

FRANK R. MIELE, MSEE
President, Pegasus Lectures Inc.



VOLUME I

ULTRASOUND PHYSICS & INSTRUMENTATION

4TH EDITION

2006
Miele Enterprises, Inc.

The author and publisher of this book have used their best efforts in preparing this book. Their efforts include the development, research, and testing of the theories and problems to determine their effectiveness. The author and publisher shall not be liable in any event for incidental or consequential damages in connection with, or arise out of, the furnishing, performance or use of these programs.

This work is protected by United States copyright laws. Dissemination or sale of any part of this work (including on the World Wide Web) destroys the integrity of the work and is not permitted.

A Cataloging In Publication Record is available from the Library of Congress

Printed in the United States of America

Last Digit is the print number: 9 8 7 6 5 4 3 2 1

ISBN: 978-1-933250-06-9 Volume 1
978-1-933250-07-6 Volume 2
978-1-933250-08-3 Set of Volume 1 and 2

Copyright 2006 by Miele Enterprises, LLC

P.O. Box 157
Forney, TX 75126
www.pegasuslectures.com

All rights reserved. No part of this book may be reproduced in any form or by any means, electronic or mechanical, including photocopy, recording, or any information storage and retrieval system, without permission in writing from Miele Enterprises, LLC.

Dedication

This book is dedicated to my wife Carol, my mother Graziella, my three-year-old daughter Gina Luisa, my twenty-month-old daughter Cristiana Graziella, and in loving memory of my grandmother Gina Luisa: four generations of women who have shaped my life.

Of course I cannot forget my twenty-month-old son Franco Raffaello whose hugs redefine affection, or my eldest son Paul (forever Paulie to me), who loves to sit in on lectures and “help out.” Finally, I must acknowledge my father Frank, whose tireless work and selflessness afforded me educational opportunities for which I feel blessed.

A special thanks to my friends and colleagues who took the time and made the effort as section reviewers and who provided quality images. Your time, suggestions, and expertise are much appreciated.

THANK YOU TO THE FOLLOWING 4TH EDITION SECTION REVIEWERS

Ali AbuRahma MD, RVT

Professor of Surgery, Chief of Vascular Surgery, and Medical Director of Vascular Laboratory
Robert C. Byrd Health Sciences Center of West Virginia University, Charleston, West Virginia

Catherine Carr-Hoefer RDMS, RDCS, RVT, RT, FSDMS

Assistant Director, Diagnostic Imaging, Radiology, Good Samaritan Regional Medical Center, Corvallis, Oregon

M. Robert De Jong RDMS, RDCS, RVT

Radiology Technical Manager, Ultrasound, The Johns Hopkins Medical Institutions, Baltimore, Maryland

Carol J. Gannon RN, RVT, RDCS, FSVU

Vice President, Pegasus Lectures, Inc., Dallas, Texas

Debra R. Goines BS, RVT, RDMS, RTR

Clinical Application Specialist, Mountain View, California

Mark J. Harry RDCS, RVT

Private Consultant, Cardiac Ultrasound Consulting,
Des Moines, Iowa

Janice D. Hickey MRT, RDMS, BSc.

Clinical Instructor, Department of Emergency Medicine, Lehigh Valley Hospital, Allentown, Pennsylvania

Bonnie Johnson RDMS, RVT, FSVU

Director, Vascular Laboratory Services, Division of Vascular Surgery, Stanford University Medical Center, Palo Alto, CA

Ann Marie Kupinski PhD, RVT, FSVU

Technical Director, Karmondy Vascular Laboratory, The Vascular Group, Albany, NY
Assistant Professor of Surgery, Albany Medical College, Albany, NY

Naresh Kumar MD

Medical Director, Whitby Cardiovascular Institute, Whitby, Ontario, Canada

Ronald Mucci, PhD

Signal Processing Engineer, Tiverton, Massachusetts

Marsha M. Neumyer BS, RVT, FSVU, FAIUM

CEO and International Director, Vascular Diagnostic Educational Services, Vascular Resource Associates, Harrisburg, Pennsylvania

Kathleen Palmieri RVT

Senior Consultant, Cardiovascular Technology Resources (A Division of KRP Accreditation Specialists, Inc.), Skaneateles, New York

Patrick Rafter MS

Electrical Engineer, Boston, Massachusetts

Terry Reynolds BS, RDCS

Director, School of Cardiac Ultrasound, Arizona Heart Institute, Phoenix, Arizona

William B. Schroedter BS, RVT, FSVU

Technical Director, Quality Vascular Imaging, Inc., Venice, Florida

Robert Scissons RVT, FSVU

Technical Director, Bend Memorial Clinic Vascular Laboratory, Bend, Oregon

Franklin W. West RN, BSN, RVT, FSVU

Director of Professional Development, Pacific Vascular, Inc., Bothell, WA

THANK YOU TO THE FOLLOWING IMAGE CONTRIBUTORS

M. Robert De Jong RDMS, RDCS, RVT

Radiology Technical Manager, Ultrasound, The Johns Hopkins Medical Institutions, Baltimore, Maryland

Jeffrey C. Hill BS, RDCS, FASE

Echocardiographic Laboratory, Division of Cardiology, University of Massachusetts Medical Center, Worcester, Massachusetts

Robert Scissons RVT, FSVU

Technical Director, Bend Memorial Clinic Vascular

Laboratory, Bend, Oregon

Michael Stasik RVT

Senior Technologist, Cleveland Clinic Foundation, Cleveland, Ohio

David Tomberlin ARRT, RDCS, RVT

Lead Clinical Specialist, Cardiovascular, Dallas, Texas

Susan Whitelaw RVT, RDMS, RTR

Laboratory Supervisor, Cleveland Clinic Foundation, Cleveland, Ohio

ATS Laboratories, Bridgeport, Connecticut

CIRS, Inc., Norfolk, Virginia

Flometrics, Inc., Solana Beach, California

GE Healthcare, Milwaukee, Wisconsin

Onda Corporation, Sunnyvale, California

Pacific Vascular, Inc., Bothell, Washington

Philips Medical Systems, Bothell, Washington

Precision Acoustics, Inc., United Kingdom

Siemens Ultrasound, Mountain View, California

and special thanks to Carol, Debbie, Eric, Halan, and Monica whose tireless efforts helped bring this book to fruition.

PREFACE

Preface

The greatest challenge with writing a textbook is that every reader brings a different level of knowledge, experience, and goals with him or her. For some people, this book represents their first exposure to ultrasound, and the book is to serve as a foundation on which to build. Others bring twenty or more years of experience and use this book as a way reinforcing the principles on which they perform their daily scans, or as a means to better understand new ultrasound techniques. Some are using this book in an ultrasound educational program, and others are using this book to prepare for a credentialing exam. Add to these differences in experience and goals the fact that some people experience dramatic feelings of fear and loathing just from hearing the word “physics” and you have a real conundrum when determining how to structure a textbook.

It should now be clear that the myriad goals and levels of experience make this a very challenging book to write. No one book can be everything to everyone. So instead, this book is really three books in one. Topics are divided into levels so that different level students can progress at a pace appropriate for their background, experience, and goals. Beginning students can follow Level 1 throughout the book, leaving Level 2 and Level 3 for when they have more ultrasound experience. More advanced students can choose to skip Level 1 and go right to Level 2, or use Level 1 as a refresher and use Level 2 as a means of preparing for the credentialing exams and advancing their knowledge. Level 3 is intended for those readers who really want to be challenged, or for content that is perhaps outside the areas generally tested on the credentialing exams. Extensive “Keypoints” sections are included at the conclusion of each chapter to both integrate concepts and serve as a study guide. The following is a description of each level:

Level 1: **Ultrasound Physics Basics**

Level 1 material focuses on the underlying physics and basic concepts critical for developing skill in the use of diagnostic ultrasound. Level 1 presumes no knowledge other than the basic abilities that come from general schooling. This level also serves as a good refresher for people who have good ultrasound experience but weaker backgrounds in physics and basic mathematics.

Level 2: **Exam Level Ultrasound Physics**

Level 2 material covers basic topics often outlined on the credentialing exams. Furthermore, Level 2 material is intended to generate a more profound understanding of the concepts so that the relationship of the physics fundamentals to the quality of the diagnostic ultrasound is understood. In other words, understanding Level 2 should not only prepare you for your board exams, but also result in better patient care.

Level 3: **Advanced Ultrasound Physics Concepts and Applications**

Level 3 material contains advanced topics, newer ultrasound techniques, or even just higher level material for those people who want to be challenged. At times, Level 3 will also contain specific applications of the physics to a specialty area such as cardiac, vascular, or general ultrasound.

Keypoints:

The keypoints serve as a chapter-by-chapter review of the fundamental principles. These sections serve both as a means of highlighting the main points as well as an exam review. Many of the keypoints included serve as the basis for exam questions, and as such should be reviewed by all exam candidates.

The Importance of Understanding the Structure of this Book

There are three reasons why understanding the structure of this book is so important:

1. So that you can customize how you use the book to your experience level and goals.
2. So that you have a clear indication of when you are knowledgeable to take a credentialing exam.
3. So that you have a systematic approach to increase your knowledge and clinical abilities from your current state.

In addition to serving as a core for an ultrasound physics program and a reference for your laboratory, this textbook has also been designed as an independent learning program to assist candidates preparing for their credentialing and board exams. Volume II, Appendix C contains a comprehensive Test Taking Strategies section to help improve your test taking skills including specific approaches detailing the incorporation of logic and reasoning skills for multiple choice exams. This section should be reviewed before and after reading the text. Volume II, Appendix M contains study suggestions, a study guide, and instructions for obtaining continuing medical education credits.

A Final Word about this Book's Structure:

There are many ultrasound physics books that either overshoot or undershoot the intended goals of the reader. In addition, there are books that are very easy to read, but stop short of building the knowledge necessary to demonstrate competence on a credentialing exam. More importantly, these books fall short of imbuing the reader with the knowledge necessary to improve patient care. There are other books that, although technically excellent, presume too much knowledge for most people such that the reader feels as if they are drowning from the very first page. By writing this book in three different levels, I am hoping to reach out to a wider audience, increasing knowledge for both the experienced and the neophyte in ultrasound. I have chosen to create a book that takes students through the first level and beyond with a clear path to the knowledge necessary to demonstrate competency at the credentialing exam level. I hope I have written a book that does not presume so much knowledge that students become overwhelmed and are afraid to utilize the text, but on the other hand pushes and challenges the student to continue learning. In essence, I have tried to write this book so that each level becomes appropriate as the reader's knowledge grows.

I believe the first step to knowledge is a true assessment of where you are, where you want to be, and what path you are willing to take to get there.

And so starts the journey ...

**Pegasus Lectures Physics and Instrumentation
Independent Learning Program**

*Jointly Sponsored by A. Webb Roberts Center for Continuing Medical Education of
Baylor Health Care System, Dallas
and Pegasus Lectures, Inc.*

CME ENDURING MATERIAL INFORMATION

Faculty

Frank Miele, MSEE
President, Pegasus Lectures, Inc.

Frank graduated cum laude from Dartmouth College with a triple major in physics, mathematics, and engineering. While at Dartmouth, he was a Proctor Scholar and received citations for academic excellence in comparative literature, atomic physics and quantum mechanics, and real analysis. After completing his graduate work, Frank was awarded the Ruth Goodrich Prize for Academic Excellence. After co-teaching a course in digital electronics at Dartmouth, Frank was a research and design engineer and project leader, designing ultrasound equipment and electronics for more than ten years. In that role, Frank designed the hardware for the first parallel processing color Doppler system, created a Doppler system platform, designed HPRF Doppler, created the first released adaptive ultrasound processing technique, designed transcranial Doppler and transcranial imaging, worked on multiple transducer project teams, and performed extensive clinical trial testing and research.

