field of view trade-offs 289–290
susceptibility 287

magnetic resonance spectroscopic imaging (MRSI) 286
magnetic resonance temperature imaging (MRTI) 145, 267
compressed sensing theory 291
contrast agents 286–287
diffusion 284–286
Kalman filters 291
longitudinal relaxation time 280–282
magnetization transfer method 287
Pennes bioheat equation 291
PRFS 277–280
proton density 275
signal intensity 275–277
spectroscopy 286
transverse relaxation time 282–284
magnetization transfer method 287

methicillin-resistant *Staphylococcus aureus* (MRSA) 417
MHH model see Marshall and Hoare and Henßge (MHH) model
microcalorimetry 411
micro-thermocouples 568
microwave therapy 634
Mie scattering 156, 158
MIL outfit 55
minimize tissue cooling delays, TH 743
mock vasculature model 109–110
moderate burn injury 520
modulated DSC (M-DSC) 406–407
Monte Carlo (MC) simulation
hybrid model of 159, 160
light propagation in tissue 157–158
principle 157
procedure 158–159
MRTI see magnetic resonance temperature imaging (MRTI)
MRI see magnetic resonance imaging (MRI)
MRI-induced heating near stents
CEE 715
methods 715–716
power deposition 716
results 716
zero-induced power 716
MRTI see magnetic resonance temperature imaging (MRTI)
M6 system 106
multi-photon microscopy 160
Murray’s law 676
muscle sympathetic nerve activity (MSNA) 451

myocardial tissue
thermal conductivity 347, 348
thermal diffusivity 347, 348

*n*
nadir temperature 599–600
nanocalorimetry
advantage 411
applications
high-throughput 414–415
label-free biochemical sensor 415–417
nanocalorimetry (contd.)
  monitoring of cells 417
  protein conformational studies 415
  characteristics 411
  nanocalorimeters 413–414
  open type differential 411, 412
  temperature measurement 411
  thermal properties 413
  thermistors 411–412
nanoparticle
  deposition 644
  nondestructive techniques 645
  retention 636
Navier–Stokes equations 34, 39, 80, 677
Néel relaxation mechanism 639, 641
neoplastic cells 598
neuronal thermal models 465
Newton-conjugate gradient method 145
Newton’s cooling law 468
nitro blue tetrazolium (NBT) 571
NM algorithm 797
non-gradient methods
  advantage 145–146
  evolutionary algorithms 146–147
  pattern search algorithms 148
  simulated annealing algorithms 148
noninvasive thermometry
  MR temperature sensitivity 304–305
  ultrasound temperature sensitivity 305–306
nonlinear ultrasound modeling 175–177
non-uniform memory access (NUMA) processor 234
normothermic conditions 470
normothermic temperatures 592
Nusselt number 77

O
open circuit voltage 224, 225
OpenMP codes 249, 252, 253
optical coherence tomography (OCT) 160
  optical property measurement 361
  refractive index measurement 364–365
optical dielectric constant 380
optical properties, tissue
  techniques
    absorption spectrophotometry 356
diffuse transmittance 356–358
inverse adding-doubling algorithm 358–359
properties of interest 355
and reflectance measurements 356–358
refractive index measurement 364–365
scattering anisotropy measurement 362–364
in situ measurement 360–362
thermally induced changes
  absorption resonance shifts 366–367
  constant-temperature measurements 365
  photothermal conversion 368–370
  protein denaturation 370–372
  thermal lensing 367–368
  osmotic imbalance forces 595
  oxyhemoglobin (HbO₂) 366–367

