m-Health

FUNDAMENTALS AND APPLICATIONS

ROBERT S. H. ISTEPANIAN
BRYAN WOODWARD

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Metin Akay, Series Editor

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'Behold, I will bring to it health
and healing, and I will heal them and reveal to them abundance of
prosperity and security'

Jeremiah 33:6

'Mespot,' to the day when the palm trees will smile again

and

To the centenary of 'Forget-Me-Not.'

Robert S. H. Istepanian

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ABOUT THE AUTHORS

ROBERT S. H. ISTEPANIAN

Robert Istepanian is recognized as one of the leading authorities and pioneers of mobile healthcare and the first scientist to have coined and defined the concept of "m-Health." He holds a Ph.D. in Electronic and Electrical Engineering from Loughborough University, UK, and he has held several academic and research posts in the UK and Canada. These included visiting professor at the Department of Electrical and Electronic Engineering, Imperial College, London; professor of Data Communications for Healthcare and founding Director of the Medical Information and Network Technologies Research Centre at Kingston University, London; senior lectureships in the Universities of Portsmouth and Brunel University, UK; and associate professor at Ryerson University, Toronto with adjunct professorship at the University of West Ontario, Canada. He has also held a visiting professorship at St. George's Medical School, University of London, and was the Leverhulme distinguished visiting fellow at the Centre for Global e-Health Innovation, University of Toronto.

Professor Istepanian was awarded the 2009 IEEE award for the best and most cited paper by the IEEE Engineering in Medicine and Biology Society for his seminal paper on mobile healthcare (m-Health) published in 2004. He was also the recipient of the IEE Heaviside Award in 1999 from the Institution of Electrical Engineering, UK. He has led numerous funded multidisciplinary research projects on m-Health, e-Health, and telehealth funded by the UK Engineering and Physical Research Council, the European Commission, the British Council, the Royal Society, the Royal Academy of Engineering, and the Leverhulme Trust, in addition to sponsored projects and clinical trials funded by global telecom and mobile industries.

He has served as the Vice-Chair of the International Telecommunication Union focus group on standardization of machine-to-machine (M2M) communications.

He has also served as an expert on numerous assessment and peer evaluation panels on healthcare technology innovations, well-being, m-Health, and e-Health, including the Dutch–Philips partnership program on "Healthy Life Style", the Science Foundation Ireland Strategic Research Cluster Grants program, the Finnish Strategic Centers of Science, Technology and Innovation, and the Canada Foundation for Innovation. In addition, he has been a peer reviewer for the following UK Funding bodies: EPSRC, BBSRC, Wellcome Trust, Department of Health, Service Delivery Organisation, Health Innovation Challenge Fund, National Institute of Health Research, BUPA Foundation, and Diabetes-UK. Further, he has served on the editorial board of *IEEE Transactions on Information Technology in Biomedicine*, *IEEE Transactions on NanoBioScience*, *IEEE Transactions on Mobile Computing*, *International Journal of Telemedicine and Applications*, *Journal of Mobile Multimedia*, and *Journal of World Medical & Health Policy*, and as guest editor of the first two of these journals.

Professor Istepanian has served on numerous IEEE committees and chaired organizing and technical committees of national and international conferences in the United Kingdom, the United States and elsewhere, including the Telemed Conferences at the Royal Society of Medicine, London, the IET, London, the 2000 World Medical Congress, Chicago, and the successive IEEE Engineering in Medicine and Biology International Annual Conferences. He has been invited to present numerous keynote lectures at international conferences and meetings in the UK, Europe, the US, Canada, and other countries. His publications exceed 200 peer-reviewed papers and books on mobile communications for healthcare, m-Health, control systems, and biomedical signal processing.

BRYAN WOODWARD

Bryan Woodward holds two UK doctorates, a Ph.D. in physics from the University of London (Imperial College) and a D.Sc. in electronic engineering from Loughborough University. He has held positions with the UK Atomic Energy Authority, the Royal Australian Navy, Guy's Hospital Medical School, the Australian Atomic Energy Commission, and Loughborough University, where he was Head of the Department of Electronic and Electrical Engineering and a professor with the department's Centre for Mobile Communications Research.