Frank has been the vice president of Research and Development and chief scientist for a medical device company investigating ultrasound related hemodynamic based measurements. As a researcher and designer of ultrasound, he has lectured across the country to sonographers, physicians, engineers, and students on myriad topics. Frank has authored the Ultrasound & Physics Instrumentation Independent Learning Program, produced multiple educational videos, created exam simulation programs, as well as created the analysis algorithm method and apparatus for evaluating educational performance (patent pending). Frank has served as an author and Co-Chief editor for the ASCeXAM Simulation Review CD in conjunction with the American Society of Echocardiography. He has also served on the faculty for the Society of Vascular Ultrasound and Society of Vascular Surgery and is credited with several ultrasound and medical device patents, trade secrets, and publications.

Purpose and Target Audience

This activity is designed to familiarize physicians and sonographers with the physics and instrumentation concepts employed in diagnostic ultrasound and provide a method to prepare for ultrasound physics credentialing exams and/or accreditation. It will be of interest to, but not limited to, radiologists, cardiologists, neurologists, vascular surgeons, cardiovascular surgeons, anesthesiologists, and/or physicians providing interpretation of diagnostic ultrasound, preparing for accreditation, and/or desiring to improve their understanding of ultrasound physics.

Medium

Printed text
CD

Objectives

Upon completion of the activity, the participant should be able to:

- Define areas of strengths and weaknesses in their understanding of ultrasound physics.
- Comprehend the effect of system controls and transducer parameters on the diagnostic quality of an ultrasound image.
- Demonstrate improved understanding of ultrasound physics and how physics can affect the integrity of a diagnostic image.
- Demonstrate improved interpretative skills for diagnostic ultrasound, Doppler and hemodynamic variables.
- Demonstrate improved preparation for the ultrasound physics credentialing exam.

CME Credit

This activity has been planned and implemented in accordance with the Essential Areas and Policies of the Accreditation Council for Continuing Medical Education (ACCME) through the joint sponsorship of the A. Webb Roberts Center for Continuing Medical Education of the Baylor Health Care System, Dallas and Pegasus Lectures, Inc.

The A. Webb Roberts Center for Continuing Medical Education of Baylor Health Care System, Dallas designates this educational activity for a maximum of 35 Category 1 credits toward the AMA Physician's Recognition Award. Each physician should claim only those credits that he/she actually spent in the activity.

The A. Webb Roberts Center for Continuing Medical Education of Baylor Health Care System, Dallas is accredited by the ACCME to provide continuing medical education for physicians.

Faculty Disclosure

Frank Miele is the president of Pegasus Lectures, Inc. and owner of Miele Enterprises, LLC.

No unlabeled or investigational uses of a product or medical device are addressed in this CME activity.

Instructions

Participants must:

1. Read Volumes I & II of Ultrasound Physics and Instrumentation
2. Complete conceptual questions and exercises within Volumes I & II
(Refer to study suggestions in Vol. II, Appendix M)
3. Complete the final exam and evaluation

Final Exam, Evaluation and Processing Fee

At the conclusion of this activity, participants must complete the final exam and the evaluation. A completed evaluation form must accompany the final exam. Please indicate on the evaluation form if you are applying for AMA/PRA Category 1 credit or SDMS CME credit and if you are a U.S. licensed physician or not. There is a \$30 processing fee for AMA/PRA Category 1 credit. **The check for AMA/PRA credit should be made payable to: A. Webb Roberts Center.** Participants should send the original final exam for scoring (no copies accepted), the processing fee, the evaluation and any correspondence to:

**Pegasus Lectures, Inc.
PO Box 157
Forney, TX 75126**

**Tel: 972-564-3056
Fax: 972-552-9186**

NOTE: Participants must achieve a **75% pass rate** on the final exam to be awarded AMA/PRA CME credit. Feedback on exam scores will be provided. A CME certificate will be mailed directly to the participant from the A. Webb Roberts Center for Continuing Medical Education of Baylor Health Care System, Dallas.

Date of Original Release: May 2001
Date of Most Recent Update: October 2005

Estimated time to complete the educational activity: 35 hours



This independent learning educational activity has been approved for 35.0 hours of SDMS CME credit. Each participant should claim only those hours of credit that he/she actually spent in the educational activity.

At the conclusion of this activity participants should complete the final exam and evaluation. A completed evaluation form must accompany the final exam. *Please indicate on the evaluation form if you are applying for AMA/PRA Category 1 credit or SDMS CME credit.* Participants should send the final exam, evaluation and any correspondence to:

**Pegasus Lectures, Inc.
P.O. Box 157
Forney, TX 75126**

**Tel: 972-564-3056
Fax: 972-552-9186**

Participants must achieve a 75% pass rate on the final exam to be awarded CME credit. A CME certificate will be mailed directly to the participant from Pegasus Lectures, Inc.

TABLE OF CONTENTS

VOLUME 1

CHAPTER 1 - Mathematics

Introduction.....	1
1. Mathematic Basics	3
1.1 Numbers.....	3
1.2 Basic Mathematical Notation (symbols used in basic mathematics)	3
1.3 Basic Mathematical Definitions	4
1.4 The Value of Estimating	4
1.5 Exercises: Estimating	4
2. Fractions, Decimal Form, and Percentages	5
2.1 Exercises: Fractions and Percentages	7
3. Reciprocals	7
3.1 Exercises: Reciprocals.....	8
4. Units	8
5. Variables	9
6. Applying Reciprocals	10
6.1 Exercises: Applying Reciprocals.....	11
7. Numbers Raised to a Power	12
7.1 Positive Powers.....	12
7.2 Exercises: Numbers to a Positive Power	13
7.3 Numbers to a Negative Power	14
7.4 Exercises: Numbers to a Negative and Positive Power.....	14
7.5 Numbers to the Zero Power and Exponent Rules.....	15
7.6 Exercises: Numbers to the Zero Power and Exponent Rules	16
8. Exponential Form (Notation)	17
8.1 Exercises: Exponential Notations.....	18
8.2 Deciding How to Write a Number.....	19
8.3 Exercises: Deciding How to Write a Number	19
9. The Metric System and Metric Abbreviations	19
9.1 Conversions for Metric and Non-metric Systems	19
9.2 Metric Abbreviations	20
9.3 Exercises: Metric Abbreviations.....	22
9.4 Abbreviations: Physical Units	22
9.5 Combining Abbreviations.....	23
9.6 Exercises: Combining Abbreviations	24
9.7 Reciprocals of Metric Units.....	24
9.8 Exercises: Reciprocals of Metric Units	24
9.9 Converting Between Metric Units.....	25
9.10 Another Approach to Conversions (a more intuitive approach).....	26
9.11 Exercises: Conversions.....	28
9.12 Exercises: Using Exponents	28
10. Proportionality and Inverse Proportionality	29
10.1 Direct Proportionality	29
10.2 Direct Linear (Simple) Proportionality.....	29
10.3 Inverse (Simple) Proportionality	30
10.4 Exercises: Proportionality and Inverse Proportionality.....	32

11. Distance Equation	33
11.1 Exercises: Distance Equation	34
12. Math Terminology	35
12.1 The Language of Mathematics: Translating English into Mathematics	35
12.2 Mathematical Definition	35
12.3 Exercises: Math Terminology	37
13. Distance Equation Revisited	39
13.1 The Roundtrip Effect	39
13.2 When the Propagation Velocity of 1540 m/sec is Incorrect	41
13.3 Exercises: Distance Equation Revisited	42
14. Non-Linear Relationships	43
14.1 Direct Non-Linear Proportionality	43
14.2 Complex - Inverse Proportionality	44
15. Interpreting Relationships Within Linear and Non-Linear Equations	44
15.1 Assessing an Equation and Expressing the Relative Relationship	44
15.2 Exercises: Assessing an Equation	46
15.3 Exercises: Proportionality	47
16. Dealing with Percentage Change	48
16.1 Simple Calculations with Proportional Variables	48
16.2 Calculations with Non-linearly Related Variables	49
16.3 Rules for Dealing with Percentage Change	49
16.4 Examples	49
17. Logarithms	51
17.1 Properties of Logarithms	52
17.2 Exercises: Logarithms	53
18. Trigonometry	53
18.1 Angles, Quadrants and Signs	57
18.2 The Value of Knowing Basic Trigonometry in Ultrasound (and Medicine)	58
18.3 Exercises: Trigonometry	59
19. The Decimal System and the Binary System	61
19.1 Decimal (Base 10) and Binary (Base 2)	61
19.2 Exercises: Decimal Conversions	62
19.3 Binary	62
19.4 Converting from Binary to Base 10	63
19.5 Converting from Decimal to Binary	64
19.6 Exercises: Binary	65
20. Analog to Digital (A/D) Conversion	66
21. Nyquist Criteria	71
22. Addition of Waves	76
22.1 Constructive Interference (In Phase Waves)	76
22.2 Destructive Interference (Out of Phase Waves)	77
22.3 Partial Constructive (or Partially Destructive) Interference	77
 CHAPTER 2 - Waves	
Introduction	81
1. The Motivation for Studying Waves	81
2. Waves	81
2.1 Definition of a Wave	81
2.2 Examples of Waves	82

3.	Classification of Waves	82
3.1	Benefit to Classifications	82
3.2	Electromagnetic (EM) Waves.....	83
3.3	Mechanical Waves.....	83
4.	Conceptual Questions.....	84
5.	Propagation of Mechanical Waves	84
5.1	Transverse Waves	84
5.2	Longitudinal Waves.....	85
5.2.1	Definition and Depiction.....	85
5.2.2	Developing a More Thorough Understanding of Longitudinal Waves.....	86
5.3	Problems with Static Drawings of Waves	86
6.	Variations in the Medium with Propagation (Acoustic Variables).....	88
6.1	Pressure.....	88
6.2	Density.....	89
6.2.1	The Equation for Density	89
6.2.2	Density as an Acoustic Variable.....	89
6.3	Temperature.....	89
6.3.1	Generation of Heat	89
6.3.2	Measuring Temperature	90
6.4	Particle Motion	90
7.	Conceptual Questions.....	90
8.	Wave Characteristics and Parameters.....	92
8.1	General.....	92
8.2	Four Basic Parameters and the Many Associated Parameters.....	92
8.3	Frequency (f) and Period (P)	93
8.3.1	General.....	93
8.3.2	Frequency of a Sound Wave	93
8.3.3	Graphical Depiction of Frequency.....	93
8.3.4	Determining the Frequency	94
8.3.5	The Relationship Between Time (Period) and Frequency	94
8.3.6	Interpreting the Period	95
8.4	Propagation Velocity.....	96
8.4.1	Defining Speed and Velocity.....	96
8.4.2	Units and Graphical Representation	96
8.4.3	What Determines the Speed of Sound	96
8.4.4	Graphical Depiction of Propagation Speed for Sound Waves	97
8.5	Wavelength	98
8.5.1	Definition	98
8.5.2	Graphical Representation.....	99
8.5.3	Distinguishing the Wavelength from the Period.....	99
8.5.4	What Determines the Wavelength.....	100
8.5.5	The Wavelength Equation.....	101
8.5.6	Different Ways of Remembering the Wavelength Equation.....	101
8.6	Amplitude.....	102
8.6.1	Definition	102
8.6.2	Units.....	102
8.6.3	Graphical Representation.....	102
8.6.4	Calculating the Amplitude	103
9.	Conceptual Questions.....	105

