Pediatric Dialysis
We thank our families for the support they provide us.
We thank our colleagues for the insight they share with us.
We thank our patients for the trust they have in us.

The editors
Preface

The provision of optimal dialysis therapy to children requires a thorough understanding of the multidisciplinary manner in which the pediatric patient is affected by renal insufficiency. It was based on this philosophy that the inaugural edition of *Pediatric Dialysis* was published in 2004. Since that time, advances have taken place in dialysis-related care with the creation of a wealth of new knowledge, outpacing much of the content that occupied a prominent place in the original text. In response, we believe that even in this age of the electronic transmission of information, the availability of a contemporary, comprehensive, and authoritative source of information such as *Pediatric Dialysis* cannot only help facilitate the provision of superb patient care by seasoned clinicians, but it also can help meet the demand of our young trainees for the information that they require as a foundation for the future advances that they will surely initiate.

We are, in turn, fortunate to have been able to enlist the collaboration of over 70 colleagues from North America, Europe, and Asia to thoroughly update this text, which remains the most comprehensive source of state-of-the-art information on the dialysis of infants, children, and adolescents currently available. To them, we are eternally grateful for their commitment to this project. The inclusion of a host of new authors from “both sides of the pond” with their unique and fresh perspectives, combined with many authors from the first edition and all with recognized expertise on the topic chosen for their review, has resulted in a text that is clinically relevant and that will someday hopefully duplicate the appearance of one of the initial editions, owned by a dialysis nurse and characterized as being “full of worn pages as a result of almost daily use.” The addition of several new chapters, including *Conservation of Residual Renal Function in Children Reaching End-Stage Renal Disease*, *Intensified Hemodialysis in Children*, and *Transitioning the Adolescent Dialysis Patient to Adult Care*, should contribute to that end.

As clinicians ourselves who have spent many hours over the past three decades on hospital wards, in the intensive care unit, and in the dialysis unit applying what we have learned from the documented experience of others, we know that this text is undoubtedly the product of the hard work and ingenuity exhibited by the global pediatric nephrology community and, as such,
cannot help but to serve as a valuable tool with a singular emphasis on successfully caring for our challenging patient population. If that goal can be achieved through the publication of the second edition of *Pediatric Dialysis* and even one child benefits from our combined efforts, it will all have been worthwhile.

Kansas City, MO, USA
Heidelberg, Germany
Stanford, CA, USA

Bradley A. Warady
Franz Schaefer
Steven R. Alexander
The editors would like to acknowledge the superb administrative support of Cynthia Kiel, whose contributions to this text were exceptional. Similarly, the editors would like to thank Kevin Wright from Springer, whose project management skills and unwavering support and patience contributed greatly to the successful completion of this book.
Contents

Part I Essential Primers

1 Notes on the History of Dialysis Therapy in Children .......... 3
  Steven R. Alexander and Pierre Cochat

2 The Biology of Dialysis .................................................. 17
  Zhongping Huang, Dayong Gao, Claudio Ronco, and William R. Clark

3 The Demographics of Dialysis in Children ......................... 37
  Jeffrey J. Fadrowski, Steven R. Alexander, and Bradley A. Warady

4 Organization and Management of a Pediatric Dialysis Program ................................................. 53
  Linda Jones and Michael Aldridge

5 Dialysis in Developing Countries ..................................... 73
  Hong Xu and Arvind Bagga

Part II Considerations Around the Initiation of Dialysis

6 The Decision to Initiate Dialysis in a Pediatric Patient ....................... 85
  Larry A. Greenbaum and Franz Schaefer

7 Initiation of Maintenance Renal Replacement Therapy in Infants ............................................. 101
  Rene G. VanDeVoorde III and Denis Geary

8 Urological Issues in Pediatric Dialysis ................................. 115
  Angus Alexander, Antoine E. Khoury, and Armando J. Lorenzo

9 Conservation of Residual Renal Function in Children Reaching End-Stage Renal Disease .............. 139
  Il-Soo Ha and Franz Schaefer
### Part III    Peritoneal Dialysis

10 **Peritoneal Access in Children Receiving Dialysis** .......................................................... 153  
   Bradley A. Warady and Walter S. Andrews