Professor Woodward has been an external examiner for higher degrees at universities in the United Kingdom, France, India, and Australia; a referee for professorial appointments at 12 universities; an invited lecturer in Australia, Burma, China, India, France, Poland, and the United Kingdom; and an expert assessor for peer review research panels for the Australian, Canadian, and Spanish governments, for the UK Engineering and Physical Sciences Research Council (EPSRC), and for the European Commission's 5th and 6th Framework Programmes. Furthermore, he has been a chief examiner and moderator for the UK Engineering Council examinations and a consultant to over 20 companies. He has published over 60 academic journal papers and 120 international conference papers, as well as many articles for professional and popular magazines, and he has also done over 30 radio interviews. Finally, he has been a publications referee and book reviewer for *Electronics Letters*;

IEEE Communications Magazine; *IEEE Journal of Information Technology in Biomedicine* (as Associate Editor and editorial board member); *International Journal of Electronic Healthcare*; *International Journal of Telemedicine and Applications; Journal of Mobile Multimedia*; *Medical Engineering and Physics*; *Optics and Lasers in Engineering*; *Proceedings of the IEE (Circuits, Devices and Systems)*; *Proceedings of the IEE (Communications)*; and *Ultrasonics*.

Professor Woodward has participated in or led 10 multinational research projects funded by the European Commission and others funded by the EPSRC, the UK Department of the Environment, the Indian Department of Science and Technology, and industrial companies. He has also co-ordinated a major m-Health project funded by the British Council's UK–India Education and Research Initiative (UKIERI), with the aim of using mobile communications to improve the monitoring of heart disease and diabetes, which are prevalent in both developed and developing countries. The UK partners were Loughborough University and Kingston University; while the Indian partners were the Indian Institute of Technology Delhi, the All-India Institute of Medical Sciences, and Aligarh Muslim University.

Having retired, Bryan Woodward is now an Emeritus Professor of Loughborough University.

FOREWORD

The prominence of mobile health technologies as a driver for national and international healthcare strategies will undoubtedly grow as modern medicine advances into the 21st century. With smartphone penetration nearly ubiquitous in both the developed and developing world, the global potential to enable high-quality, cost-effective healthcare services - and meaningful patient engagement with patients and the public - is enormous. However, there are unique challenges in tailoring these m-Health strategies to make them accessible in the developing world and to an ageing population burdened with chronic disease. We must also address the important issues of public trust in data sharing, security, consent and privacy that will enable the profound benefits of digital, connected healthcare systems or, which, as likely, could inhibit progress if not tackled head-on.

m-Health: Fundamentals and Applications is a wonderfully comprehensive introduction to the subject of m-Health with valuable examples of studies and successful applications of this rapidly emerging innovation in healthcare. It highlights the crucial work that needs doing if we are to close the gap between what we know—in terms of the clinical evidence supporting m-Health innovation—and the challenges of consumer acceptability that may prevent wider adoption and diffusion of this exciting technological platform.

Professor the Lord Ara Darzi of Denham OM KBE PC FRS
Director, Institute of Global Health Innovation, Imperial College London

PREFACE

Mobile health (m-Health): Is it one of the greatest technological breakthroughs of our time or just another much-hyped smart healthcare technology bubble that could burst soon? Such a paradoxical view is perhaps an accurate reflection of the current status of m-Health. This important, if not essential, healthcare technology is known today to millions of people, both medical and nonexpert alike, as a powerful and transformative concept much needed for twenty-first century healthcare services.

This book has been written to continue the story of m-Health and its development since 2003. Over a decade ago, when m-Health was first introduced and defined, there was no indication then that it would be transformed into today's global multibillion dollar industry, albeit viewed critically and cautiously by the medical and healthcare communities.