10. Exercises.....	108
11. Relating Wave Characteristics to Application and Relevance in Diagnostic Ultrasound	110
12. Wave Characteristics and Parameters.....	110
12.1 Frequency and Period	110
12.2 The General Term Frequency	110
12.2.1 Classifications of Sound.....	111
12.2.2 Intravascular Ultrasound (Frequencies Above the Typical Diagnostic Range)	113
12.2.3 Therapeutic Ultrasound (Physiotherapy and HIFU).....	113
12.2.4 Relation to Future Topics.....	114
12.3 Propagation Velocity.....	114
12.3.1 General.....	114
12.3.2 Terminology: Elasticity, Compressibility, Stiffness, and Bulk Modulus.....	114
12.3.2.1 Elasticity	114
12.3.2.2 Compressibility.....	115
12.3.2.3 Stiffness (Inelasticity).....	115
12.3.2.4 Bulk Modulus	115
12.3.2.5 Table Relating Terminology	115
12.3.3 The Propagation Velocity Analogy	116
12.3.4 Relating the Analogy to the Speed of Sound	118
12.3.5 Putting the Pieces Together to Create the Equation.....	119
12.3.6 Propagation Velocities for Various Materials	120
12.3.7 Discussion of Values in the Materials Table	120
12.3.8 What Affects Velocity Most in the Body	121
12.3.9 Propagation Velocities in the Body.....	121
12.3.10 Discussion of Values in the Biological Table.....	122
12.3.11 The Propagation Velocity Assumed by the Ultrasound System	122
12.3.12 Relation to Future Topics.....	123
12.4 Wavelength	123
12.4.1 The Equation and its Importance.....	123
12.4.2 Control of the Wavelength	123
12.4.3 Calculating the Wavelength	123
12.4.4 Relation to Future Topics.....	125
12.5 Amplitude	125
12.5.1 Control of Electrical Amplitude and Transmit Gain.....	125
12.5.1.1 Effect on Acoustic Pressure Field.....	125
12.5.1.2 Relationship to Acoustic Power.....	126
12.5.1.3 Relationship to Acoustic Intensity.....	127
12.5.2 Relation to Future Topics.....	129
13. Decibels (dB).....	130
13.1 The Need for Decibels.....	130
13.2 The Definition of Decibels	130
13.3 The Equation for Decibels.....	130
13.4 Applying the Equation for Decibels	131
13.5 The Amplitude Form of the Decibel Equation	132
13.6 Why Two Forms and When to Use Which Form	133
13.7 Exercises.....	134
14. Comparing Frequency with Amplitude	135
14.1 Frequency and Amplitude are Disjoint.....	135
14.2 Graphical Representation	135
14.3 Exercises.....	136
15. Conceptual Questions.....	137

CHAPTER 3 - Attenuation

Introduction.....	143
1. Attenuation.....	143
2. Absorption.....	143
2.1 Absorption and Viscosity.....	144
2.2 Absorption and Frequency Dependence.....	144
3. Reflection.....	144
3.1 Geometric Aspects of Reflection.....	144
3.1.1 Defining Terms.....	144
3.1.2 Specular Reflection.....	148
3.1.3 (Back) Scattering.....	149
3.1.4 Rayleigh Scattering.....	149
3.2 Acoustic Aspects of Reflection.....	150
3.2.1 Momentum Analogy.....	150
3.2.2 Defining the Acoustic Impedance.....	150
3.2.3 Impedance Mismatch Analogy.....	151
3.2.4 Conservation of Energy.....	151
3.2.5 Reflection Equation.....	151
3.2.6 Transmission Equation.....	152
3.2.7 Applying the Concept of Acoustic Impedance Mismatch.....	153
4. Refraction.....	153
4.1 Refraction Defined.....	153
4.2 Visualizing Refraction.....	153
4.3 Oblique Incidence but No Change in Propagation Velocities.....	154
4.4 Normal Incidence (Incident angle = 0 degrees).....	155
4.5 Snell's Law.....	156
4.5.1 The Equation.....	156
4.5.2 Determining Degrees of Refraction from the Transmission Angle.....	157
4.6 The Critical Angle.....	158
5. Conceptual Questions.....	159
6. Ultrasound Terminology.....	160
6.1 Echogenicity.....	160
6.2 Uniformity.....	161
6.3 Plaque Surface Characteristics.....	162
7. Attenuation Rates.....	162
7.1 Table of Attenuation Rates.....	162
7.2 Calculating Approximate Attenuation.....	162
7.3 Interpreting Calculated Attenuation.....	163
8. Absorption in the Body.....	163
8.1 In Soft Tissue, Absorption is the Dominant Factor Creating Attenuation.....	163
8.2 Absorption Increases Exponentially with Increasing Frequency.....	164
8.3 Fluids and Absorption.....	164
9. Reflection in the Body Based on Geometric Conditions.....	164
9.1 Specular Reflection.....	164
9.1.1 Examples of Specular Reflectors.....	165
9.1.2 Specular Reflection the Principal Source of Imaging Artifacts.....	166
9.1.3 Identifying Specular Reflection Based Artifacts (Step-by-Step).....	167
9.2 Scattering in the Body.....	168
9.2.1 Speckle and "Tissue Texture".....	168

9.2.2	Examples of Scattering in the Body	168
9.3	Rayleigh Scattering.....	169
9.3.1	Wavelength Relative to Red Blood Cells (RBCs)	169
9.3.2	Some Consequences of Rayleigh Scattering	169
9.4	Reflection in the Body Based on Acoustic Aspects.....	169
9.4.1	The Acoustic Impedance Mismatch.....	169
9.4.2	The Acoustic Impedance.....	170
9.4.3	Examples.....	170
9.4.4	Considering Tissue as an Infinite Series of Small Mismatches	174
9.4.5	Water-Path Scanners	174
9.4.6	Important Points About Scattering, Specular Reflections, and Rayleigh Scattering ..	175
10.	Refraction in the Body	176
10.1	Effects of Refraction.....	176
10.2	The Critical Angle and Refractive Shadowing	178
10.3	Applying Snell's Law	179
10.4	Important Points about Refraction.....	181
11.	Exercises.....	182
12.	Review of Attenuation.....	183
13.	Table of Acoustic Values	185
14.	Reflection and Transmission Percentage for Non-normal Incidence	186
15.	Matching Layer	186
16.	Two Matching Layers.....	188
17.	Determining the Maximum Imaging Depth for the Dynamic Range.....	190

CHAPTER 4 - Pulsed Wave Operation

Introduction.....	193
1. Motivation for Using Pulsed Wave (PW).....	193
1.1 Range Ambiguity and Continuous Wave (CW).....	193
1.2 Range Specificity and Very Short Pulse	194
1.3 Range Specificity and Longer Pulse Pulsed Wave (PW).....	194
1.4 Range Ambiguity and a Longer Pulse	195
2. Pulsed Wave Definitions	196
2.1 Time Related Pulsed Wave Definitions	196
2.1.1 Pulse Duration (PD).....	196
2.1.2 Pulse Repetition Period (PRP).....	196
2.1.3 Duty Factor (Duty Cycle)	197
2.2 Distance Related Pulsed Wave Definitions	199
2.2.1 Spatial Pulse Length (SPL).....	199
2.2.2 The Spatial Pulse Length and Range Resolution.....	200
2.2.3 Other Names for Range Resolution	201
3. Relating Wave Parameters and Pulsed Wave (PW) Parameters.....	201
3.1 The Difference Between a Wave Parameter and a PW Parameter	201
3.2 Time Related Wave Parameters and a PW Parameters.....	201
3.2.1 Pulse Duration (PD) and Period (P).....	201
3.2.2 PRP (and PRF) and Propagation Velocity and Imaging Depth.....	202
3.2.3 Duty Factor and Wave Parameters.....	202
3.3 Distance Related Pulsed Wave Definitions.....	203
3.3.1 Spatial Pulse Length and Wavelength.....	203
3.3.2 Axial Resolution	204

4.	The Foundational Drawing for Pulsed Wave	204
5.	Pulsed Wave and the Need to Understand Timing	205
6.	Definitions for Pulse Wave Related Imaging Parameters.....	205
7.	Scanned and Non-Scanned Modalities.....	206
7.1	Scanned Modalities.....	206
7.2	Non-scanned Modalities.....	207
8.	Relating PW Parameters to Ultrasound.....	208
8.1	The Pulse Duration.....	208
8.2	The Pulse Repetition Period and the PRF	209
8.2.1	Dependence on the Imaging Depth.....	209
8.2.2	Sample Calculations	210
8.2.3	The Use of the Words Maximum and Minimum.....	211
8.3	The Spatial Pulse Length.....	211
8.3.1	Frequency and Pulse Length.....	211
8.3.2	Cycles and Pulse Length.....	212
8.3.3	Backing (Damping) Material.....	212
8.4	Using the PRP (Line Time) to Calculate the Frame Time (and Frame Rate).....	212
8.4.1	Temporal Resolution and Non-Scanned Modalities	212
8.4.2	Temporal Resolution and Scanned Modalities	213
8.4.3	Frame Time and Frame Rate.....	213
8.4.4	Frame Time (Frame Rate) Equation	214
8.4.5	Frame Rate Examples	214
8.5	Comparing Temporal Resolution for Scanned and Non-Scanned Modalities.....	215
9.	Color Doppler, Frame Rate, and Temporal Resolution	215
9.1	General.....	215
9.2	Creating a Color Scan.....	215
9.3	Calculating the Color and Overall Frame Rate	216
9.4	Color and Poor Temporal Resolution	217
9.5	Choosing a Packet Size, the Trade-Off.....	218
10.	Optimizing Frame Rate and Temporal Resolution.....	218
11.	Typical Values and Ranges for Wave, PW and Frame Parameters.....	219
12.	The Foundational Drawing for Pulse Wave Revisited	220
13.	Exercises	221
14.	Bandwidth	222
14.1	Bandwidth Defined.....	222
14.2	Pictorial Representation of Bandwidth.....	222
14.3	Bandwidth Calculation	223
14.4	Fractional Bandwidth	223
14.5	Quality Factor.....	223
14.6	The Value of Greater Bandwidth	223
14.6.1	Flexibility.....	223
14.6.2	Dynamic Frequency Tuning (Sliding Receive Filters).....	224
14.6.3	Harmonic Imaging.....	226
14.6.4	Frequency Fusion (Frequency Compounding)	226
14.6.5	CW Doppler and Bandwidth.....	226
15.	Pulse Duration (Width) vs. Bandwidth	227
15.1	The Reciprocal Relationship	227
15.2	The Meaning of the Operating Frequency and Bandwidth Relationship.....	228
15.3	Bandwidth Required for Doppler	228
16.	Conceptual Questions.....	228

