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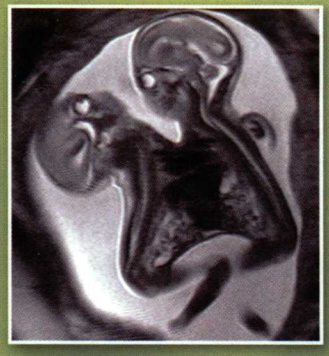
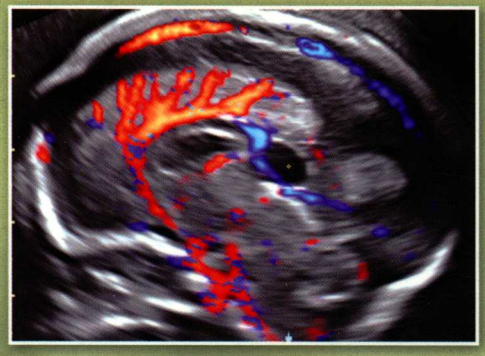
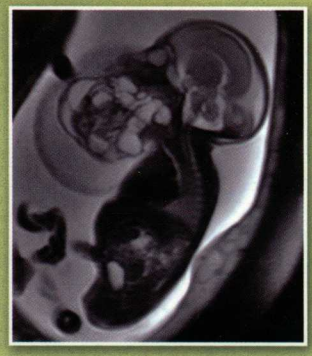
FETAL IMAGING

Ultrasound and MRI

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Fundamental and Advanced

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Philadelphia • Baltimore • New York • London
Buenos Aires • Hong Kong • Sydney • Tokyo

Acquisitions Editor: Ryan Shaw
Product Development Editor: Amy G. Dinkel
Production Project Manager: David Salztberg
Design Coordinator: Stephen Druding
Prepress Vendor: S4Carlisle Publishing Services

9 8 7 6 5 4 3 2 1

Printed in China

Library of Congress Cataloging-in-Publication Data
Fundamental and advanced fetal imaging : ultrasound and MRI / editors, Beth M. Kline-Fath, Dorothy I. Bulas, Ray Bahado-Singh.
p. ; cm.
Includes bibliographical references and index.
ISBN 978-1-4511-7583-7 (hardback) — ISBN 1-4511-7583-3 (hardback)
I. Kline-Fath, Beth M., editor. II. Bulas, Dorothy I., editor. III. Bahado-Singh, Ray, editor.
[DNLM: 1. Magnetic Resonance Imaging—methods. 2. Ultrasonography, Prenatal—methods. 3. Congenital Abnormalities—diagnosis. 4. Fetal Diseases—diagnosis. 5. Fetus—abnormalities. WQ 209]
RC78
616.07'57—dc23

2014019723

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Fundamental and Advanced Fetal Imaging

Ultrasound and MRI

To my husband, Tom, who without his love and support, this book would not be possible. To my daughters, Kelsey and Abby, I will always love you more. To my father who is looking down on me and my mother by my side, thank you for your love and guidance and for teaching me to always reach for more. And to my family, especially my nieces Natasha and Naomi, thank you for believing in me; for it is through your lives that I understood the importance of this field.

BMKF

To my husband, Neal, who despite all the hours and weekends spent on this book, was always encouraging and supportive. To Mark and Adam for the love and joy you bring to my life. And to my parents who continue to inspire me to enjoy the gifts medicine has to offer.

DIB

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PREFACE

The development of prenatal ultrasound ushered in an exciting new age in fetal assessment and represented the proverbial great leap forward. The systematic investigation of both fetal behavior and anatomy became a reality. Subsequent technological advances have ensued at a relentless pace. Pulse and color Doppler facilitated the near complete interrogation of the fetal vasculature while 3-dimensional ultrasound provided enhanced realism and novel perspectives of fetal structure.

The introduction of fetal MR imaging is proving equally transformational. Structural details have been dramatically enhanced with the promise of providing previously unachievable metabolic fingerprint of fetal tissues. Techniques such as bright blood imaging, diffusion spectroscopy and other functional modalities promise to transform our understanding of intrauterine life with the anticipated rewards being improved clinical management and fetal outcome.

Initial concerns that MRI development would be at the expense of ultrasound now appear unsubstantiated. Evidence suggests that these two modalities are deeply complementary and that their simultaneous deployment is critical for optimal fetal assessment for many important fetal disorders.