11 **Technical Aspects and Prescription of Peritoneal Dialysis in Children**  .................................................. 169  
   Enrico Verrina and Katia Perri

12 **Peritoneal Dialysis Solutions** ................................................................................................... 205  
   Claus Peter Schmitt

13 **Peritoneal Dialysis During Infancy** ................................................................................................. 219  
   Tuula Hölttä, Christer Holmberg, and Kai Rönholm

14 **Peritonitis and Exit-Site Infections**  ................................................................................................. 231  
   Vimal Chadha, Franz Schaefer, and Bradley A. Warady

15 **Non-infectious Complications of Peritoneal Dialysis in Children** ......................................................... 257  
   Sevcan A. Bakkaloglu

### Part IV    Hemodialysis

16 **Hemodialysis Vascular Access in Children** ....................................................................................... 275  
   Deepa H. Chand and Mary L. Brandt

17 **Technical Aspects of Hemodialysis in Children** ............................................................................... 287  
   Marcus R. Benz and Franz Schaefer

18 **Prescribing and Monitoring Hemodialysis for Pediatric Patients** ....................................................... 313  
   Stuart L. Goldstein

19 **Maintenance Hemodialysis During Infancy** ....................................................................................... 321  
   Tim Ulinski and Pierre Cochat

20 **Intensified Hemodialysis in Children** ................................................................................................. 329  
   Dominik Müller and Denis Geary

21 **Common Complications of Haemodialysis** ......................................................................................... 345  
   Daljit K. Hothi and Elizabeth Harvey

### Part V    Management of Secondary Complications of Chronic Dialysis

22 **Meeting Nutritional Goals for Children Receiving Maintenance Dialysis** ....................................... 377  
   KDOQI Work Group

23 **Technical Aspects of Controlled Enteral Nutrition in Pediatric Dialysis** ............................................. 439  
   Bethany J. Foster and Dagmara Borzych
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>Growth and Pubertal Development in Dialyzed Children and Adolescents</td>
<td>453</td>
</tr>
<tr>
<td></td>
<td>Dieter Haffner and Dagmar-Christiane Fischer</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Diagnosis and Management of Renal Osteodystrophy in Children</td>
<td>483</td>
</tr>
<tr>
<td></td>
<td>Katherine Wesseling-Perry and Isidro B. Salusky</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>The Cardiovascular Status of Pediatric Dialysis Patients</td>
<td>505</td>
</tr>
<tr>
<td></td>
<td>Rukshana Shroff, Elke Wuhl, and Mark Mitsnefes</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Management of Renal Anemia in Children with Chronic Kidney Disease</td>
<td>531</td>
</tr>
<tr>
<td></td>
<td>Peter D. Yorgin and Joshua Zaritsky</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Immune Function and Immunizations in Dialyzed Children</td>
<td>569</td>
</tr>
<tr>
<td></td>
<td>Annabelle N. Chua and Alicia M. Neu</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Neurological Effects and Cognitive Development</td>
<td>581</td>
</tr>
<tr>
<td></td>
<td>Debbie S. Gipson and Stephen R. Hooper</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Psychosocial Adjustment and Adherence of Children and Adolescents on Dialysis</td>
<td>593</td>
</tr>
<tr>
<td></td>
<td>Ahna L.H. Pai and Lisa M. Ingerski</td>
<td></td>
</tr>
</tbody>
</table>

**Part VI  Drugs and Dialysis**

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>Drug Administration and Pharmacogenomics in Children Receiving Acute or Chronic Renal Replacement Therapy</td>
<td>609</td>
</tr>
<tr>
<td></td>
<td>Douglas L. Blowey and J. Steven Leeder</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Use of Contrast Agents in Children with Chronic Kidney Disease</td>
<td>629</td>
</tr>
<tr>
<td></td>
<td>Carlos E. Araya and Vikas R. Dharnidharka</td>
<td></td>
</tr>
</tbody>
</table>