CHAPTER 5 - Transducers

Introduction.....	233
1. Transducer Basics.....	233
1.1 Transducers Defined.....	233
1.2 Examples of Transducers.....	234
1.3 Ultrasound Transducers and Bi-directionality.....	234
2. Ultrasound Transducers and the Piezoelectric Effect.....	234
2.1 The Piezoelectric Effect.....	234
2.2 The Piezoelectric Mechanism.....	235
2.3 Natural Piezoelectric Materials.....	236
2.4 Manufactured Piezoelectric Materials.....	236
2.5 Poling.....	237
2.6 Curie Point.....	237
3. Frequency of Operation and Crystal Dimension.....	237
3.1 Pulse Wave.....	237
3.2 Continuous Wave.....	239
4. Impulse Response of a Transducer.....	240
5. Beam Characteristics with a Simple, Single Disc Transducer.....	240
5.1 Simple, Single, Disc Transducers.....	240
5.1.1 Physical Dimensions of the Crystal.....	240
5.1.2 The Beamshape.....	241
5.2 The Beam Parameters.....	243
5.2.1 Depth (axial, longitudinal, radial, axial).....	243
5.2.2 Beamwidth: Lateral (azimuthal, side-by-side, transverse, angular).....	243
5.3 The Natural Focus.....	243
5.4. Varying the depth of the Natural Focus.....	244
6. Limitations of the Simple Crystal.....	244
7. Minimizing the Acoustic Impedance Mismatch.....	245
7.1 High Impedance Piezoceramics.....	245
7.2 Matching Layer.....	245
7.3 Quarter Wavelength Thickness.....	246
7.4 Composites with Lower Acoustic Impedances.....	246
8. Axial Resolution and Backing Material.....	247
8.1 Axial Resolution.....	247
8.2 Backing Material.....	247
9. Lateral Resolution.....	248
9.1 Equation.....	248
9.2 Changing the Focus.....	249
9.2.1 Lenses.....	249
9.2.2 Curved Surface.....	250
9.2.3 Diffraction Limiting.....	250
10. Simple Block Diagram Model of a Transducer.....	250
11. Exercises.....	251
12.	Beam Dimensions Revisited
252	
12.1 Depth of Focus (Focal depth) and Equation.....	252
12.1.1 Equation.....	252
12.1.2 Using the Modified Equation.....	253

12.1.3	Effect of Aperture on NZL.....	253
12.1.4	Effect of Frequency on NZL.....	254
12.2	Depth of Field (focal region).....	255
12.3	True Beam Shapes.....	255
12.4	Changing Intensity from Beam Convergence and Divergence.....	256
13.	Transducer Evolution Overview.....	257
14.	Imaging Dimensions.....	258
15.	..... The Pedof (Blind, Doppler Only Transducer)	259
16.	Sequencing.....	260
17.	Linear Switched Array.....	261
18.	Mechanically Steered.....	262
19.	Mechanical Annular Array.....	265
20.	Electronic Steering.....	267
20.1	Understanding the Term Phase.....	267
20.2	Electronic Steering for Transmit.....	268
20.3	Electronic Steering for Receive.....	269
20.4	Electronic Focusing for Transmit.....	270
20.5	Electronic Focusing for Receive.....	271
20.6	Focusing and Steering Together.....	271
21.	Phased Array Sector.....	272
22.	..... Linear Phased Array	275
23.	Curved Linear Phased Array.....	280
24.	..... Multi-dimensional Arrays	281
24.1	1.5-D Arrays.....	281
24.2	2-D Arrays.....	282
25.	Piezocomposite Materials.....	282
26.	Detail Resolution.....	283
26.1	Lateral Resolution.....	283
26.2	Elevation Resolution.....	284
26.3	Axial Resolution.....	285
27.	..... Important Concepts for Transducers	285
28.	Exercises.....	287
29.	Conceptual Questions.....	290
30.	The Piezoelectric Effect.....	294
30.1	Use of Piezoelectric Materials.....	294
30.2	Crystal Structures.....	294
30.3	Intermolecular Bonds.....	294
30.4	Polarization.....	295
 CHAPTER 6 - System Operation		
	Introduction.....	301
1.	The Basic Processes of Real-Time Imaging.....	301
2.	Important System Definitions.....	302
2.1	Transmit Power.....	302
2.2	Dynamic Range.....	303

2.3	Signals, Noise, and Signal-to-Noise Ratio (SNR).....	303
2.3.1	Definitions.....	303
2.3.2	What Determines a Good SNR.....	303
2.3.3	Apparent SNR, Gain, and True SNR.....	304
2.3.4	Relating SNR, Noise Floor, and Apparent SNR Ultrasound Images.....	305
2.3.5	Sources of Noise.....	307
2.3.6	Clutter One Moment May Be Signal the Next.....	307
2.4	Preprocessing and Post Processing.....	308
2.4.1	Conventional Definitions.....	308
2.4.2	Changes in the Preprocessing and Post Processing Paradigm.....	308
3.	Basic Functions of a System (Simplified).....	308
3.1	Putting the Pieces Together.....	309
4.	Transmitter (Pulser – Transmit Beamformer).....	309
4.1	Function.....	309
4.2	The System Control for Transmit Power.....	310
4.3	Practical Concerns.....	310
5.	Receiver.....	310
5.1	Amplification (Receiver Gain).....	310
5.1.1	Need for Amplification.....	310
5.1.2	Amplification of the RF Signal.....	311
5.1.3	The System Control.....	312
5.2	Compensation (Time Gain Compensation).....	313
5.2.1	The Role of TGC.....	313
5.2.2	Compensation of the RF Signal.....	313
5.2.3	The Relationship Between TGCs and Receiver Gain.....	313
5.2.4	Depth and TGC Zones.....	314
5.3	Compression.....	315
5.3.1	Dynamic Range.....	315
5.3.2	Compression and Dynamic Range.....	315
5.3.3	Effects of Compression and Information Loss.....	316
5.3.4	Compression of the RF Signal.....	316
5.4	Demodulation.....	318
5.4.1	Modulation and Demodulation.....	318
5.4.2	Rectification.....	318
5.4.3	Envelope Detection (Smoothing).....	318
5.4.4	The Detected Signal and A-Mode.....	319
5.5	Reject.....	320
6.	A-mode (Amplitude mode).....	320
6.1	A-mode Display.....	320
6.2	Interpreting an A-mode.....	321
6.3	The Use of A-mode.....	321
7.	Exercises.....	322
8.	System Block Diagram.....	323
9.	Controls that Affect Transmit and Power Distribution.....	324
9.1	Transducer Frequency and Transmit Power.....	324
9.2	Imaging Modalities and Image Size Transmit Power.....	324
9.3	Imaging Depth and Transmit Power.....	324
9.4	Focus and Transmit Power.....	324
10.	TGC and Gain Revisited.....	326

10.1	Internal TGC Profiles.....	326
10.2	Internal Color TGC Profiles	327
10.3	“Pre-compensated” TGC Profiles.....	327
10.4	TGCs and Imaging Scenarios.....	328
11.	Analog to Digital Conversion	331
11.1	Front End and Back End of an Ultrasound System.....	331
11.2	Role of the Beamformer	331
11.3	Analog Received Signal and Digital Output to Back End.....	331
11.4	The Motivation for Converting from Analog to Digital	332
12.	Scan Conversion.....	332
12.1	Paradigm Shift: From A-mode to B-mode	332
12.2	Creating a B-mode From an A-mode	333
12.3	The Role of the Scan Converter	335
12.4	Polar Scan Conversion and Lateral Distortion	335
12.5	Inconsistent Terminology in the Field	336
13.	Preprocessing and Post Processing Revisited	336
13.1	Understanding the Difference.....	336
14.	Compression.....	337
14.1	Compression: A Multi-Stage Process	337
14.2	Dynamic Range of 2-D Echoes	337
14.3	Dynamic Range of the Human Eye	338
14.4	Why the System Allows for Compression in the Back End of the System.....	339
14.5	Compression Controls on the System.....	340
14.6	Using Compression Controls Correctly.....	342
15.	Tissue Colorization.....	343
16.	Measurements	344
16.1	Area Measurements	344
16.1.1	Tracing an Area.....	344
16.1.2	Calculated From the Radius.....	345
17.	Video Display and Monitors.....	346
17.1	CRT.....	346
17.2	Monitor Formats and “Standards”	346
17.2.1	NTSC (United States) Format.....	347
17.2.2	PAL	347
17.2.3	SECAM.....	347
17.3	Why the Monitor Frame Rate Matters.....	348
17.4	Non-Interlaced Monitors	348
17.5	Subdividing Horizontal Lines into Pixels.....	349
17.5.1	Pixels and Brightness Levels	349
17.6	Relating Brightness Levels to Binary	350
17.7	Brightness Levels and Ambient Light	351
18.	Data Storage Devices (External).....	352
18.1	Disadvantages of Analog Storage Devices.....	352
18.2	VHS and SVHS (VCR)	353
18.3	Disadvantages of Digital Storage Devices	353
18.3.1	Digital Storage Advantages	353
18.3.2	Digital Storage Disadvantages.....	353
19.	Data Storage (Internal).....	353
19.1	Cine (Cineloop) Review	353

19.2	Purposes for Cine Review	354
19.3	The Recording Length of a Cine Memory.....	354
20.	Zoom (Res Mode, Magnification).....	354
20.1	Acoustic Versus Non-acoustic	354
20.2	Non-acoustic Zoom (Read Zoom).....	355
20.3	Acoustic Zoom (Write Zoom)	356
21.	Transmit and Focus Related Alternatives to Conventional B-mode Imaging.....	357
21.1	Multiple Transmit Foci	357
21.1.1	Improved Lateral Resolution	357
21.1.2	Degraded Temporal Resolution	358
21.1.3	Banding Noise.....	360
21.1.4	Dynamic (Continuous) Receive Focus	360
21.2	Parallel Processing.....	362
21.2.1	History of Parallel Processing.....	362
21.3	Multiple Receive Beams Per Transmitted Beam.....	362
21.4	How Parallel Processing Works.....	362
22.	Averaging Based Techniques.....	363
22.1	Adding Signals	363
22.1.1	Improvement in SNR.....	363
22.1.2	Calculating the Improvement in SNR.....	364
22.2	(Spatial) Compound Imaging	366
22.2.1	Benefits to Compound Imaging.....	366
22.2.2	Frame Rate and Temporal Resolution Degradation.....	366
22.2.3	Imaging Example.....	367
22.3	Image Persistence	367
22.4	Spatial Averaging.....	368
23.	Ultrasound Modes	369
23.1	Three-Dimensional (3-D) and Four-Dimensional (4-D) Imaging.....	369
23.2	C-mode (Constant Depth Mode)	370
23.3	M-mode (Motion Mode).....	370
24.	Resolution Formally Revisited.....	371
24.1	Detail Resolution	372
24.2	Contrast Resolution	372
24.3	Temporal Resolution.....	373
25.	Real-Time Imaging.....	373
26.	Exercises.....	374
27.	Conceptual Questions.....	376
28.	Video Formats Revisited	378
28.1	Comparing Line Resolution of Video Formats.....	378
28.2	Issues with Analog Videotape.....	378
28.3	Duplication and Conversion Between Formats.....	379
29.	Analog to Analog (Video Copying).....	379
30.	Analog Data to Digital Data Issues (Digitizing Videotape)	380
31.	Comparison of Digital Memory Devices	380
32.	Digital Formats and Compression	381
32.1	Data Compression and Decompression (CODEC).....	381
32.2	Video Formats Versus CODEC	381
32.3	Comparison of Video Formats.....	382
32.4	A Partial List of CODEC.....	382