M-Health was first defined as *mobile computing, medical sensor, and communications technologies for health care*. This simple yet powerful interpretation of m-Health as a scientific and technological concept has been driven to successful implementation by enthusiastic stakeholders and by rapid developments of these three enabling pillars. Unsustainable healthcare costs and ever-increasing demands for better access and quality of care make m-Health an important technology concept. Unfortunately, m-Health has been distorted and undermined by misleading interpretations, leading to the current spectrum of contradictions and paradoxical views. The collision of the end objectives, requirements, and evidence from opposing business and medical targets is fuelling this *status quo* and inhibiting the as yet unseen potential of m-Health. As an example of this scenario, we all see today major industrial power houses from global telecom, mobile phone, pharmaceutical, health, and insurance companies, and other health-related industries, all vigorously advocating different "consumer m-Health" products and services in a variety of standards and formats.

They range from smart consumer well-being trackers and health monitors, smart health watches, and various targeted healthcare and mobile disease management tools. These and other consumer-based m-Health monitoring devices are becoming increasingly popular and widely used in spite of the absence of large-scale clinical evidence of their healthcare outcomes and improved patient care. The proponents of this consumer's face of m-Health argue that this represents the best realistic path for future predictive healthcare and well-being, and that it potentially alleviates the current burdens of the symptomatic healthcare costs.

At the opposite end of the spectrum, we witness an increasing level of interest in the academic and medical research communities, which target cutting-edge research conducted in different areas of mobile healthcare, leading to many publications, reports, and articles that reflect the clinical outcomes of these studies. Mobile health is also being increasingly taught in related medical and health information training courses. However, regardless of the clinical outcomes of m-Health, there is an increasing trend by some healthcare providers to voice a cautionary note concerning the hype of m-Health, with nonconviction as to the real benefits, questioning its clinical effectiveness and efficacy. These are increasingly justified by the lack of global evidence of large-scale endorsements and acceptance of m-Health by healthcare providers and services. This picture, however, detracts from the clear global health benefits of m-Health.

Increasingly, experts and nonexperts alike are also confused by the plethora of alternative terms and abbreviations being used, such as *connected health*, *smart health*, and even *digital health*, which perhaps reflect this conundrum. These terms are being increasingly used to either replace or justify a new beginning or even shy away from m-Health for one reason or another. Perhaps these newer terms might also reflect the answer to the key question that everyone has been asking for years: *Is m-Health dead or has it just moved address?*

The answer clearly lies in the powerful market forces and economic benefits already mentioned, in addition to the daily supplement of hundreds of m-Health-related documents published in research and NGO reports, academic papers, books, market analysis documents, and online blogs and articles, as well as annual conferences and summits organized globally, reflecting a decade-long evolution of this healthcare technology concept.

Consideration for brevity and the desire to avoid wearying the well-informed by cataloguing what they will regard as obvious has led us to omit from these pages lengthy explanations of certain broad technical issues as much as possible. These issues might be unknown to that large group of general readers who look perplexed when the name "m-Health" arises in conversations, and who only brighten up when it is explained to them that in its most simplistic form it is the use of smartphones for healthcare! This book may, however, serve to bring before the wider spectrum of interested readers some clarification of such a "black hole" and outline something of the infinite variety of the concept. Furthermore, we hope that it will help both expert and lay readers to understand the complexity of m-Health. For this reason we have omitted mathematical equations from the text, but have referenced more detailed papers and books where appropriate.

Chapter 1 charts the evolution of m-Health more than a decade ago and how it was transformed from a mere academic concept to a global, albeit controversial, healthcare technology phenomenon.

Chapters 2–4 describe in detail the basics of the three enabling scientific technological elements of m-Health (sensors, computing, and communications). We describe how each of these key ingredients has evolved and matured over the last decade. We describe, for example, the rapid evolution of m-Health in parallel with the maturing process of its enabling technologies from biowearable sensors to the wireless and mobile communication technologies of 4G and 5G systems and beyond. We also detail in these chapters the impact of new computing and Internet paradigms from the Internet of things (IoT) to Web 2.0 and Health 2.0 on m-Health. We also discuss the role of the current m-Health Apps phenomenon and their clinical efficacy and design challenges, together with other issues such as the role of social networking and healthy data mining concepts on the future advances of "m-Health 2.0."