P
pain management 707–708
parallel plate capacitor 384
paraxial approximation 172–173
particle-based visualization images 102, 103
particle image velocimetry (PIV) techniques 102
passive implant devices 203
patient-specific models 111–112
pattern search algorithms 148
PCD see programmed cell death (PCD)
P60DA102M probe 343
Pennes’ BHTM
  blood temperature in 8
  performance of 8
  perfusion-related parameter 8
  vs. two-compartment GBHTM
    implicit and explicit assumptions 4, 9
    temperatures changes measured 4, 9–11
  in vivo temperatures determination 8
Pennes bioheat transfer equation (BHTE) 133, 478, 621, 622, 650, 676, 747
Penn State system 94, 95
perfectly matched layer (PML) 195
perfused tissues, thermal model for 
generic bioheat transfer model 3
‘N + 1’ compartments 7–8
simplifications 6–7
three-compartment 7
two-compartment 4–5
personal protective equipment (PPE) 56, 57
pharmacokinetics 535
phase drift 288
photochemical hazard 161–162
photon absorption 158
photon scattering 158
photothermal effect
Arrhenius integral 163
finite difference method 163
finite element analysis 163
melanin granule mode 163–164
optical energy distribution 162–163
physical models, cardiovascular system
black box modeling 77–79
dimensional analysis
dependent vs. independent variables 75
Nusselt number 77
power of 75
Prandtl number 76–77
Reynolds number 75
Womersley number 76
dynamic similitude 75
geometric similitude 74–75
historical background
Kolf model 72, 74
Starling model 72–73
Windkessel model 71–72
kinematic similitude 75
lumped-parameter models
Akaike information criterion 87–88
balance of impedance 79–80
compliance, definition 80
effect of measurement accuracy 88–89
four-element $R-L-RC$ model 85–86
least-squares matching 86–87
RC Windkessel model 80–82
R-RC modified Windkessel model 83–85
physical systems 89–91
and clinical training 106–112
compliance 92
inertance 92
and other blood pumps 93–98
physiologic system research 106–112
resistance 91–92
testing artificial hearts 93–98
testing prosthetic valves 98–106
purposes 71
plasma osmolality 489
Poisson’s ratio 648
polydimethylsiloxane (PDMS) 412, 413
posteriori distribution 798
post-thaw injury 595
power compensated DSC (PC DSC) 404–405
Prandtl number 76–77
preoptic area and anterior hypothalamus (POAH) 502
PRF see proton resonance frequency (PRF)
PRFS see proton resonance frequency shift (PRFS)
probability of ice formation (PIF) 675, 679
programmed cell death (PCD) 576, 602–603
propidium iodide (PI) 571
protective garments, firefighters
effect on heat stress 57–58
heat stress effect 66–67
human thermal model
ambient conditions 64
finite-element programs 59–60
physiological variables 60–61
twenty-one element 58
uses 68
validation 61–64
metabolic rates during firefighting 55–56
thermal injury 64–66
thermal properties
MIL outfit 55
RB90 outfit 55
thermal and evaporative resistance 54–55
thermal insulation 54
Index

protection garments, firefighters (contd.)
  types of material layers 54
  UW outfit 55
protein denaturation 370–372, 399–401
proton density 275
proton resonance frequency (PRF) 304–305
proton resonance frequency shift (PRFS) 277–280
pulse duplicators 99

r
radiant heat flux 57
radiation burns
  acute radiation dermatitis 525–526
  chronic radiation dermatitis 526
radiation emissivity 790
radiation heat exchange 760
radiation-induced dermatitis 525–526
radiation therapy 594, 631
radiation thermometry 264–265
radiative heat exchanges 468
radiofrequency (RF)
  body heat balance 502
  cosmetic procedures 565
  energy 508
  and homeostatic response 506–508
  induced heat 203
  load 502
  localized heating 506–508
  methods 622–623
  power 506, 621
  results 623–624
  thermoeffector capacity 504
  thermoregulatory behavior 504–506
  thermoregulatory pathways 502–503
  whole body thermal homeostasis 508–510
radiofrequency ablation (RFA) 301, 302
radiofrequency (RF) waves
  application, MRI
    dielectric board 189–190
    dielectric pad 187
    thin dielectric pad 188–189
  reflection and refraction
    materials 183
    reflection/transmission coefficients 185–187
  Snell’s Law 184–185
  radiotelemetry 538, 546
Rayleigh scattering 156
Rayleigh–Sommerfeld integral 170–172
RB90 outfit 55, 62–63, 66
RC Windkessel model 80–82
recrystallization effects 600
recursive echo strain filter (RESF) 309
region of interest (ROI) 183, 189, 200
regulated hypothermia 538–540
renal system changes 519
resistance
  calculation 124
  for physical systems 91–92
resistance temperature detector (RTD) 147, 605
resonance frequency 388
respiratory system, lumped-parameter models
  clinical applications 127–129
  construction 120–121
  mechanical properties
    adjustable electrical components 119–120
    distribution 124
  model selection
    criteria 122–123
    four-candidate model soft 123
    impedance characteristics 122
    open electrical circuit 123
    RLC and RLCRC models 123
    three-and four-element models 122
  parameters
    calculation 124
    four candidate models 123
    identification 125–126
    inverse modeling 127
    optimization method 126–127
    vs. RLCRC model 125
    speculation of 129
    upper and lower generation 125
    Zm estimation 126
  properties 119
  validation 129
  viscous forces 124
  resting heat exposures
    sudomotor responses during 485–487
    three-dimensional surfaces for 485
vascular responses during 484–485
rete pegs 515
retinal damage 568
Reul system 106–107
Reynolds number 75, 76, 91, 95, 101, 102, 104, 106, 758
R-RC modified Windkessel model 83–85