33. Compression Algorithms and Techniques	383
33.1 Truncation.....	383
33.2 Run Length Encoding (RLE).....	383
33.3 Indexing (Lookup Table).....	384
33.4 Spatial Interpolation	384
33.5 Temporal Interpolation	385
33.6 Mathematical Transforms.....	385
33.7 Statistical Approaches.....	385
33.8 Motion Detection.....	386
33.9 Combining Algorithms	386
34. Digital to Digital Format Conversion.....	386
34.1 Multiple (Iterative) Compressions.....	386
34.2 An “Idealized” Controlled Test	387
34.3 A “Closer to Real World” Controlled Test.....	388
35. DICOM.....	389
36. Analog Versus Digital Systems	389
APPENDIX A - Supplemental Exercises.....	395 - 418
APPENDIX B - Answers to Chapter Exercises.....	419 - 468
APPENDIX C - Answers to Supplemental Exercises.....	469 - 498
APPENDIX D - Resource Information.....	499 - 502
APPENDIX E - Index.....	503 - 510
APPENDIX F - Abbreviations and Physical Units.....	511 - 512
APPENDIX G - Equations.....	513 - 516
APPENDIX H - Additional Information About Pegasus Lectures	517 - 518

VOLUME 2

CHAPTER 7 - Doppler

Introduction.....	519
1. The Doppler Effect.....	519
1.1 Change in Frequency.....	519
1.2 The Doppler Thought Experiment.....	520
1.3 The Relationship Between Velocity (v) and the Doppler Shift.....	523
1.4 Wavelength (λ) and the Doppler Effect.....	523
1.5 Relative Motion.....	523
1.6 The Relative Shift.....	523
1.7 Determining the Relative Doppler Shift Numerically.....	524
1.8 Exercises.....	524
2. Relationships in the Doppler Equation.....	526
2.1 Velocity (v) and Wavelength (λ).....	526
2.2 Wavelength (λ) and the Transmit Frequency (Operating Frequency f_0).....	526
2.3 Wavelength (λ) and the Propagation Velocity (c).....	527
2.4 Roundtrip Effect.....	528
3. A Simplified Doppler Equation.....	528
3.1 Equation with No Angle Effects.....	528
3.2 Simplified Numeric Form.....	529
3.3 Examples of Doppler Relations Applied.....	529
4. Solving the Doppler Equation for Velocity.....	530
5. Conceptual Questions.....	531
6. Completing the Doppler Equation.....	532
6.1 Removing the “Directly Toward or Directly Away” Assumption.....	532
6.2 Relative Motion and Angle.....	532
7. Doppler Shifts from Red Blood Cells.....	534
7.1 The Rayleigh Scattering/Frequency Paradox.....	534
7.2 The Optimal Frequency for Doppler.....	534
7.3 Red Blood Cell Aggregation and Reflectivity.....	535
7.4 Rouleau and Spontaneous Contrast.....	535
8. Identifying the Doppler Angle (Insonification or Insonation Angle).....	536
8.1 Standardized Angle Determination.....	536
8.2 Examples of Insonification Angles.....	536
8.2.1 Reviewing the Cosine.....	539
9. Exercises.....	539
10. Spectral Doppler System Operation.....	540
10.1 The Value of a Block Diagram.....	540
10.2 Why You Need to Also Know About Analog Waveform and Unidirectional Doppler.....	540
10.3 The Doppler Block Diagram.....	541
11. The Processes Involved in Spectral Doppler.....	541
11.1 Transmit Ultrasound Into the Body: (Pulser).....	541
11.2 Frequency Shift from Moving Blood.....	542
11.3 Amplification: (Amplifier).....	543
11.4 Doppler Shift Detection: (Mixers).....	543
11.5 Wall Filtering.....	544
11.5.1 Dynamic Range of Doppler.....	544
11.5.2 Clutter Signals.....	545
11.5.3 Graphic Depiction of Dynamic Range Issues.....	545

11.5.4	Wall Filter Theory.....	545
11.5.5	Graphic Depiction of Wall Filters.....	546
11.5.6	Effects of Wall Filters.....	546
11.5.7	Wall Filter Appearance on Doppler Spectrum.....	547
11.5.8	Appropriate Wall Filter Settings for Various Clinical Applications.....	548
11.5.9	Effect of Operating Frequency on Wall Filter Settings.....	548
11.5.10	Saturation of Wall Filters.....	548
11.6	Variable Gain (Gain).....	549
11.7	Audio (speakers).....	549
11.8	Analog to Digital Conversion (A/D).....	550
11.9	Fast Fourier Transform (FFT).....	550
11.10	Post-processing (Compression and Reject or Grayscale).....	551
11.11	Display.....	551
12.	Frequency vs. Amplitude.....	552
13.	PW vs. CW Comparison.....	553
13.1	Trade-offs.....	553
13.2	Timing and Basics of CW Doppler.....	553
13.3	Timing and Basics of PW Doppler.....	553
13.4	Range Specificity: Advantage PW.....	553
13.5	Aliasing: Advantage CW.....	554
13.6	The Maximum Detectable Frequency Shift (PW).....	555
13.7	Parameters Affecting Aliasing in PW Doppler.....	555
13.8	Appearance of Aliasing in a Doppler Spectrum.....	555
13.9	Practical Limit in CW Doppler and Aliasing.....	556
13.10	Changing the Scale in PW Doppler.....	557
14.	The Maximum Detectable Velocity.....	559
15.	The Presence of a Spectral Window.....	560
16.	PW Versus CW Comparison.....	562
17.	PW Range Ambiguity.....	562
17.1	Dispelling the Myth.....	562
17.2	The Mechanism that Causes Range Ambiguity.....	563
17.3	Important Questions about Range Ambiguity and Mitigating Factors.....	563
17.4	Risk Factors.....	564
17.5	Determining if Range Ambiguity is Present.....	564
18.	HPRF Doppler.....	564
18.1	Using the Trade-offs.....	564
18.2	Using Range Ambiguity to Create HPRF Doppler.....	564
19.	Doppler Insonification Angle and Error Sources.....	565
19.1	Cardiac and Alignment with Flow.....	565
19.2	Vascular Doppler and the Need to Angle Correct.....	566
19.3	Review of the Cosine.....	567
19.4	Peak Velocity and Pressure Gradient.....	567
19.5	Angle Correction Error (5 Degree Table).....	567
20.	Color Flow.....	569
21.	Color Doppler Versus Spectral Doppler.....	569
22.	Overview of How Color Doppler is Performed.....	570
22.1	Similarities of Color to Spectral Doppler and 2-D Imaging.....	570
22.2	Creating the Color Scan.....	570
22.3	Temporal Resolution and Color.....	571

22.4	Color Display and Velocity Interpretation.....	571
22.4.1	Toward and Away.....	571
22.4.2	How the System Applies a Color Map.....	571
23.	Time Correlated Color.....	572
24.	Color Gain	572
24.1	Setting the Appropriate Color Gain.....	572
25.	Interpreting the Color Bar Relative to Spectral Doppler.....	573
26.	Color Invert and Aliasing.....	573
27.	Color Wall Filters	574
27.1	Wall Filter and Color Scale Integrated	574
27.2	The Absence of Color	574
27.3	Interpreting the Color Bar Relative to Nyquist and the Wall Filters	575
28.	Determining Flow Direction in Color Doppler.....	576
28.1	Why Colors Change Even When Velocity Doesn't.....	576
28.2	Defining the Insonification Angle.....	577
28.3	Cosine Revisited.....	577
28.4	Step-by-Step Approach.....	578
29.	Color Persistence.....	582
29.1	The Purpose and Effects of Color Persistence.....	582
29.2	Persistence and Temporal Distortion	582
29.3	Important Points about Persistence	582
30.	Color Priority.....	583
30.1	How Color Priority Works.....	583
30.2	Important Points about Color Priority:	583
31.	Understanding Color Wall Filters Behavior	584
31.1	Digital Filtering	584
31.2	Comparing Spectral Doppler Wall Filters with the Color Wall Filter	584
31.3	Color Wall Filters and Nyquist.....	585
31.4	Effect of Signal Strength on Color Wall Filtering	585
31.5	Angle Correction Error (10 degree error).....	588
32.	Conceptual Questions.....	589

CHAPTER 8 - Artifacts

	Introduction.....	593
1.	Categorizing Artifacts.....	594
1.1	Image Detail Resolution Related.....	594
1.2	Locational Artifacts	594
1.3	Attenuation Artifacts.....	594
1.4	Doppler Artifacts	594
2.	Detail Resolution.....	595
2.1	Lateral and Axial Resolution	595
2.2	Elevation Resolution.....	596
3.	“Locational” Artifacts	596
3.1	Refraction	596
3.2	Reverberation	598
3.2.1	A Simple Case: Between a Specular Reflector and the Transducer Face	598
3.2.2	A More Complex Case: Between Multiple Specular Reflectors.....	600
3.2.3	A Very Complex Case: “Ghosting” or “Mirrored” Arteries	600
3.2.4	Be Vigilant Not to Confuse a Reverberation Artifact with a Thrombus.....	601

3.2.5	Ring Down and Comet Tail (Specific Forms of Reverberation).....	603
3.3	Multi-Path Artifact.....	604
3.4	Side Lobe (Single Element) and Grating Lobe (Arrays) Artifacts.....	605
3.5	Speed Error Artifact.....	605
3.6	Range Ambiguity Artifact	607
3.7	Mirror Artifact	607
4.	Attenuation Artifacts	608
4.1	Shadowing	608
4.2	Enhancement Artifact	610
4.3	Speckle.....	611
5.	Doppler Artifacts.....	611
5.1	Aliasing.....	611
5.2	Range Ambiguity.....	612
5.3	Mirroring (Spectral).....	612
5.4	Spectral Spread (Broadening) Artifact	613
5.5	Blossoming.....	615
5.6	Wall Filter Saturation.....	616
5.7	Refraction	616
6.	Conceptual Questions.....	617

CHAPTER 9 - Bioeffects

Overview.....	621
1. Mechanisms of Bioeffects	622
1.1 Thermal Bioeffects	622
1.2 Mechanical Bioeffects	622
1.2.1 Stable Cavitation.....	622
1.2.2 Inertial Transient Cavitation	623
1.3 The Concept of a Threshold Effect.....	623
2. The Desire to Safeguard the Patient.....	624
2.1 Confirming Safe Levels.....	624
3. Research and Standards.....	625
4. Power Measurements as a Basis for Gauging the Risk of Bioeffects	626
5. Common Intensities.....	626
5.1 Pulsed Wave Timing Revisited.....	626
5.2 The Common Intensities.....	627
5.3 Deciphering the Common Intensities by Concepts	627
5.4 Putting the Concepts Together.....	629
6. The Significance of the Common Intensities	630
6.1 Common Intensity Analogy.....	630
6.2 Mechanical Bioeffects and the ISPPA	631
6.3 Thermal Bioeffects and the ISPTA.....	631
6.4 Conversion Between a PA and a TA intensity: (Duty Factor)	631
6.5 Conversion Between SP and SA Intensity: (BUF)	632
6.5.1 The Beam Uniformity Factor (BUF)	632
6.5.2 Converting between the SA and the SP	632
7. Exercises.....	633
8. Relating Risks of Bioeffects to Ultrasound Modes	634
8.1 Scanned Versus Non-scanned Modalities.....	634
8.2 Ultrasound Modalities in Order of Thermal Risks	634

