

Artificial Kidney

Fundamentals, Research Approaches and Advances

人工肾
原理、研究方法和进展



By

Dayong Gao

Zhongping Huang

高大勇 黄忠平 著

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内 容 简 介

本书系统介绍了人工肾的起源、结构系统、工作原理及发展前景,详细论述了多种人工肾数理模型和计算机模拟优化方法,并运用大量实例阐述了人工肾实验研究方法。本书适合生物医学工程、临床医学、血液透析、膜科学、传热传质、化工领域的学生、教师以及研究人员阅读,可作为相应课程的教学参考书及新型人工肾研发的实用手册。

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总 序

侯建国

(中国科学技术大学校长、中国科学院院士、第三世界科学院院士)

大学最重要的功能是向社会输送人才.大学对于一个国家、民族乃至世界的重要性和贡献度,很大程度上是通过毕业生在社会各领域所取得的成就来体现的.

中国科学技术大学建校只有短短的 50 年,之所以迅速成为享有较高国际声誉的著名大学之一,主要就是因为她培养出了一大批德才兼备的优秀毕业生.他们志向高远、基础扎实、综合素质高、创新能力强,在国内外科技、经济、教育等领域做出了杰出的贡献,为中国科大赢得了“科技英才的摇篮”的美誉.

2008 年 9 月,胡锦涛总书记为中国科大建校五十周年发来贺信,信中称赞说:半个世纪以来,中国科学技术大学依托中国科学院,按照全院办校、所系结合的方针,弘扬红专并进、理实交融的校风,努力推进教学和科研工作的改革创新,为党和国家培养了一大批科技人才,取得了一系列具有世界先进水平的原创性科技成果,为推动我国科教事业发展和社会主义现代化建设做出了重要贡献.

据统计,中国科大迄今已毕业的 5 万人中,已有 42 人当选中国科学院和中国工程院院士,是同期(自 1963 年以来)毕业生中当选院士数最多的高校之一.其中,本科毕业生中平均每 1 000 人就产生 1 名院士和 700 多名硕士、博士,比例位居全国高校之首.还有众多的中青年才俊成为我国科技、企业、教育等领域的领军人物和骨干.在历年评选的“中国青年五四奖章”获得者中,作为科技界、科技创新型企业界青年才俊代表,科大毕业生已连续多年榜上有名,获奖总人数位居全国高校前列.鲜为人知的是,有数千名优秀毕业生踏上国防战线,为科技强军做出了重要贡献,涌现出 20 多名科技将军和一大批国防科技中坚.

为反映中国科大五十年来人才培养成果,展示毕业生在科学研究中

的最新进展,学校决定在建校五十周年之际,编辑出版《中国科学技术大学校友文库》,于2008年9月起陆续出书,校庆年内集中出版50种.该《文库》选题经过多轮严格的评审和论证,入选书稿学术水平高,已列为国家“十一五”重点图书出版规划.

入选作者中,有北京初创时期的毕业生,也有意气风发的少年班毕业生;有“两院”院士,也有 IEEE Fellow;有海内外科研院所、大专院校的教授,也有金融、IT 行业的英才;有默默奉献、矢志报国的科技将军,也有在国际前沿奋力拼搏的科研将才;有“文革”后留美学者中第一位担任美国大学系主任的青年教授,也有首批获得新中国博士学位的中年学者;……在母校五十周年华诞之际,他们通过著书立说的独特方式,向母校献礼,其深情厚意,令人感佩!

近年来,学校组织了一系列关于中国科大办学成就、经验、理念和优良传统的总结与讨论.通过总结与讨论,使我们更清醒地认识到,中国科大这所新中国亲手创办的新型理工科大学所肩负的历史使命和责任.我想,中国科大的创办与发展,首要的目标就是围绕国家战略需求,培养造就世界一流科学家和科技领军人才.五十年来,我们一直遵循这一目标定位,有效地探索了科教紧密结合、培养创新人才的成功之路,取得了令人瞩目的成就,也受到社会各界的广泛赞誉.

成绩属于过去,辉煌须待开创.在未来的发展中,我们依然要牢牢把握“育人是大学第一要务”的宗旨,在坚守优良传统的基础上,不断改革创新,提高教育教学质量,早日实现胡锦涛总书记对中国科大的期待:瞄准世界科技前沿,服务国家发展战略,创造性地做好教学和科研工作,努力办成世界一流的研究型大学,培养造就更多更好的创新人才,为夺取全面建设小康社会新胜利、开创中国特色社会主义事业新局面贡献更大力量.

是为序.