**Part VII  Outcomes of Chronic Dialysis**

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>Long-Term Outcome of Chronic Dialysis in Children</td>
<td>645</td>
</tr>
<tr>
<td></td>
<td>Sarah Ledermann, Lesley Rees, and Rukshana Shroff</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Health-Related Quality of Life in Children on Dialysis</td>
<td>661</td>
</tr>
<tr>
<td></td>
<td>Arlene C. Gerson and Susan Furth</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Transitioning the Adolescent Dialysis Patient to Adult Care</td>
<td>673</td>
</tr>
<tr>
<td></td>
<td>Maria E. Ferris and Lorraine E. Bell</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>The Ethics of Withholding or Withdrawing Dialysis in the Pediatric ESRD Patient</td>
<td>689</td>
</tr>
<tr>
<td></td>
<td>Pierre Cochat and Bruno Ranchin</td>
<td></td>
</tr>
</tbody>
</table>
37  Acute Kidney Injury: Diagnosis and Treatment
    with Peritoneal Dialysis, Hemodialysis, and CRRT ............... 697
    Patrick D. Brophy, Hui Kim Yap, and Steven R. Alexander

Part VIII  Special Indications and Techniques
            of Blood Purification

38  The Development of CRRT for Infants and Children .......... 739
    Claudio Ronco and Zaccaria Ricci

39  Extracorporeal Liver Replacement Therapy
    for Pediatric Patients .................................................. 755
    Claus P. Schmitt and Franz Schaefer

40  Dialytic Therapy of Inborn Errors of Metabolism .......... 765
    Philippe Jouvet and Franz Schaefer

41  Pediatric Therapeutic Apheresis .................................. 775
    Stuart L. Goldstein, Gunter Klaus, David F. Friedman,
    and Haewon C. Kim

42  Extracorporeal Therapy for Drug Overdose
    and Poisoning ............................................................. 797
    Vimal Chadha

Index ......................................................................................... 809
Contributors

Michael Aldridge, MSN, RN, CCRN, CNS  Department of Nursing, Concordia University of Texas, Concordia, TX, USA

Angus Alexander  Senior Fellow, Division of Urology, The Hospital for Sick Children, Toronto, Canada

Steven R. Alexander, MD  Division of Pediatric Nephrology, Stanford University School of Medicine and Lucile Packard Children’s Hospital at Stanford, Stanford, CA, USA

Walter S. Andrews, MD  Department of General Surgery, University of Missouri - Kansas City School of Medicine, Children’s Mercy Hospitals and Clinics, Kansas City, MO, USA

Carlos E. Araya, MD  Department of Pediatrics, University of Florida College of Medicine, Gainseville, FL, USA

Arvind Bagga, MD  Department of Pediatrics, All India Institute of Medical Sciences, New Delhi, India

Sevcan A. Bakkaloglu, MD  Department of Pediatric Nephrology, Gazi University Faculty of Medicine, Ankara, Turkey

Lorraine E. Bell, MDCM, FRCPC  Department of Pediatrics, Division of Nephrology, McGill University Health Centre, Montreal, Canada

Marcus R. Benz, MD  Division of Pediatric Nephrology, Children’s University Hospital, Ludwig-Maximilian University Munich, Munich, Germany

Douglas L. Blowey, MD  Department of Pediatrics, Children’s Mercy Hospital and University of Missouri, Kansas City, MO, USA

Dagmara Borzych, MD, PhD  Department of Pediatric and Adolescent Nephrology and Hypertension, Medical University of Gdansk, Gdansk, Poland

Mary L. Brandt, MD  Division of Pediatric Surgery, Department of Surgery, Baylor College of Medicine, Houston, TX, USA
Patrick D. Brophy, MD  Department of Pediatrics, University of Iowa
Children’s Hospital, Iowa City, IA, USA

Vimal Chadha, MD  Department of Pediatrics, Section of Pediatric
Nephrology, Children’s Mercy Hospitals and Clinics, Kansas City,
MO, USA

Deepa H. Chand, MD, MHSA  Department of Nephrology
and Hypertension, Akron Children’s Hospital, Akron, OH, USA

Annabelle N. Chua, MD  Department of Pediatrics, Renal Section,
Baylor College of Medicine and Texas Children’s Hospital, Houston,
TX, USA

William R. Clark, MD  Gambro Renal Products, Lakewood, CO, USA

Pierre Cochat, MD, PhD  Service de néphrologie et rhumatologie
pédiatriques, Centre de référence des maladies rénales rares, Hospices
Civils de Lyon & Université Claude-Bernard Lyon, Lyon, France