8.3	Transmit Voltages for Various Modalities	634
8.4	Ultrasound Modalities in Terms of Cavitation	635
8.5	Theory of FDA Limits	636
9.	Acoustic Power Measurements	636
9.1	Overview of Acoustic Power Measurements	636
9.2	The Hydrophone	637
9.3	Six Degrees of Freedom	638
9.4	Beamplots	639
10.	Output Display Standards.....	641
11.	Mechanical Index (MI).....	641
12.	Thermal Indices.....	642
12.1	Absorption Rates of Various Mediums.....	642
12.2	Thermal Indices Defined	642
12.3	The Three Thermal Indices.....	642
12.4	Underestimation of Worst Case.....	642
13.	AIUM Statements Regarding Ultrasound and Bioeffects	643
13.1	Acknowledging the AIUM	643
13.2	How Best to Use the Following Pages	643
13.3	Conclusions Regarding the Safety of Ultrasound.....	643
13.4	ALARA Principle	644
13.5	Prudent Use.....	644
13.6	Safety Concerns Regarding the Use of Ultrasound in Training and Research.....	645
13.7	Statement Regarding Non-Human Mammalian In Vivo Biological Effects	645
13.8	The Mechanical Index and Conclusions Regarding Gas Bodies.....	646
13.9	Conclusion Regarding Heat and the Thermal Indices (TIS, TIB, TIC).....	648
13.10	Thermal Effects on the Fetus.....	650
13.11	The AIUM Statement Regarding “In Vitro” Biological Effects.....	650
13.12	AIUM Conclusions Regarding Epidemiology for Obstetric Ultrasound	651
14.	Conceptual Questions.....	651
15.	Review Sheet For Converting Intensities.....	653
15.1	Conversion Between Spatial Peak and Spatial Average.....	653
15.2	Converting Between the Pulse Average and the Temporal Average.....	653
15.3	.....	653
16.	Hydrophones	655
16.1	Comparison Table.....	655
16.2	Membrane Hydrophones (HMA and HMB)*.....	656
16.3	Capsule “Golden Lipstick” Hydrophones (HGL)*	656
16.4	Needle Hydrophones (HNZ and HNV)*	656
16.5	Needle Reflecting Hydrophones (HNR)*.....	656

CHAPTER 10 - Contrast and Harmonics

1.	Motivation for Contrast Imaging.....	659
1.1	Overcoming Too Much Attenuation	659
1.2	Conventional Approaches.....	659
1.3	Increasing the Acoustic Impedance Mismatch	659
1.4	Increase in Signal Amplitude with Contrast.....	660
2.	Fundamentals of Harmonics.....	660
2.1.	Motivation for Harmonic Imaging	660
2.2	Mechanisms that Produce Harmonic Signals	661

3. Technology Advances.....	662
4. Relative Amplitudes	663
5. Generation of Harmonics	664
5.1 Non-linear Wave Propagation.....	664
5.2 Harmonics and Depth Dependence	665
5.3 Effective Harmonic Beam Shape	666
6. Advantages and Disadvantages of Conventional Harmonics.....	666
6.1 Improved Lateral Resolution.....	666
6.2 Reduction in Grating Lobes.....	667
6.3 Reduction in Reverberation and Clutter Artifacts	667
6.4 Reduction in Phase Aberration	670
6.5 Degradation in Axial Resolution	670
7. Pulse or Phase Inversion.....	671
8. Current Uses of Contrast Imaging.....	673
9. Properties of Contrast.....	673
9.1 Composition of Bubbles.....	673
9.2 Microbubble Interaction with Ultrasound and Resonance	673
10. The Mechanical Index (MI).....	675
10.1 Understanding the MI.....	675
10.2 Non-uniformity of the MI.....	675
10.3 Effect of MI on Microbubbles.....	676
10.3.1 Linear Response for Low MIs	676
10.3.2 Non-linear response for Higher MIs.....	676
10.4 Bubble Disruption.....	678
11. Transmit Focus	680
11.1 Bubble Concentration and Signal Amplitude	680
12. Contrast Specific Detection Techniques.....	681
12.1 Contrast Harmonic Imaging	681
12.2 High MI Techniques	682
12.2.1 Triggered Imaging	682
12.2.2 Harmonic Power Doppler	683
12.2.3 Benefits of Lower than Conventional Fundamental Frequencies.....	684
13. Challenges at High MI: Triggered Acquisition	685
14. Low MI Techniques.....	685
14.1 Fundamentals of Low MI Imaging.....	685
14.2 Pulse or Phase Inversion.....	686
14.3 Amplitude or Power Modulation.....	686
14.4 Importance of Low Frequencies.....	687
15. Challenges at Low MIs: Signal-to-Noise	688
16. The Future	688
16.1 Coded Pulses.....	688
16.2 Direction.....	688
16.3 Molecular Imaging Field.....	688
16.4 Therapeutic Applications.....	689
CHAPTER 11 - Quality Assurance	
Introduction.....	691
1. The Laboratory Accreditation	691
1.1 Accreditation Providers	691

1.2	Commitment to Quality	691
1.3	The Individual Certification.....	692
1.4	Personnel Qualifications.....	692
1.5	Document Storage and Record Keeping	694
1.6	Instrumentation and Quality Assurance.....	694
2.	Equipment Testing.....	695
2.1	The Need for Tight Testing Controls.....	695
2.2	Purpose of Testing	695
3.	2-D and Doppler Testing	695
3.1	Tested Parameters.....	695
4.	Doppler Testing and Phantoms.....	696
4.1	Types of Doppler Phantoms	696
4.2	Flow Phantoms	697
4.2.1	Basic Design	697
4.2.2	Blood Mimicking Fluids.....	697
4.2.3	Other Potential Issues	698
4.2.4	Example of Flow Phantoms.....	698
4.3	Non-flow Phantoms	702
4.3.1	Eliminating Variable Reflectivity.....	702
4.3.2	String Phantoms (Moving Targets).....	702
4.3.3	Blossoming	702
4.3.4	Need to Use Much Lower Gains and Transmit Power	703
5.	Imaging Phantoms and Test Objects	706
5.1	Detecting Performance Degradation	706
5.2	Test Repeatability	707
5.3	Testing Detail Resolution	707
6.	Commercially Available Imaging Phantoms.....	708
7.	Conceptual Questions.....	720
8.	Quality Assurance Statistics	720
8.1	As Part of the Quality Program	720
9.	Q&A Statistics.....	721
9.1	The Values of Statistics:	721
9.2	What is a Statistical Testing?.....	721
10.	Making Statistical Indices More Intuitive:.....	721
10.1	Presume that the Gold Standard is Perfect, *Adhering to the “Golden” Rule.	722
10.1.1	The Golden Rule:.....	722
10.1.2	The Meaning of the Words “True” and “False” with Respect to the Golden Rule.....	722
10.2	Pay Particular Attention to the English of the Statistical Terminology.	722
10.2.1	The Meaning of the Words “Positive” and “Negative”	723
10.3	Pay Close Attention to the Labels and Layout of any Table of Data.....	723
11.	Building the Table of Data	723
12.	Exercises: Interpreting the Statistical Table	726
13.	Statistical Parameters	726
13.1	Sensitivity	727
13.2	Specificity:.....	727
13.3	Accuracy.....	727
13.4	Positive Predictive Value.....	727
13.5	Negative Predictive Value	727
14.	Numerical Example	728

15. Real World Understanding	729
16. Exercises: Statistical Indices	730

CHAPTER 12 - Fluid Dynamics

1. Flow Analogy	733
1.1 Foreword on Flow	733
1.2 Flow Analogy	733
1.3 Flow Analogy Exercises	734
2. Fluid Dynamics	737
2.1 Fluid Dynamics: Flow and Related Terms	737
2.2 Fluid Dynamics: Definitions	737
2.3 Power, Work and Energy in Practical Terms	739
2.4 Energy	740
2.5 Potential and Kinetic Energy	741
2.6 Hydrostatic Pressure	742
2.7 Volumetric Flow (Q)	743
2.8 Velocity (v)	744
2.9 Capacitance	744
2.9.1 Capacitance Defined	744
2.9.2 Understanding the Capacitance	744
2.10 Compliance	745
2.11 Fluid Viscosity	746
2.12 Exercises: Flow and Related Definitions	746
3. Derivation of Equations	747
3.1 Introduction	747
3.2 The Resistance Equation	748
3.3 Volumetric Flow (continuity equation)	751
3.4 Simplified Law of Hemodynamics	752
3.5 Poiseuille's Law	754
3.6 Simplifications Made for the Equation	754
4. Bernoulli's Equation and Energy	755
4.1 Conservation of Energy and an Apparent Contradiction	755
4.2 Bernoulli's Equation (simplified)	755
4.3 Simplified Bernoulli and Modified Simplified Bernoulli Equation	758
4.4 Bernoulli's Equation with Hydrostatic Pressure Term	758
4.5 Bernoulli's Equation Heat Term	759
4.6 Understanding Bernoulli's Equation (An Airfoil and Lift)	759
5. Basics of Flow and Flow Diagrams	761
5.1 Simplifications and Assumptions for These Equations to be Employed	761
5.2 Flow Definitions	761
5.3 Steady Flow Diagram in a Rigid Tube	762
5.4 Steady State Flow in a Curved Vessel	763
5.5 Flow Examples	764
6. Reynold's Number and Turbulence	767
6.1 Reynold's Number	767
7. Exercises	770

CHAPTER 13 - Hemodynamics

Introduction	775
--------------------	-----

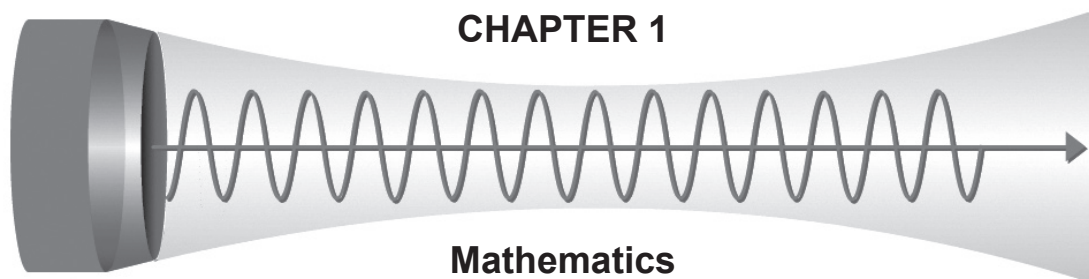
1.	Removing Some of the Simplifications.....	775
1.1	The Assumption: Steady State Flow.....	776
2.	The Assumption: Rigid Flow Conduits.....	776
2.1	Elastic Arteries.....	776
2.2	The Impact on Poiseuille’s Law.....	776
2.2.2	Compliance.....	777
2.2.3	Pressure Volume Relationship of a Compliant Vessel.....	778
2.2.4	Pressure Volume Relationship of a Incompliant Vessel.....	778
2.2.5	Elastic Veins.....	779
2.3	The Assumption: Single Flow Conduit.....	779
2.3.1	Regulation of Flow.....	779
2.3.2	Multiple Vessels: Series and Parallel Combinations.....	780
2.3.2.1	Series Combinations.....	780
2.3.2.2	Parallel Combinations.....	780
2.3.3	Combinations and Effective Resistance.....	781
2.3.4	Extrapolating these Results to Complex Networks.....	783
2.4	The Assumption: Conservation of Energy and No Energy Loss to Heat.....	784
2.4.1	General Heat Loss.....	784
2.4.2	Impact on Bernoulli’s Equation and Calculating Pressure Gradients.....	784
2.4.3	The Assumption: Smooth Straight Vessels.....	784
2.4.4	The Assumption: Large Vessels.....	785
2.4.5	The Assumption: Newtonian Fluid (and Blood Viscosity).....	788
2.4.6	The Assumption: No Turbulence (and Reynold’s Number).....	788
3.	Pressure, Flow, and Resistance in the Cardiovascular System (The Simplified Law).....	788
3.1	Overview.....	788
3.2	Left Heart.....	789
3.3	The Arterial System.....	790
3.3.1	Flow and Pressure in the Aorta.....	790
3.3.2	Arterial Vessel Sizes.....	790
3.3.3	Resistance in the Arterial System.....	791
3.3.4	Volumetric Demand and Vascular Bed Resistance.....	791
3.3.5	Effective Resistances in the Arterial System.....	791
3.3.6	Flow and Pressure in the Arteries.....	792
3.3.7	Flow and Pressure in the Arterioles.....	792
3.3.8	Flow and Pressure in the Capillaries.....	792
3.4	Venous System.....	793
3.4.1	Relative Vessel Sizes.....	793
3.4.2	Resistance of the Venules.....	793
3.4.3	Resistance of the Veins and the Vena Cava.....	793
3.5	Right Heart.....	793
3.6	The Lungs.....	794
3.7	Return to the Left-Sided Heart.....	794
4.	The Healthy Cardiovascular System as a Whole.....	794
4.1	Velocity Versus Cross-Sectional Area.....	794
4.2	Pressure Changes Across the Arterial System.....	795
4.2.1	Overview.....	795
4.2.2	Increasing Pulse Pressure.....	796
4.2.3	Decrease in Pulsatility and Pressure Drop.....	796
4.2.4	Pressure Drop Across the Capillaries.....	797