In this book, the specialties of radiology and obstetrics converge to provide a reference on the complex field of fetal imaging. The first part of the book is dedicated to normal prenatal US and MR imaging. In that section, US evaluation in the first and second trimesters, growth, Doppler, and basic cardiac anatomy of fetus are reviewed. Normal MR imaging discussion includes a how-to technical section and provides normal examples of the entire fetal anatomy, with emphasis on the fetal brain. Advanced fetal brain and cardiac MR techniques are also detailed. The second part of the book reviews the major fetal pathologies by organ system with a separate chapter dedicated to common genetic and chromosomal disorders. This section of the book reflects the approach in a prior edition by Nyberg. The incidence, pathogenesis, etiology, and diagnosis with US and MRI, as well as prognosis and management for fetal pathologies are examined. Color diagrams, tables, and, most importantly, images utilizing both US and MRI provide the reader with an enhanced understanding of the anomalies. The appendix offers important biometry tables for easy reference. These tables contain normal MR values, including essential measurements of the fetal brain at different gestational ages.

Another unique feature of this book is that a diverse group of fetal subspecialists graciously helped author chapters, including cardiologists, geneticists, and Doppler specialists. International experts, including Kypros Nicolaides and Fred Avni, provided a global perspective of this discipline.

Our goal for *Fundamental and Advanced Fetal Imaging* was to provide the most up-to-date and encompassing reference for fetal imaging. We hope all fetologists, including radiologists and obstetricians, as well as pediatric specialists such as surgeons, geneticists, counselors, neurologists, urologists, and neurosurgeons, will turn to this reference for basic and advanced imaging information. This book should also serve as an excellent resource for the resident and medical student.

Understanding normal development and pathologies in the fetus is essential for optimal prenatal and postnatal care. We hope you find this book illuminating and that it will contribute to fetal research, therapeutic techniques, perinatal care, and counseling. Our objective has been the integration of two critical technologies for fetal assessment. We believe that the finished product is in alignment with our original intent.

Beth M. Kline-Fath
Dorothy I. Bulas
Ray Bahado-Singh

ACKNOWLEDGMENTS

First and foremost, we would like to thank all the authors from so many different specialties who have generously shared their expertise, research and images.

We cannot thank them enough for their hard work, and leadership in this growing field of fetology.

We want to acknowledge the authors of the first edition of Diagnostic Imaging of Fetal Anomalies, David A. Nyberg, John P. McGahan, Dolores H. Pretorius, and Gianluigi Pilu, whose important initial work was the basis of this new text.

We thank the sonographers, obstetricians, radiologists, and fetal specialists who have worked together to improve the care of the fetus.

We thank the fellows, residents and students in training who have asked questions pushing us to search for better answers.

We would like to thank Glenn Minano for his creative assistance with regard to the artwork presented in this book.

We thank the staff of Lippincott Williams and Wilkins/Wolters Kluwer Health; Charley Mitchell for getting us started, Ryan Shaw, Amy Dinkel, Emilie Moyer, Jonathan Pine for their guidance, Grace Caputo for keeping us on track and Mohamed Hameed for his gracious efficiency.

BMKF, DIB, RBS

I would like to thank my coworkers at Cincinnati Children's, especially Juanita Hunter, for their constant support and enthusiasm about this project. To those who encouraged and directed my medical career, I would like to express gratitude to Ben Felson, Hugh Hawkins, Alan Chambers, John Egelhoff and Lane Donnelly. For those who taught me the importance of team work to improve fetal and neonatal care, I would like to thank Constance Bitters, Maria Calvo-Garcia, Bill Polzin, Foong-Yen Lim, Tim Crombleholme and all of my fetal co-workers, many of whom have gone to other institutions to continue work in this innovative field. Finally, I would like to thank all families who entrust the care of their unborn; it is their lives that inspire me to learn more to improve fetal care.

BMKF

I want to thank my department and coworkers for their support during this process. I could not have completed this work without them. I am grateful to all my colleagues who have shared my enthusiasm for caring for the fetus. Their collaboration has been a source of inspiration through the years. Lastly, I want to thank all the families I have had the privilege to work with. It is their stories that move me to continue to work in this field.

DIB

I wish to express my gratitude to the contributing authors, chosen for their expertise and leadership in the field, who so selflessly gave of their valuable time. A very special thank you to my associate editors, Drs. Dorothy Bulas (George Washington University) and Beth Kline-Fath (Cincinnati Children's). It is their vision and limitless reserves of energy and commitment that made this book a reality.

On a personal note, may I also express my profound gratitude to my mentors who have made transformative contributions in the field of prenatal imaging, and women's health: Drs. Jeremiah Mahoney, John Hobbins, Roberto Romero, Frederick Naftolin and Joshua Copel. Their example has served as a beacon over these many years. In like manner, I am indebted to Drs. Roger Freeman, Thomas Garite and Mike Nageotte for opening our eyes to both the challenges and bountiful rewards that flow from the care of the pregnant woman and her fetus. Finally, to the thousands of such women without whose permission we could not have gained this knowledge, a my most sincere- Thank you!