2008年9月

List of Symbols

Roman Letters

A	total membrane area
A_c	cross section area of control volume
A_H	cross section area of one hollow fiber
A_m	membrane area in control volume
C	solute concentration
C_{bi}	solute concentration at blood inlet
C_{bo}	solute concentration at blood outlet
C_{bs}	solute concentration at the surface of inner skin on blood side
C_{ds}	solute concentration at the surface of outer skin on dialysate side
C_{NP}	solute concentration in non-perfused compartment
C_m	solute mean concentration in the membrane
C_p	solute concentration in perfused compartment
C_{uf}	concentration in the ultrafiltration fluid
CL	solute clearance
d_H	outer diameter of hollow fiber
d_i	inner diameter of hollow fiber
D	solute free diffusion coefficient
D_f	dilution factor
D_s	solute diffusion coefficient across membrane
D_{eff}	effective solute diffusion coefficient
E	dialyzer efficiency
f_p	packing density
G	solute generation rate
G_{nu}	non-urea nitrogen generation rate
G_u	urea generation rate
I	unit tensor
J_s	solute flow rate across unit membrane area

J_v	volumetric flow rate across unit membrane area
k	Darcy permeability
k_B	solute mass-transfer coefficients in blood compartment
k_D	solute mass-transfer coefficients in dialysate compartment
K	urea clearance
$K_{b, \text{diff}}$	diffusive solute clearance determined from the blood compartment
$K_{b, \text{total}}$	total solute clearance determined from the blood compartment
$K_{d, \text{diff}}$	diffusive solute clearance determined from dialysate compartment
$K_{d, \text{total}}$	total solute clearance determined from the dialysate compartment
K_{diff}	diffusive solute clearance determined from given K_OA
K_D	dialyzer clearance
K_{IC}	intercompartment clearance
K_m	mean of blood-side and dialyzer-side solute clearances
K_{NR}	nonrenal clearance
K_O	overall mass transfer coefficient
K_{uf}	ultrafiltration coefficient
L	effective length of the module
L_{wet}	permeable length of the wet fiber
L_p	membrane permeability
M_s	solute molecular weight
N	number of hollow fibers
N_A	Avogadro's number
P	hydrostatic pressure
P_{BL}	additional permeability due to the boundary layer
Pe	Peclet number
P_{obs}	observed diffusive permeability
P_s	solute permeability in the membrane
Q_b	blood-side flow rate
Q_{bi}	blood flow rate at blood inlet
Q_{bo}	blood flow rate at blood outlet
Q_d	dialysate-side flow rate
Q_{di}	dialysate flow rate at dialysate inlet
Q_D	solute diffusive mass-transfer rate
Q_{uf}	ultrafiltration rate

Q_p	plasma flow rate
Q_s	substitute fluid rate
r_s	solute Stokes radius
r_p	pore radius
R	universal gas constant
R_B	solute mass-transfer resistance in the blood compartment
R_D	solute mass-transfer resistance in the dialysate compartment
R_c	outer radius of the fictitious annular duct
R_m	module inner radius
R_M	solute mass-transfer resistance within the membrane
R_o	fiber outer radius
R_{OR}	overall mass-transfer resistance of the solute
R_i	fiber inner radius
S_c	sieving coefficient
S_m	water source term
S_s	solute source term
S_1	mass source/sink term
S_2	solute source/sink term
T	absolute temperature
$\mathbf{u}$	fluid velocity vector
u_r	fluid velocity in the radial direction
u_z	fluid velocity in the axial direction
V_{NP}	volume of non-perfused compartment
V_P	volume of perfused compartment
V_t	distribution volume
W	patient weight
W_d	net weight loss rate of the patient

Greek symbols

β	membrane area per unit volume
λ	ratio of solute to pore radius
κ	Boltzmann constant
ϵ	porosity
μ	fluid viscosity
ρ	fluid density

σ	solute reflection coefficient
ϕ	fraction of the volume occupied by the fibers

Subscripts and superscripts

b	blood
$conv$	convection
d	dialysate
$diff$	diffusion
i	z -, r -, or θ -direction
T	transpose of a matrix

Abbreviation

ART	Acute Renal Therapy
BUN	Blood Urea Nitrogen
BUN_i	Initial BUN
CRRT	Continuous Renal Replacement Therapy
DDQ	Direct Dialysis Equation
EKR	Equivalent Renal Clearance
ESRD	End-Stage Renal Disease
HD	Hemodialysis
HDF	Hemodiafiltration
HF	Hemofiltration
ICU	Intensive Care Unit
IHD	Intermittent Hemodialysis
$nPCR$	normalized Protein Catabolic Rate
NIDDK	National Institute of Diabetes and Digestive and Kidney Diseases
PD	Peritoneal Dialysis
SLED	Sustained Low-Efficiency Dialysis
TAC	Time-Averaged Concentration
USRDS	the United States Renal Data System
VVSC	Variable-Volume Single-Compartment
VVDC	Variable-Volume Double-Compartment
β_2M	β_2 - microglobulin

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Section I

Introduction