4.2.5	Pressures in the Venous Side are Low	797
4.3	The Venous System	797
4.3.1	Dichotomizing the Cardiovascular System.....	797
4.3.2	Venous Pressure	797
4.3.3	Venous Capacitance and Circulatory Pressure.....	798
4.3.4	Hydrostatic Pressure	798
4.3.5	The Calf Muscle Pump	799
4.3.6	Respiration Related Changes	800
4.3.7	Venous Resistance and Transmural Pressure	801
4.3.8	When Things Go Wrong: Effects of Edema	802
5.	The Subcritical Diseased Cardiovascular System at Rest	803
5.1	Asymptomatic Patients	803
5.2	Asymptomatic Patients with Exercise (Unmasking a Subcritical Stenosis).....	805
5.3	Symptomatic Patients and Critical Stenoses	807
6.	Spectral Doppler as a Means of Assessing Hemodynamics.....	808
6.1	What Doppler Tells Us	808
6.2	Returning to the Hemodynamic Equations	809
6.3	Characteristics of the Spectrum.....	809
6.3.1	Systolic Acceleration and Pressure	809
6.3.1.1	Doppler Acceleration for a Healthy Large Vessel	809
6.3.1.2	Doppler Risetime for a Diseased Vessel.....	810
6.3.2	The Spectral Window	811
6.3.2.1	Presence in Healthy Vessel.....	811
6.3.2.2	Absence in Diseased Vessel.....	811
6.3.2.3	Absence of the Spectral Window in a Healthy Vessel.....	812
6.3.3	Systolic Acceleration and Velocity Distribution	812
6.3.4	Flow Reversal and Phasicity.....	813
6.3.4.1	Normal Flow Reversal.....	813
6.3.4.2	Abnormal Flow Reversal.....	814
6.3.4.3	Arterial Signal Components	815
6.4	Velocity Criteria.....	815
6.4.1	Peak Velocity	816
6.4.2	Mean Velocity	816
6.5	Doppler Indices and Ratios.....	816
6.5.1	General.....	816
6.5.2	Doppler Indices Defined	817
6.5.3	Interpreting the Doppler indices	817
6.5.4	Angle independence of the Doppler indices	817
6.6	Murmurs and Bruits.....	818
6.6.1	Murmurs.....	818
6.6.2	A Doppler Bruit	818
6.6.3	Harmonic Bruit	819
6.6.4	Fluttering.....	819
7.	Flow Visualization.....	820
 APPENDIX A: Vascular Principals		
	Introduction.....	825
1.	Electrical Principles.....	825
1.1	Ohm's Law	825

1.2	Power	826
1.3	Why Electrical Principles Matter to Vascular Principles.....	827
2.	Relating Electrical Signals to Physical Parameters.....	827
2.1	Information Display.....	827
2.1.1	The Cathode Ray Tube (CRT)	827
2.1.2	Strip Chart.....	827
2.1.3	Calibration of a strip chart	828
3.	Two-Wire vs. Four-Wire Measurements and Calibration	828
3.1	AC vs. DC Coupling.....	829
3.1.1	AC (alternating current).....	829
3.1.2	Direct Current	829
3.1.3	Choosing the Appropriate Coupling for Indirect Arterial and Venous Testing.....	830
4.	Plethysmography	831
4.1	Displacement (pneumatic cuff) Plethysmography:	831
4.2	Strain-gauge Plethysmography.....	831
4.3	Impedance Plethysmography (IPG).....	831
4.4	Inflow and Outflow Studies	832
4.4.1	Venous Capacitance/Venous Outflow (VO/VC).....	832
4.5	Photoplethysmography	833
4.5.1	Venous Reflux Testing	833
4.5.2	Arterial Testing with Photoplethysmography	835
5.	Pressure Measurements	837
5.1	Methods of Pressure Measurements.....	837
5.1.1	Palpatory method	837
5.1.2	Ausculatory method.....	837
5.1.3	Flow Meter (Doppler).....	838
5.2	The Correct Cuff Size.....	838
6.	Arterial Pressure Measurements.....	839
6.1	Lower Extremity Segmental Pressures.....	839
6.2	Upper Extremity Arterial Pressures.....	841
7.	Reactive Hyperemia	842
8.	Skin Temperature and Skin Changes.....	842
9.	Occlusion Pressures.....	843
10.	Oculoplethysmography (OPG)	843
11.	Miscellaneous.....	845
11.1	Arteriovenous Fistula	845
11.2	Autogenous Arteriovenous Fistulae.....	845
11.3	Pseudoaneurysm	845
12.	Transcutaneous Oximetry.....	845
13.	Transcranial Doppler.....	846
13.1	General.....	846
13.2	Identifying Vessels.....	847
13.3	Technical Limitations:	848
 APPENDIX B: Cardiovascular Principals		
	Introduction.....	849
1.	The Circulatory System.....	849
1.1	Pulmonary vs. Systemic Circulatory Components.....	850
1.2	Pulmonary vs. Systemic Circulation	850

1.3	Arteries	850
1.4	Veins	851
1.5	Comparison of Arteries and Veins	851
1.6	Comparison of Arterioles and Capillaries	851
2.	Muscle Contraction and the Sodium Ion Pump.....	852
2.1	Positive and Negative Potentials	852
2.2	Action Potentials.....	853
2.3	Repolarization.....	853
2.4.	The Depolarization Wave	853
2.5.	The Refractory Period	853
3.	Cardiac Muscle Contraction.....	854
3.1	Differences Between Skeletal and Cardiac Muscle.....	854
3.2	Extended Refractory Period.....	855
3.3	Automaticity	855
3.4.	High Speed Electrical Pathway	856
4.	Electrical Signals: The EKG	857
4.1	Phases of an EKG.....	857
4.2	Interpreting Timing and the Heart Rate.....	858
5.	Pressure and Volume	860
5.1	A few Fundamental Concepts.....	860
5.1.1	The Simplified Law of Hemodynamics.....	860
5.1.2	Mechanical Events Lag Electrical Events	860
5.1.3	Isovolumic Contraction.....	860
5.1.4	The Continuity Equation.....	860
5.2	Aortic Arterial Pressure	861
5.2.1	The Pulse Pressure	861
5.2.2	The Mean Arterial Pressure (MAP).....	861
5.3	Isovolumic Contraction	862
5.4	Compliance of the Aorta.....	862
5.5	Physiologic Back-flow and Valve Closure	862
5.6	Left Ventricular Pressure	863
5.6.1	Passive Filling.....	863
5.6.2	Atrial Kick and Ventricular Contraction.....	863
5.6.3	Isovolumic Contraction.....	863
5.7	Left Atrial Pressure.....	864
6.	The Complete Cardiac Cycle	864
7.	The Right Side and the Cardiac Cycle	865
8.	Efficiency and Heart Performance	866
8.1	Stroke Volume	866
8.2	Cardiac Output.....	866
8.3	Ejection Fraction.....	866
8.4	Cardiac Index.....	866
8.5	Mitral Regurgitant Fraction	866
9.	Frank-Starling's Law	867
9.1	Cardiac Reserve and the Normal Heart	867
9.2	Damage and Loss of Reserve	867
10.	Pressure Volume Curves	868
10.1	Diastolic Pressure Curve	868
10.2	Isovolumic Systolic Pressure Curve.....	869

10.3	Pressure Volume Loop	870
10.4	Understanding the Pressure Volume Loop	870
10.5	Preload and Preload Effects.....	871
10.6	Afterload and Afterload Effects.....	872
10.7	The Effects of Increased Contractility.....	873
11.	Pressure and Volume Overload	873
11.1	Pressure Overload.....	873
11.2	Volume Overload.....	873
12.	Fetal Heart Development	874
12.1	Early Development of the Heart.....	874
12.2	Partitioning of the Heart	874
12.2.1	Early Embryonic Development Of The Heart	875
13.	Factors Affecting Jet Size	877
14.	Shunts.....	877
15.	Pulmonary Disease.....	878
16.	Pericardial Disease.....	878
16.1	Pericardial Effusion	878
16.2	Pericarditis.....	878
17.	Stress Testing	879
17.1	Detection of coronary artery Disease (CAD)	879
17.2	The Premise of a Stress Test.....	879
17.3	Exercise Cardiac Stress Test	880
17.4	Stress Echocardiography	880
17.5	Physiologic stress testing.....	880
17.6	Indications	880
17.7	Stress Testing: Interpretation	880
18.	Maneuvers altering Physiology.....	880
19.	Control Mechanisms	881
19.1	The Sympathetic Nervous System.....	881
19.2	The Parasympathetic Nervous System	881
APPENDIX C: Developing a Test Taking Strategy.....		883 - 896
APPENDIX D: Supplemental Exercises for Chapters 7-13		897 - 916
APPENDIX E: Ultrasound Exam		917 - 934
APPENDIX F: Hemodynamics Exam		935 - 942
APPENDIX G: Ultrasound Exam and Hemodynamics Exam Answers.....		943 - 958
APPENDIX H: Answers to Chapter Exercises.....		959 - 976
APPENDIX I: Answers to Supplemental Exercises		977 - 998
APPENDIX J: Resource Information		999 - 1002
APPENDIX K: Glossary.....		1003 - 1020
APPENDIX L: Index		1021 - 1028
APPENDIX M: Studay Suggestions and CME Materials		1029 - 1052
APPENDIX N: Abbreviations and Physical Units		1053 - 1054
APPENDIX O: Equations.....		1055 - 1058
APPENDIX P: Additional Information About Pegasus Lectures		1059 - 1060



Introduction

Without math, it is not possible to learn physics. Math is to physics what a paintbrush is to a painter or physical conditioning is to an athlete. The foundation of physics is mathematics. Therefore, to understand physics, and not just memorize facts, you must have at least a rudimentary understanding of mathematics.