Chapter 5 illustrates some of the relevant medical aspects and clinical applications of m-Health. We endeavor to clarify some of the concerns and varying views that are being discussed and advocated by the medical community, particularly on the clinical efficacies and effectiveness of some of these smartphone-centric m-Health interventions and applications. These applications are supplemented by clinical examples and current studies, particularly in acute and chronic disease management, and in other important medical conditions. The studies provide clear clinical outcomes in some areas as well as ambiguous and unclear evidence in others.

Chapter 6 presents one of the most rewarding and successful areas of m-Health, which is the endorsement of the success of mobile health as a global health phenomenon. In this chapter, we describe successful applications and deployments of m-Health in various global health settings, particularly in developing countries. We also describe some examples of m-Health in postconflict regions in the world. These examples represent ample proof of the success of m-Health as a transformative concept for better and more effective healthcare delivery, especially in those areas where it is most needed, and where its clinical evidence is clear and its economic impact is justified.

Chapter 7 discusses m-Health markets, business and ecosystem models, and policy-related issues. This illustrates how consumer-led "m-Health" markets are, and will continue to be, one of the driving forces behind the global proliferation of m-Health markets, especially in specific areas of wellness and health monitoring, regardless of the healthcare outcomes and medical efficacy objectives and the pros and cons of markets.

In the last chapter, Chapter 8, we discuss the future of m-Health and we present a vision for its future direction and how this concept can potentially shape and transform healthcare services in the coming decades of the twenty-first century.

Finally, although it is not an easy task to write a book on m-Health and at the same time cover all the important aspects in one volume, we have attempted to include the most relevant issues. This book is mainly written to increase the general awareness and importance of m-Health, not only to interested stakeholders, such as clinicians, healthcare providers, patients, consumers, telecommunications and mobile phone

industries, and health insurers, but also to interested lay readers. The aim is to describe the initial philosophy of m-Health, its evolution, and current state of the art, where it is heading and, most importantly, how it can transform some the current healthcare services to better, more efficient, and affordable means of personalized care delivery.

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Special Acknowledgement: To Bryan, what can I say? Fate brought us together one autumn day in October 1990 when I stood for the first time at your office door at Loughborough University as your new Ph.D. student. Perhaps now you wish you had

the Star Trek "Tricoder" to "energize" me away to another Galaxy! Many thanks for your wonderful friendship and English sense of humor, and most of all for all the years of support that I will not forget.

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ACRONYMS

AAA	Authentication, Authorization, and Accounting
AAL	Ambient Assisted Living
ACA	Affordable Care Act
AECOPD	Acute Exacerbation of Chronic Obstructive Pulmonary Disease
AED	Academy for Educational Development
AHIMA	American Health Information Management Association
AI	Artificial Intelligence, Adherence Index
API	Application Programming Interface
ART	Anti-Retroviral Therapy
ASHA	Accredited Social Health Activists
ATM	Asynchronous Transfer Mode
BAN	Body Area Network
BANN	Body Area Nano-Network
BASN	Body Area Sensor Network
BG	Blood Glucose
BLE	Bluetooth Low Energy
BMI	Body Mass Index
BPM (bpm)	Beats Per Minute
BPSK	Binary Phase Shift Keying
BRICS	Brazil, Russian Federation, India, China, and South Africa
BSN	Body Sensor Network
BVP	Blood Volume Pulse
BWL	Behavioral Weight Loss
CCM	Chronic Care Model
CDISC	Clinical Data Interchange Standards Consortium