Vikas R. Dharnidharka, MD, MPH  Department of Pediatrics,
University of Florida College of Medicine, Gainesville, FL, USA

Jeffrey J. Fadrowski, MD, MHS  Department of Pediatrics,
Johns Hopkins University School of Medicine, Baltimore, MD, USA

Maria E. Ferris, MD, MPH, PhD  Department of Medicine and Pediatrics,
Division of Nephrology, University of North Carolina at Chapel Hill
and University of North Carolina Children’s Hospital, Chapel Hill,
NC, USA

Dagmar-Christiane Fischer, PhD  Department of Pediatric Kidney,
Liver and Metabolic Diseases, Hannover Medical School,
Hannover, Germany

Bethany J. Foster, MD, MSCE  Department of Epidemiology,
Biostatistics and Occupational Health and Department of Pediatrics,
Division of Nephrology, McGill University Health Centre and Montreal
Children’s Hospital, Montreal, QC, Canada

David F. Friedman, MD  Associate Medical Director, Transfusion Service
and Apheresis Service, Philadelphia, PA, USA
Medical Director, Phlebotomy Service, Children’s Hospital
of Pennsylvania, Philadelphia, PA, USA

Susan Furth, MD, PhD  Department of Nephrology,
The Children’s Hospital of Philadelphia, Philadelphia, PA, USA

Dayong Gao, Ph.D  Department of Biomedical Engineering,
University of Washington, Seattle, WA, USA

Denis Geary, MB, MRCP(UK), FRCPC  Department of Paediatrics,
The Hospital for Sick Children and University of Toronto, Toronto,
Ontario, Canada
Arlene C. Gerson, PhD  Department of Pediatrics and Epidemiology, Johns Hopkins University School of Medicine, Baltimore, MD, USA

Debbie S. Gipson, MD  Department of Pediatrics, University of Michigan, Ann Arbor, MI, USA

Stuart L. Goldstein, MD  Department of Pediatrics, University of Cincinnati College of Medicine, Division of Nephrology and Hypertension & The Heart Institute, Cincinnati, OH, USA
Center for Acute Care Nephrology, Pheresis Service, Cincinnati Children’s Hospital Medical Center, Cincinnati, OH, USA

Larry A. Greenbaum, MD, PhD  Department of Pediatrics, Emory University and Children’s Healthcare of Atlanta, Atlanta, GA, USA

Il-Soo Ha, MD, PhD  Department of Pediatrics, Seoul National University Children’s Hospital, Seoul, Republic of Korea

Dieter Haffner, MD  Department of Pediatric Kidney, Liver, and Metabolic Disease, Hannover, Germany

Elizabeth Harvey, MD, FRCPC  Division of Nephrology, The Hospital for Sick Children, University of Toronto, Toronto, Ontario, Canada

Tuula Hölttä, MD  Department of Pediatric Nephrology and Transplantation, University of Helsinki and Hospital for Children and Adolescents, Helsinki, Finland

Christer Holmberg, MD  Department of Pediatric Nephrology and Transplantation, University of Helsinki and Hospital for Children and Adolescents, Helsinki, Finland

Stephen R. Hooper, PhD  Carolina Institute for Developmental Disabilities, University of North Carolina School of Medicine, Chapel Hill, NC, USA

Daljit K. Hothi, MBBS, MRCPCH, MD  Department of Nephro-Urology, Great Ormond Street Hospital for Children, London, United Kingdom

Zhongping Huang, PhD  Department of Mechanical Engineering, Widener University, Chester, PA, USA

Lisa M. Ingerski, PhD  Center for the Promotion of Adherence and Self-Management, Cincinnati Children’s Hospital Medical Center, Cincinnati, OH, USA

Linda Jones, MHA, RN  Section of Pediatric Nephrology, Children’s Mercy Hospitals, Kansas City, MO, USA

Philippe Jouvet, MD, PhD  Department of Pediatrics and Pediatric Intensive Care Unit, University of Montreal and Sainte-Justine Hospital, Montreal, QC, Canada
Antoine E. Khoury  Department of Urology, Children’s Hospital of Orange County and University of California Irvine Medical Center, Orange, CA, USA