S
safe zone, definition 64–65, 68
SAR see specific absorption rate (SAR)
scald burns 514
danger of 731–732
severity 725
scattering
angle 156
coefficient 156
electric field 211
elastic/inelastic 155–156
light 155
MC simulation 158
in tissue 156
Scharfschwerdt, Misfeld, and Sievers system 105, 106
Schichl and Affeld system 103–104
second-degree burns 723
second law of thermodynamics 468
set-point temperature ($T_{set}$) 538–539
Sharp and Dharmalingam system 96
simulated annealing algorithms 148
skin anatomy
dermis 515
epidermis 514
skin burns 569
calculating burn injuries 726–731
categorization 723–724
causes of 724
clinical data 731
clothing impact 725
and cooling 724–725
danger of scald burns 731–732
heat extraction 724–725
misunderstanding of severe burns 731
treatment of 724–725
smoke detectors 513
Snell’s law 184–185
solid cancers, cryoaablation for
advantages of 698–699
cryoprobes 690–695
equipment 690–695
history of 687–690
mechanisms of tissue destruction by
extreme cold 695–698
metastatic cancers in bone 702–704
metastatic cancers in liver 704–705
metastatic cancers in lungs 702
pain management 707–708
prostate cancers 705–707
renal cancers 699–701
treatment 698–707
spatial discretization 179
spatial frequency domain imaging (SFDI) 361, 362
specific absorption rate (SAR) 508, 621, 633, 715
specific loss power (SLP) 633
specific surface area dependency 475
spectroscopy 286
spinal cord stimulator 225–227
stable cavitation 177
Starling model 72–73
Starling resistor 72
superparamagnetism 637, 638
surface-catalyzed nucleation (SCN) 679
surface cooling, TH
measurements 744
methods 744
surface temperature imaging technique 146
susceptibility 287
sweat flow 463
sweat gland output 487
systemic cold output 445–447
systemic heat stress
 cardiac pump 440
cardiac responses 440–442
non-painful research protocol 440
passive 444
vascular responses 443–444