RBS

CONTENTS

1 Normal Fetal Ultrasound Survey

Jiri D. Sonek • Jason D. Retzke • John Hyett

Prenatal ultrasound represents one of the most important advances in modern obstetrics. Prior to the advent of this technology, the contents of the uterus were essentially a black box. Ultrasound has evolved significantly since Ian Donald et al. first demonstrated its potential value. It provides an effective means of evaluating the fetus from both a structural and a functional perspective. As a consequence, obstetrics has evolved from a discipline that dealt almost exclusively with maternal health concerns to one that also focuses on the health and development of the fetus.[1,2]

A complete obstetric ultrasound includes evaluation of the uterus, the adnexa, and the intrauterine contents.[3–7] In this chapter, we focus on examination of the fetus. Examinations of the umbilical cord, placenta, and amniotic fluid are discussed in Chapter 7, and assessment of the uterine cervix is discussed in Chapter 10.

The obstetric ultrasound is a comprehensive exam with different components of the exam emphasized at various stages of fetal development. While examination at 8 weeks' gestation is not currently considered the optimal gestational age for fetal ultrasound assessment, it does provide an opportunity to assess viability and intrauterine location of the pregnancy, to reliably determine chorionicity in the case of a multiple gestation, and to date the pregnancy with a great degree of accuracy. The 12-week scan is a relatively recent addition, but is now accepted as a point for routine assessment and is rapidly gaining recognition as one of the most important points for fetal evaluation. Most fetal chromosomal and severe structural abnormalities can be detected even at this early stage of development. Recognition of a problem at this point in pregnancy allows the parents ample time for counseling with a wide range of options regarding termination or continuation of pregnancy.[8–12] More recently, the 12-week scan has also been shown to be valuable in the prediction of obstetric complications such as preeclampsia and growth restriction, allowing obstetricians to take preventive action at a point early in gestation, potentially reducing the risk of adverse pregnancy outcome.[13]

For many years, the 20-week scan has been the cornerstone of obstetric imaging. Systematic examination at this stage identifies a high proportion of major structural anomalies. At this gestation, the fetus is already relatively large, and the formation of major fetal structures except for the brain has been completed. Therefore, more anomalies can be detected at this point than at 12 weeks, and those that are suspected at an earlier gestational age can now be confirmed and better defined. Still, some important abnormalities such as neuronal migration defects will remain undetectable until the late third trimester or until after birth. Finally, most data regarding the value of cervical assessment also pertain to the 20-week gestational age window.

Even though a complete structural survey can be performed at ≥28 weeks' gestation, scans at this stage are limited by bone shadowing from the calvarium, ribs, spine, and limbs. However, investigation at this point in gestation provides invaluable information regarding fetal well-being and placental function. In addition to the evaluation of fetal growth and amniotic fluid volume, Doppler ultrasound can be employed to evaluate placental and fetal hemodynamics, and to look for changes indicative of placental insufficiency and fetal hypoxia. This information is helpful in determining timing and mode of delivery of growth restricted fetuses. This approach is also useful in identifying late onset growth restriction and the failing placenta at term.[14–23]

Obstetric ultrasound has its limitations, a fact that both clinicians and patients need to recognize. Anomalies may be missed for a variety of reasons. In early pregnancy, structures may be too small for examination, the embryologic development process may be incomplete, or secondary pathologic change may have not yet occurred. As noted above, development of some structures, such as the central nervous system, continues throughout the pregnancy and even into infancy; therefore, anomalies may not be evident at the time of a routine 20-week ultrasound examination. Other important abnormalities, such as autism, are functional rather than structural and therefore cannot be detected by ultrasound.[24]

The exact prognosis associated with a particular anomaly finding might be unclear. For example, with certain ultrasound findings most fetuses might have a normal outcome, yet a small proportion may be severely incapacitated. Clinicians that report ultrasound findings have to be able to define risks as clearly as possible, recognize the inherent uncertainties, and have the skill to communicate them effectively to the patient.[25]