Haewon C. Kim, MD  Medical Director, Apheresis Service, The Children’s Hospital of Philadelphia, Philadelphia, PA, USA
Department of Pediatrics, University of Pennsylvania School of Medicine, Philadelphia, PA, USA

Gunter Klaus, MD  Pediatric Kidney Center, KfH-Kuratorium fur Dialyse und Nierentransplantation, Marburg, Germany

Sarah Ledermann, MB, MRCPCH  Department of Pediatric Nephrology, Great Ormond Street Hospital for Children, London, United Kingdom

J. Steven Leeder, PharmD, PhD  Department of Pediatrics, Division of Pharmacology and Medical Toxicology, Children’s Mercy Hospitals and Clinics, Kansas City, MO, USA

Armando J. Lorenzo, MD  Division of Urology, The Hospital for Sick Children, Toronto, Canada

Mark Mitsnefes, MD  Division of Nephrology and Hypertension, Cincinnati Children’s Hospital, Cincinnati, OH, USA

Dominik Müller, MD  Department of Pediatric Nephrology, Hospital Charite, Berlin, Germany

Alicia M. Neu, MD  Department of Pediatric Nephrology, Johns Hopkins Medical Institutions, Baltimore, MD, USA

Ahna L.H. Pai, PhD  Center for the Promotion of Adherence and Self-Management, Cincinnati Children’s Hospital Medical Center, Cincinnati, OH, USA

Katia Perri, MD  Department of Nephrology, Dialysis and Transplantation, Giannina Gaslini Institute, Genoa, Italy

Bruno Ranchin, MD  Service de néphrologie et rhumatologie pédiatriques Centre de référence des maladies rénales rares, Hospices Civils de Lyon, Lyon, France

Lesley Rees, MBChB, FRCP, FRCPCH, MD  Department of Pediatric Nephrology, Great Ormond Street Hospital for Children, London, United Kingdom

Zaccaria Ricci, MD  Department of Cardio-Anesthesiology and Pediatric Intensive Care, Ospedale Bambin Gesù, Rome, Italy

Claudio Ronco, MD  Nephrology Department, International Renal Research Institute, St. Bortolo Hospital, Vicenza, Italy

Kai Rönnholm, MD  Department of Pediatric Nephrology and Transplantation, University of Helsinki and Hospital for Children and Adolescents, Helsinki, Finland
Contributors

Isidro B. Salusky, MD  Department of Pediatric Nephrology, University of California-Los Angeles, Los Angeles, CA, USA

Franz Schaefer, MD  Pediatric Nephrology Division, Heidelberg University Hospital, Heidelberg, Germany

Claus Peter Schmitt, MD  Department of General Pediatrics, Center for Pediatric and Adolescent Medicine, Heidelberg, Germany

Rukshana Shroff, MD, FRCPCH, PhD  Department of Nephrology, Great Ormond Street Hospital for Children, London, United Kingdom

Tim Ullinski, MD, PhD  Service de Néphrologie Pédiatrique, Hôpital Armand Trousseau, AP-HP and University Pierre and Marie Curie, Paris, France

Rene G. VanDeVoorde III, MD  Department of Nephrology and Hypertension, Cincinnati Children’s Hospital Medical Center, Cincinnati, OH, USA

Enrico Verrina, MD  Department of Nephrology, Dialysis and Transplantation, Giannina Gaslini Institute, Genoa, Italy

Bradley A. Warady, MD  Department of Pediatrics, University of Missouri - Kansas City School of Medicine, Section of Pediatric Nephrology, Children’s Mercy Hospitals and Clinics, Kansas City, MO, USA

Katherine Wesseling-Perry, MD  Department of Pediatrics, University of California-Los Angeles, David Geffen School of Medicine, Los Angeles, CA, USA

Elke Wuhl, MD  Department of Pediatric Nephrology, University of Heidelberg, Heidelberg, Germany

Hong Xu, MD  Department of Pediatric Nephrology, Children’s Hospital of Fudan University, Shanghai, China

Hui Kim Yap, MD  Department of Pediatrics, National University of Singapore, Singapore

Peter D. Yorgin, MD  Division of Nephrology, University of California-San Diego School of Medicine, San Diego, CA, USA

Joshua Zaritsky, MD, PhD  Department of Pediatrics, Mattel Children’s Hospital at UCLA, Los Angeles, CA, USA