CDMA	Code-Division Multiple Access
CGM	Continuous Glucose Monitor
CHA	Continua Health Alliance
CHD	Coronary Heart Disease
CHW	Community Healthcare Worker
COPD	Chronic Obstructive Pulmonary Disease
CPS	Cyber-Physical System
CRED	Center for Research on the Epidemiology of Disasters
CRM	Cardiac Rhythm Management
CVD	Cardio Vascular Disease
D-AMPS	Digital Advanced Mobile Phone Access
DICOM	Digital Imaging and Communications in Medicine
DID	Device IDentification
DoS	Denial of Service
DPWS	Devices Profile for Web Services
DSCDMA	Direct Sequence Code-Division Multiple Access
ECG	Electro Cardio Gram
EDGE	Enhanced Data Rates for GSM Evolution
EEG	Electro Encephalo Gram
EHR	Electronic Health Record
EMA	Ecological Momentary Assessment
EMG	Electro Myo Gram
EMR	Electronic Medical Records
EPC	Evolved Packet Core or Electronic Product Code
EPR	Electronic Personal Record
ETSI	European Telecommunications Standard Institute
EU	European Union
EV-DO	Evolution-Data Optimized
FC	Frequency Channel, Frequency Control
FCC	Federal Communications Commission
FDA	Food and Drug Administration
FDD	Frequency-Division Duplex
GB	gigabyte
GDM	Gestational Diabetes Mellitus
GFSK	Gaussian Frequency Shift Keying
GHS	Ghana Health Services
GOLD	Global Initiative for Chronic Obstructive Lung Disease
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications, Group Spécial Mobile
GSMA	Group Spéciale Mobile Association
HA	Home Agent
HARQ	Hybrid Automatic Repeat Request
HBC	Human Body Communications
HbA1c	glycated hemoglobin (A1c)
HDFS	Hadoop Distributed File System

HetNet	Heterogeneous Networks
HIMSS	Healthcare Information and Management Systems Society
HIPAA	Health Insurance Portability Accountability Act
HITECH	Health Information Technology for Economic and Clinical Health
HIV	Human Immunodeficiency Virus
HR	Heart Rate
HRV	Heart Rate Variability
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSPA+	Evolved High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
HTTP	Hypertext Transfer Protocol
IaaS	Infrastructure as a Service
ICT	Information and Communication Technology
IDRC	International Development Research Council
IEEE	Institution of Electrical and Electronics Engineers (USA)
IETF	Internet Engineering Task Force
IHD	Ischemic Heart Disease
IHE	Integrating the Healthcare Enterprise
IHTSDO	International Health Terminology Standardization Committee
IHTT	Institute of Health Technology Transformation
IMS	Information Management System
IMT	International Mobile Telecommunications
IoE	Internet of Everything
IoT	Internet of Things
IP	Internet Protocol
IrDA	Infrared Data Association
ISM	Industrial, Scientific, and Medical (band)
ISO	International Organization for Standardization
IT	Information Technology
ITS	Intelligent Transport System
ITU	International Telecommunications Union
IVR	Interactive Voice Response
IWBAN	Implantable Wireless Body Area Network
IWG	Innovation Working Group
JIC	Joint Initiative Council
KM	Knowledge Mobilization
LEARNS	LEprosy Alert and Response Network and Surveillance System
LED	Light-Emitting Diode
LOS	Line-Of-Sight
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
LoWPAN	Low-Power Wireless Personal Area Network
MAC	Media Access Control

MARP	Most At-Risk Populations
MBAN	Medical Body Area Network
MBOFDM	Multiband Orthogonal Frequency-Division Multiplexing
MCC	Mobile Cloud Computing
MC-CDMA	Multi-Carrier Code-Division Multiple Access
MCOT	Mobile Cardiac Outpatient Telemetry
MDDS	Medical Device Data Systems
MDG	Millennium Development Goal
MEC	Mobile Edge Computing
MENA	Middle East and North Africa Region
MGMP	Mobile Gateway/Mobile Patient
MGSP	Mobile Gateway/Static Patient
MHRA	Medicine and Health Care Products Regulatory Agency
MICS	Medical Implant Communications Service
MIMO	Multiple-Input Multiple-Output
MMA	Mobile Medical Apps
MMC	Massive Machine Communication
MMS	Multimedia Messaging Service
MoH	Ministry of Health
MNO	Mobile Network Operator
MOS	Mean Opinion Score
m-QoE	Medical Quality of Experience
m-QoS	Medical Quality of Service
MTD	Machine-Type Device
M2M	Machine-to-Machine
M4RH	Mobile for Reproductive Health
NB	narrowband
NCD	Non Communicable Disease
NFC	Near-Field Communications
NGN	Next-Generation Networks
NGO	Nongovernment Organization
NHS	National Health Service
NICE	National Institute for Health and Care Excellence
N-LOS	Non-Line-Of-Sight
OFDMA	Orthogonal Frequency-Division Multiple Access
OLAP	Online Analytical Processing
OMI	Operational Medicine Institute
OQPSK	Offset Quadrature Phase-Shift Keying
PaaS	Platform as a Service
PAN	Personal Area Network
PANACeA	Pan-Asian Collaboration for e-Health Adoption and Application
PCC	Patient-Centered Care
PDA	Personal Digital Assistant