The quality of the ultrasound image may be affected by a number of maternal and fetal factors, including maternal obesity and fetal position. Increased maternal body mass index (BMI) has become a notable impediment to the performance of obstetric ultrasound. Ultrasound does not penetrate adipose tissue well, leading to decreased image quality and prolonged examination time. The increased study length and physical stress is a major health issue for sonographers.[26,27] Nonetheless, it also needs to be kept in mind that increased maternal BMI is associated with an increased risk of a number of fetal anomalies such as neural tube defects, cardiac defects, and facial clefts.[28] It therefore becomes important to attempt to maximize the diagnostic potential of the ultrasound examination, while minimizing risks to staff. This can be accomplished by defining a maximum time limit for an exam and termination of an exam at a point where it is determined that optimal images are not obtainable. Difficulties relating to fetal position are relatively easier to deal with by alteration of the angle of insonation, manipulation of the fetus, combined transabdominal and transvaginal imaging, or simply waiting until the fetus spontaneously changes its position. Despite these difficulties, we need to remember that image interpretation is fundamentally dependent on image quality, and sonographers should be encouraged to be single-minded in their pursuit of excellence.

Table 1.1 Summary of Recommendations for Diagnostic Ultrasound Parameters and Indices

In the low-megahertz frequency range, there have been no independently confirmed adverse biologic effects in mammalian tissues exposed in vivo under experimental ultrasound conditions, as follows:

1. Thermal mechanisms
   a. No effects have been observed for an unfocused beam having free-field spatial-peak temporal-average (SPTA) intensities[a] below 100 mW/cm^2, or a focused[b] beam having intensities below 1 W/cm^2, or thermal index values of <2.
   b. For fetal exposures, no effects have been reported for a temperature increase above the normal physiologic temperature, ΔT, when $\Delta T < 4.5 - (\log_{10} t/0.6)$, where t is exposure time ranging from 1 to 250 min, including off time for pulsed exposure.[30]
   c. For postnatal exposures producing temperature increases of 6°C or less, no effects have been reported when $\Delta T < 6 - (\log_{10} t/0.6)$, including off time for pulsed exposure. For example, for temperature increases of 6.0°C and 2.0°C, the corresponding limits for the exposure durations t are 1 and 250 min.[31]
   d. For postnatal exposures producing temperature increases of 6°C or more, no effects have been reported when $\Delta T < 6 - (\log_{10} t/0.3)$, including off time for pulsed exposure. For example, for a temperature increase of 9.6°C, the corresponding limit for the exposure duration is 5 s (=0.083 min).[31]
2. Nonthermal mechanisms
   a. In tissues that contain well-defined gas bodies, e.g., lung, no effects have been observed for in situ peak rarefactional pressures below approximately 0.4 MPa or mechanical index values approximately <0.4.
   b. In tissues that do not contain well-defined gas bodies, no effects have been reported for peak rarefactional pressures below approximately 4.0 MPa or mechanical index values approximately <4.0.[29]

[a]Free-field SPTA intensity for continuous wave and pulsed exposures.
[b]Quarter-power (–6 dB) beam width smaller than 4 wavelengths or 4 mm, whichever is less at the exposure frequency.

Modified from American Institute of Ultrasound in Medicine. *AIUM Statement on Mammalian In Vivo Ultrasonic Biological Effects*. November 8, 2008. http://www.aium.org/.

Sound waves transmit energy, which has the potential to heat and disrupt tissue.[29–44] While diagnostic grayscale imaging delivers a low amount of energy, other forms of ultrasound such as pulse wave and color Doppler, focus higher levels of energy on small areas of tissue. The limited data available suggest that the application of diagnostic ultrasound to human pregnancy is safe and that the value of the information gained through examination easily outweighs any risk to the fetus. All ultrasound machines report power output as the thermal index (TI), a measure of the potential increase in temperature that ultrasound causes in tissue, and the mechanical index (MI), a measure of the potential for tissue cavitation (Table 1.1).[29–32] Ultrasound technology should always be applied according to the "as low as reasonably achievable" (ALARA) principle, which states that one should perform the shortest exam with the lowest amount of ultrasound energy required to successfully complete a diagnostic examination. The Bioeffects Committee of the American Institute of Ultrasound in Medicine, comprising 35 experts in various fields pertaining to ultrasound safety, has defined acceptable limits for diagnostic investigation. Selected safety recommendations are included in Table 1.2.[33,34]

Effective prenatal diagnosis relies on a high standard of imaging. Several national and international bodies have described standards for imaging in the first, second, and third trimester of pregnancy. These include organizations such as the American College of Obstetricians and Gynecologists (ACOG), American Institute of Ultrasound in Medicine (AIUM), Australasian Society of Ultrasound in Medicine (ASUM), National Health Service (NHS) in the United Kingdom, and the International Society of Ultrasound in Obstetrics and Gynecology (ISUOG) (Table 1.3).[3–7] Guidelines typically describe the essential components of an obstetric ultrasound examination. However, many experts in the field advocate the use of additional views to improve diagnostic performance. In addition to describing the basic components of an obstetrical ultrasound examination in this chapter, we also present extended views that improve the quality of the examination and the detection of pregnancy-related problems. This chapter deals with normal fetal anatomy; however, frequent