Types of Math

Most people think of mathematics in terms of basic arithmetic and numerical manipulation. Whereas, this is certainly true, it is a very narrow view of mathematics. Mathematics is really an enormous field that includes many different topics. The field of mathematics includes many disciplines such as algebra, number theory, geometry, calculus, trigonometry, topology, and even logic and reasoning. Although you will not need to become an expert in any of these disciplines, the more you learn in mathematics, the easier it will be to understand physics.

How Much Math Will You Need?

Many people in the field of ultrasound will state that there is very little mathematics on the board exams. I do not agree. I think this disparity in opinions stems from the very narrow definition of mathematics as numerical calculations. It is true that there are very few numerical calculations on most of the credentialing exams, and certainly never such intensive calculations such that one would require a calculator. However, depending on the specific credentialing test and the test version, there are approximately twenty-five to forty percent of the questions that involve some form of mathematics.

As you will discover throughout this book, the mathematics included on the credentialing exams generally does not include performing many calculations, but rather asks relative relationships and logical conclusions from the mathematical relationships between variables. In other words, instead of asking you to calculate the resistance to flow for a fluid flowing through a vessel, you may be asked how the resistance to flow will change with changes in parameters that define the vessel. Instead of asking you to calculate a Doppler shift for a given transducer frequency, given a specific angle to flow and a blood flow velocity, you may be asked how the Doppler shift would change if a different transducer operating frequency were used given the same angle to flow and blood flow velocity. Answering this type of “relative” question involves math skills, which many students have not used for a long period of time, or worse, never developed. This last point is precisely why it is so critical for you to learn the basic mathematics, as outlined below.

To learn the basics of ultrasound (Level 1) you will need a proficiency in the basic mathematical functions. Specifically, you will need to:

- Be comfortable with the language of mathematics and translating English into mathematical functions.
- Add, subtract, multiply, and divide.
- Deal with fractions, percentages, and decimal notation.
- Understand exponential form and become fluent with the metric system.
- Understand the concept of reciprocals.
- Understand basic relationships of variables within an equation (proportionality and inverse).
- Perform algebraic manipulation of equations.

To master Level 2, you will need some higher-level math skills such as:

- Understand the difference between absolute and relative information.
- Understand the difference between linear and non-linear relationships.
- Recall or determine the equations commonly used in ultrasound physics and in hemodynamics.
- Understand the basic trigonometric functions of the sine and the cosine.
- Understand and apply the concepts of logarithms and decibels.
- Understand the basics of the binary system (relative to base 10).

To master Level 3, you will not necessarily need to develop many more math skills than suggested for Level 2. However, Level 3 presumes a more fluid working knowledge of the mathematics needed to master Level 2. The few additional mathematical topics that might help with Level 3 but are not necessarily required are:

- Some basic calculus.
- Understand rates of change (derivatives).
- Understanding integration.

How to Learn Mathematics

The good news is I have never encountered a student unable to master the mathematics necessary to pass the examination. The bad news is that learning this mathematics requires a structured approach, time, work, and patience.

A Structured Approach, Time, Work and Patience

Adults don't learn the same way children learn. Children tend not to be afraid of making a mistake in front of their peers. Adults, in comparison, live in fear and dread that someone will recognize that they are ignorant of even the slightest detail. I believe this approach of learning in fear puts an extraordinarily heavy and unfair burden upon adults in the position of student.

There is no way that anyone will understand everything just by reading the material once. Expecting to understand immediately is not only unreasonable, but puts a tremendous stress on the student. If you realize that learning is a process that only comes slowly over time through work and patience, you will not panic when something isn't clear the first time. It is not fair to yourself to lose self-esteem because you don't fully

understand a concept the first time through the material. I often use the analogy that learning is like building a house. Before you can get to the fun part of decorating the interior with intricate art and furniture, you have to go through the backbreaking work of digging a hole in the ground, setting up forms, and building a foundation. Without a solid foundation, the house will never stand.

It is time to dig the hole and do the work necessary so that you can build the foundation.

1. Mathematic Basics

1.1 Numbers

In mathematics, there are many categorizations which group numbers together based on their similar properties. For example, there are counting numbers (the natural numbers), negative counting numbers (the negative natural numbers), the set of all the natural numbers, negative numbers and 0 (called the integers), numbers which can be expressed as the ratio of two integers (rational numbers), and numbers which cannot be expressed as the ratio of two integers (irrational numbers), etc.

Natural Numbers: 1, 2, 3, 4, ...

Negative Natural Numbers: -1, -2, -3, -4, ...

Integers: -5, -4, -3, -1, 0, 1, 2, 3, 4, 5, ...

Rational Numbers: (all numbers which can be expressed as p/q where p and q are integers)

Irrational Numbers: (all numbers which cannot be expressed as p/q where p and q are integers)

For ultrasound physics, you will not need to know precise definitions of all of the various classifications of numbers. What you will need is a general ability to work with numbers including the basic mathematical operations of addition, subtraction, division, and multiplication.

1.2 Basic Mathematical Notation (symbols used in basic mathematics)

Addition	+	
Subtraction	-	
Multiplication	x	Example: $m \times f$ implies the variable m multiplied by the variable f .
	*	Example: $t * v$ implies the variable t multiplied by the variable v .
	•	Example: $c \cdot v$ implies the variable c multiplied by the variable v .
	()	Example: $3(7)$ implies the number 3 times the number 7.
No symbol		Example: $3z$ implies the number 3 multiplied by the variable z .
Division	/	Example: m / f implies the variable m divided by the variable f .
	÷	Example: $j \div k$ implies the variable j divided by the variable k .
Equality	=	
Inequalities:		
Greater than	>	Example: $g > 3$ is read as g is greater than the number 3.
Less than	<	Example: $h < 6$ is read as h is less than the number 6.
Greater than or equal to	≥	Example: $k \geq r$ is read as k is greater than or equal to r .
Less than or equal to	≤	Example: $h \leq 6$ is read as h is less than or equal to 6.

Note: Children generally learn to use the letter “x” to stand for multiplication. Once students reach algebra, there is generally a shift that occurs such that symbols other than “x” are often used to denote multiplication. This shift occurs since the letter x is generally used to stand for the unknown quantity in an algebraic expression. Since it is easy to confuse the “x” that stands for multiplication with the “x” that stands for a variable, other symbols become more commonly used. Therefore, there are many symbols used to indicate multiplication, such as: \times , \bullet , $$, and sometimes (\cdot). All of these symbols will be used throughout this text and interchanged freely so as to accustom you to each of these notations.*

1.3 Basic Mathematical Definitions

Constant:	A number which cannot change (Example: 3, 7, -14, 6 are all constants).
Natural constant:	A number which reoccurs naturally in the universe in relation to a specific parameter (Example: pi (π) for circles).
Coefficient:	A constant term used as a multiplier of a variable (Example: in the expression $7z^2$, the number 7 is the coefficient for the variable term z^2).
Variables:	A physical quantity which can vary or change (Example: in the expression $3x^2$, the variable is represented by the letter x).

1.4 The Value of Estimating

The ability to estimate quickly is very handy in every day life. Learning to make good estimates comes from practice and a little bit of thinking. For example, if you were asked to solve the problem what is 19 times 20, and you were not allowed to use a calculator or paper and pencil, what would you do.

Approach 1: (rounding off: estimation)

Find a way of rounding off the numbers into two numbers you can easily multiply in your head. For example 19×20 is a little less than 20×20 . Since 20×20 is 400, your first answer would be just a little less than 400.

Approach 2: (actual answer using estimation to simplify the math)

Start with Approach 1 and add one more step. Since 19×20 can be written as $(20-1) \times 20$ which is the same as $(20 \times 20) - (1 \times 20)$, you can actually solve this problem exactly in your head. As you solved in Approach 1, 20×20 is 400. Since the correct answer is actually 20 less than 400, the answer is 380.

In terms of ultrasound physics and hemodynamics, there are times when you should estimate the answer to a problem to make certain that you have not made a simple math calculation error. The best way to develop this ability is to put away the calculator and start practicing calculating and estimating in your head.

1.5 Exercises: Estimating

1. What is 24×6 ? (calculate both a rounded off answer and the actual answer)
2. What is 249×3 ? (calculate both a rounded off answer and the actual answer)
3. What is $12 \div 3.1$? (calculate a rounded off answer only)
4. What is $199 \div 5$? (calculate a rounded off answer only)
5. What is 37×11 ? (calculate both a rounded off answer and the actual answer)

2. Fractions, Decimal Form, and Percentages

One of the skills in mathematics that we learn earliest is how to deal with fractions and percentages. Unfortunately, the use of calculators has, for most people, caused this skill to deteriorate. Being able to deal with fractions and percentages is critical in physics and medicine.

A fraction consists of two parts: a number on top called the numerator, and a number on the bottom called the denominator. An increase in the numerator with no change to the denominator results in an increase in the fraction (see proportionality in Section 10.1).

For the fraction defined as: $Fraction = \frac{p}{q}$.

*An increase in p implies an increase in $\frac{p}{q}$: $\left(\text{if } p \uparrow \Rightarrow \frac{p}{q} \uparrow \right)$.

Conversely, an increase in the denominator with no change to the numerator results in a decrease in the fraction (see inverse proportionality in Section 10.3).

For the same fraction defined as: $Fraction = \frac{p}{q}$.

An increase in q implies a decrease in $\frac{p}{q}$: $\left(\text{if } q \uparrow \Rightarrow \frac{p}{q} \downarrow \right)$.

Often, a fraction is not written in its simplest form, implying that there is a multiplying factor which is common between the numerator and the denominator. In these cases, the fraction can be “simplified”, or reduced to “simplest form” by dividing both the numerator and denominator by the common multiple.

$$\diamond \text{ Examples: } \frac{4}{8} = \frac{4 * 1}{4 * 2} = \frac{4}{4} * \frac{1}{2} = 1 * \frac{1}{2} = \frac{1}{2}$$

$$\frac{14}{200} = \frac{2 * 7}{2 * 100} = \frac{2}{2} * \frac{7}{100} = 1 * \frac{7}{100} = \frac{7}{100}$$

$$\frac{120}{1200} = \frac{120 * 1}{120 * 10} = \frac{120}{120} * \frac{1}{10} = 1 * \frac{1}{10} = \frac{1}{10}$$

*Note: the symbol (\Rightarrow) stands for the word “implies.”

Additionally, all fractions can be written in decimal form and as percentages. Converting from fractions to decimal form is simply the process of division. Converting from decimal form to percentages is just multiplication by 100%.

◇ *Examples:*

$$\frac{1}{1} = 1 = 100\%$$

$$\frac{1}{2} = 0.5 = 50\%$$

$$\frac{1}{3} = 0.333 = 33.3\%$$

$$\frac{1}{4} = 0.25 = 25\%$$

$$\frac{2}{1} = 2 = 200\%$$

$$\frac{5}{2} = 2.5 = 250\%$$

Another way of thinking of fractions is how many times something occurs per hundred events. As such, it is easy to convert fractions to percentages when the denominator is a factor of 10. (You should notice that this process is equivalent to counting the number of decimal point shifts.)

◇ *Examples:*

$$\frac{7}{100} = 0.07 = 7\%$$

$$\frac{2}{10} = \frac{20}{100} = 0.2 = 20\%$$

$$\frac{43}{1000} = \frac{4.3}{100} = 0.043 = 4.3\%$$

$$\frac{16}{10} = \frac{160}{100} = 1.6 = 160\%$$