T
T-cell activation 604
TDE see time of death estimation (TDE)
temperature dependence
contrast agents 286–287
diffusion 284–286
temperature dependence (contd.)  
longitudinal relaxation time 280–282  
magnetization transfer method 287  
PRFS 277–280  
proton density 275  
repetition time 276  
signal intensity 275–277  
spectroscopy 286  
transverse relaxation time 282–284  
temperature measurement  
  fiber-optic temperature sensors 265  
  MRI  
    fast imaging 290–291  
    motion 288–289  
    phase drift 288  
    resolution vs. field of view trade-offs 289–290  
    susceptibility 287  
radiation thermometry 264–265  
thermistor 263  
thermocouples (see thermocouples)  
thermometers 262  
temperature sensitivity  
  MR 304–305  
  ultrasound 305–306  
TH see therapeutic hypothermia (TH)  
thawing injury 594–595  
thawing rate 600  
therapeutic hypothermia (TH)  
  challenge of 742–744  
  cooler temperatures 743  
  endovascular cooling 745–749  
  induction phase of 744  
  localized cooling 743  
  minimize tissue cooling delays 743  
  need for cooling 741–742  
  surface cooling 744–745  
thermal ablation 652  
thermal breakdown 571  
thermal clamping 484  
thermal coagulation 302  
thermal conductivity  
  of air 758  
  and atherosclerotic plaque 346  
  of blood 677  
  definition 333–334  
of frozen and unfrozen tissue 678  
human aorta 346  
  ice crystals and intracellular ice 601  
measurement 344  
of myocardial tissue 347, 348  
thermal material properties 783  
transfer rates 468  
thermal damage 371–372  
  Arrhenius models for 559–564  
  constant temperatures 560–564  
  predictions 582–584  
  process coefficients 563–564  
  tissue 557  
thermal diffusivity 758  
  and atherosclerotic plaque 346, 347  
  definition 334–335  
  human aorta 346, 347  
  measurement 344  
  of myocardial tissue 347, 348  
thermal dose 301  
thermal effects 534  
  boundary equation 26  
  elementary control volume 25–26  
  non-dimensional governing equation 26–27  
  non-dimensional volume-averaged tissue temperature 27–28  
  physiologic flow 27  
  tissue-blood heat transfer rate 28–29  
thermal energy  
  chemical energy conversion into 468  
  influx of 469  
  transfer of 463  
thermal gradients  
  deep-body to skin 469–471  
  temperature and 467–471  
thermal homeostasis 508–510, 530, 531  
thermal injury 64–66  
thermal insult  
  cardiovascular responses  
    focal cold stress 450–451  
    focal heat stress 450  
    systemic cold stress 445–447  
    systemic heat stress 440–442  
  local  
    cold stress 438–439  
    heat stress (see heat stress)
tissue temperature and metabolic responses 435–436
thermoregulation and metabolic rate
systemic cold insults 445
systemic heat insults 439–440
tissue temperature and metabolic responses
focal 435–436
local 435–436
vascular responses
systemic cold stress 447–449
systemic heat stress 443–445
thermally significant blood vessels (TSBVs) 670–672
thermal model
ambient conditions 64
core temperature estimation 16
finite-element programs 59–60
GBHTM 20–22
generic bioheat transfer model 3
‘N + 1’ compartments 7–8
physiological variables 60–61
simplifications 6–7
three-compartment 7
twenty-one element 58
two-compartment 4–5
uses 68
validation 61–64
in vivo temperature change
due to local source term 22
worst-case 20–22
thermal normality 470
thermal probes 338, 343
thermal properties
definitions
significance 333
specific heat 336
thermal conductivity 333–334
thermal diffusivity 334–336
tissue perfusion 336–337
of ethylene glycol 351–352
and fat content 349–350
function of water 349–350
of glycerol 352
measurements
calibration 343–344
complexities 338–339
constant temperature heating
technique 339–343
electronic controller 339
probe design 343
reviews of 337–338
self-heated thermistors 339
temperature-dependent
canine arterial tissue 347
of frozen tissue 347, 349
human arterial tissue 346–347
of organ tissue 345–346
swine myocardial tissue 347, 348
of water 349–351
thermal relaxation time 33
thermal resistances 62, 64
thermal sensation 505
thermal steady state 464
thermal stress 55–57, 504, 655
thermistors 263, 467
thermo-acoustic lens effect 320–321
thermocouples 467, 605
examples 264
materials 263, 264
Seebeck effect 263
sensitivity of 263–264
sensors 313
thermopile 264
thermodynamic fundamentals
and ablation damage processes 564–569
Arrhenius models for 559–564
biomedical applications 393
chemical reaction kinetics 555–559
damage process 554–564
high temperature surgery 564–569
hyperthermic temperatures 569–584
kinetic modeling
of protein denaturation 399–401
water solidification 396–399
material properties 790
systems 463
water solidification 396–397
thermoeffector
capacity 504
function 465, 489
thresholds 482
Index