PGHD	Patient-Generated Health Data
PHC	Primary Health Centre
PHD	Personal Health Device
PHR	Public Health Record
PHY	PHYsical layer
PIN	Personal Identification Number
POC	Point Of Care
POTS	Plain Old Telephone Service
PPG	Photo Plethysmo Graphy
PQRST	Refers to Specific Points on an Electrocardiogram
PwC	PricewaterhouseCoopers
P2P	Peer-to-Peer
QCI	Quality of Service Class Identifier
QoE	Quality of Experience
QoS	Quality of Service
RCT	Randomized Control Trial
R&D	Research and Development
RFID	Radio Frequency Identification
RHM	Remote Health Monitoring
RMNCH	Reproductive, Maternal, Newborn, and Child Health
ROI	Return Of Investment
ROM	Read-Only Memory
RR	Respiratory Rate
SaaS	Software as a Service
SBA/FD	Skilled Birth Attendance and Facility Delivery
SC-FDMA	Single-Carrier Frequency-Division Multiple Access
SCII	Subcutaneous Insulin Infusion
SCL	Service Capabilities Layer
SD	Standard Deviation
SDN	Software-Defined Networking
SDO	Standards Development Organizations
SGSP	Static Gateway/Static Patient
SGMP	Static Gateway/Mobile Patient
SHARP	Strengthening HIV/AIDS Response Partnerships
S-ICD	Subcutaneous Implantable Cardiac Defibrillator
SIM	Subscriber Identity Module
SMAC	Social Networking, Mobile, Analytics and Cloud
SMBG	Self-Monitoring Blood Glucose
SME	Small-to-Medium-Sized Enterprise
SMS	Short Message Service
SNMP	Simple Network Management Protocol
SOC	System-On-Chip
SO-FDMA	Scalable Orthogonal Frequency-Division Multiple Access
SpO_2	Blood Oxygen Saturation

STI	Sexually Transmitted Infections
TB	Tuberculosis
TCP/IP	Internet Protocol
TDD	Time-Division Duplex
TDM	Time-Division Multiplexing
TDMA	Time-Division Multiple Access
TTC	Text to Change
T1D	Type 1 Diabetes
T2D	Type 2 Diabetes
UID	User Identification
UKIERI	United Kingdom–India Education and Research Initiative
UMTS	Universal Mobile Telecommunications System
UNHCR	United Nations High Commissioner for Refugees
USAID	United States Agency for International Development
UWB	Ultra-Wide Band
VLAN	Virtual Local Area Network
WAN	Wide Area Network
WBAN	Wireless Body Area Network
W-CDMA	Wideband Code-Division Multiple Access
WHO	World Health Organization
WIBSN	Wearable and Implantable Body Sensor Network
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WISE	Wireless Intelligent Sensors
WLAN (and Wi-Fi)	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WMTS	Wireless Medical Telemetry Services
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
WWAN	Wireless Wide Area Network
WWBAN	Wearable Wireless Body Area Network
1G	First Generation of mobile phones
2G	Second Generation of mobile phones
2.5G	"Two and a half G," midstage between 2G and 3G
3G	Third Generation of mobile phones
3GPP-LTE	Third Generation Partnership Program Long Term Evolution
3.5G	"three and a half G," midstage between 3G and 4G
3.9G	pre-4G Generation of mobile phones
4G	Fourth Generation of mobile phones
4PSK	Quadrature Phase Shift Keying
5G	Fifth Generation of mobile phones
5GPP	Fifth Generation Public–Private Partnership
8PSK	8 Phase Shift Keying