thermometers 754
  constant volume gas 262
  liquid-in-glass 262
  thermometric properties 261, 262
  thermometric property 261
  thermometric substance 261
  thermometry device 261
  thermoneutral environment 505
  thermoneutral zone (TNZ) 529, 533
  thermopile 264
  thermoreceptor feedback 465, 480
  thermoregulation
    behavior 504–506
    pathways 502–503
    responses 503
    source of error 467
    zones of 480–482
  thermosensitive liposomes (TSLs) 302
  thermosensitivity 482–484
  third-degree burns 723
  three-dimensional vascular network
    boundary conditions 677–679
    fractal vascular network 675–676
    freezing injuries 680–681
    IIF during cryosurgery 681–682
    and initial conditions 677–679
    model verification 681
    physical model 676–681
    probability of IIF 679–680
    and thermal injuries 680–681
    thermal properties 677–679
    tumor destruction 681
  thrombogenesis testing 98
  thyroid stimulating hormone (TSH) 503
  time-dependent bioheat model 233
  time of death estimation (TDE)
    asymptotic phase 775, 776
    body cooling experiments 785, 790–791
    CPD method 797–803
    in early postmortem phase 773–774
    empirical models 779–782
    FE model 795–796
    heat transfer model 782–789, 803–804
    hypothetic error of 801
    intrinsic model errors 777
    in late postmortem phase 774
    MHH model 790–795
  plateau phase 775, 776
  from postmortem body cooling
    775–779
  quasi-linear phase 775, 776
  types of errors 777
  Timms system 110
  tissue
    background electric field 203
    dielectric properties measurement
      cavity measurement technique (see
cavity measurement technique)
      coaxial probe measurement technique
      385–387
    dielectric constant 380
    electronic polarization 379
    frequency conductivity 382, 383
    Kramers–Kronig relationship 383
    parallel plate capacitor 384
    parameters, Cole–Cole plot of
      381–382
    relaxation times 381, 382
    transmission line system 384–385
    electromagnetic distribution (see
      electromagnetic distribution)
    hydrated 379
    light propagation in (see light
      propagation)
    optical properties
      absorption spectrophotometry 356
      diffuse transmittance 356–358
      inverse adding-doubling algorithm
      358–359
      properties of interest 355
      and reflectance measurements
      356–358
      refractive index measurement
      364–365
      scattering anisotropy measurement
      362–364
      in situ measurement 360–362
      thermally induced changes 365–372
    temperature
      interpreting (and misinterpreting)
      467
      and metabolic responses 435–436,
        449–450
non-dimensional volume-averaged reductions 741
thermal damage 557
ultrasound propagation in (see ultrasound propagation)
TNF-receptor interacting protein (RIP) sequence (TNF-RIP1) 577
Toner’s intracellular ice formation model 697
total body surface area (TBSA) 517
total internal reflection 185
toxicant-induced fever 546–548
toxic response
acute thermoregulatory 537–542
hypothermia modulates toxicity 534–537
impact of environmental temperature 532–537
thermal effect on magnitude and duration 534
thermoregulatory effects, alcohol 542–546
thermoregulatory profile 529–532
toxicant-induced fever 546–548
traditional hyperthermia 302
transepidermal water loss 472
transmission line (wave) model, lead characteristics
characteristic impedance 216
discretization 216
electric field transfer function 219–222
header current transfer function 222–224
heating process 214–215
parameters 215
propagation constant 215–216
transfer function measurements 217–219
transmission line system 384–385
transmission polarized-light microscopy (TPM) 566
transverse electric magnetic (TEM) mode 386
TSH see thyroid stimulating hormone (TSH)
two-dimensional vascular network 672–674
ultrasound propagation
high-intensity therapeutic 167
medical imaging 167
numerical simulation
discretization (see discretization) 178
resolution 178
splitting 178–179
physical processes
absorption of energy 168
acoustic characteristics 170
cavitation 177
frequency-dependent absorption 168
linear ultrasound modeling (see linear ultrasound modeling)
nonlinear ultrasound modeling 175–177
wave propagation effects 168
Westervelt-type equations 169
power density due to 167–168
ultrasound thermography (UST) 317–320
application
image-guided thermotherapy 322–323
real-time closed-loop temperature 321–322
closed-loop temperature 321–322
echo-shift method
echo-shift model 307–308
echo spectrum estimation 306
filter design 311
infinitesimal echostrain imaging equation 308
MSS estimation 307
recursive echo strain imaging equation 309
temperature estimation algorithm 309–310
time-shift estimation 310–311
experimental validation
imaging system 312–313
phantom heating and cooling experiment 314–315
setup components 311–312
temperature estimation accuracy 313–314
therapeutic system 312

V

van der Waals force 649 vapour-permeable clothing 472 vapour-pressure gradient 471–472 vascularized tissue 669 vascular network branch levels of 676 fractal 675–676 initial temperature of 679 three-dimensional (see three-dimensional vascular network) two-dimensional 672–674 vascular simulations system 112 vasculatures, computer-generated bioheat equation 34 examples

W

water
<table>
<thead>
<tr>
<th>Index</th>
<th>Page Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>wind chill equivalent temperature (WCET)</td>
<td>765–770</td>
<td>application of whole body models</td>
</tr>
<tr>
<td></td>
<td></td>
<td>blood perfusion effects on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>convective heat transfer coefficients</td>
</tr>
<tr>
<td></td>
<td></td>
<td>development of</td>
</tr>
<tr>
<td></td>
<td></td>
<td>steady-state vs. wind speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Windkessel model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Womersley number</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wound care</td>
</tr>
<tr>
<td></td>
<td>241–244</td>
<td>X15 code performance</td>
</tr>
<tr>
<td></td>
<td>648</td>
<td>Young's modulus</td>
</tr>
<tr>
<td></td>
<td>716</td>
<td>zero-induced power</td>
</tr>
<tr>
<td></td>
<td>467</td>
<td>Zeroth law of thermodynamics</td>
</tr>
<tr>
<td></td>
<td>516</td>
<td>zone of coagulation</td>
</tr>
<tr>
<td></td>
<td>516</td>
<td>zone of hyperemia</td>
</tr>
<tr>
<td></td>
<td>516</td>
<td>zone of stasis</td>
</tr>
</tbody>
</table>