Table 1.2 Selected Safety Recommendations for Diagnostic Ultrasound

- Ultrasound exposures that elevate fetal temperature by 4°C above normal for 5 min or more have the potential to induce severe developmental defects
- Apply the ALARA principle if the tissues to be exposed contain stabilized gas bodies (lung) and the MI exceeds 0.4
- There is no epidemiologic support for a causal relationship between diagnostic ultrasound during pregnancy and adverse biologic effects to the fetus observed for outputs under a spatial-peak temporal-average intensity of 94 mW/cm^2
- The temperature of the fetus should not safely rise more than 0.5°C above its normal temperature
- When MI is above 0.5 or the TI is above 1.0, the NCRP recommends that the risks of ultrasound be weighed against the benefits

From Fowlkes JB; Bioeffects Committee of the American Institute of Ultrasound in Medicine. American Institute of Ultrasound in Medicine consensus report on potential bioeffects of diagnostic ultrasound. *J Ultrasound Med.* 2008;27:503–515. National Council on Radiation Protection and Measurements. *Exposure Criteria for Medical Ultrasound, II: Criteria Based on All Known Mechanisms*. Bethesda, MD: National Council on Radiation Protection and Measurements; 2002. NRCP report 140.

Table 1.3 Summary of Recommendations Regarding Evaluation of Fetal Anatomy on Prenatal Ultrasound

	ISUOG	*AIUM and ACOG*	*ASUM*	*NHS (UK)*
Head and Neck				
Skull bones, calvarium	X		X	X (shape)
- Biparietal diameter (measure)	X	X	X	
- Head circumference (measure)	X	X	X	X
- Nuchal fold	X	X (measure if increased age)	X	X (measure if increased)
Brain				
- Cavum septum pellucidum	X	X	X	X
- Cerebral ventricles, choroid plexus	X	X	X	X (measure)
- Cerebellum	X	X	X	X (measure)
- Cisterna magna	X	X	X	
- Midline falx	X	X	X	
Face				
Orbits	X		X	
Nose	X (if tech feas)		X	
Lips	X (upper)	X (upper)	X	X (coronal)
Mouth	X			
Jaw			X	
Profile	X (if tech feas)		X	
Chest				
Heart				
- Cardiac activity	X	X	X	
- Four-chamber view	X	X	X	X
- Outflow tracts	X (if tech feas)	X (if tech feas)	X	X
Lungs	X			X
Diaphragm	X		X (right/left)	
Abdomen and Pelvis				
Stomach	X (presence, situs)	X (presence, size, situs)	X (presence, situs)	X
Abdominal wall			X	X
- Abdominal circumference (measure)	X	X	X	X
- Umbilical cord insertion	X	X	X	
- Umbilical cord vessel number	X	X	X	
Bowel	X			X
Kidneys	X	X	X	X
- Renal pelvis (measure if increased)	X			X
Bladder	X	X	X	X
Spine				
Vertebrae	X	X	X	X
Skin covering			X	X

(continued)

Table 1.3 Summary of Recommendations Regarding Evaluation of Fetal Anatomy on Prenatal Ultrasound *(continued)*

	ISUOG	AIUM and ACOG	ASUM	NHS (UK)
Limbs				
Upper extremity	X	X	X	X
- Metacarpals (right and left)	X		X	X
Lower extremity	X	X	X	X
- Femur length	X (measure)	X (measure)	X	X (measure)
- Metatarsals (right and left)	X		X	X
Uterus, Cervix, and Adnexa				
Cervical length		X (if tech feas)	X	
Adnexa	X (if tech feas)	X (if tech feas)	X	
Amniotic fluid volume (subj or meas)	X	X	X	X
Placental position	X	X	X	X

ISUOG, International Society of Ultrasound in Obstetrics and Gynecology; AIUM, American Institute of Ultrasound in Medicine; ACOG, American College of Obstetricians and Gynecologists; ASUM, Australasian Society of Ultrasound in Medicine; NHS, National Health Service, UK.
From Salomon LJ, Alfirevic Z, Berghella V, et al. Practice guidelines for performance of the routine mid-trimester fetal ultrasound scan (ISUOG). *Ultrasound Obstet Gynecol.* 2011;37:116–126. American Institute of Ultrasound in Medicine. AIUM practice guideline for the performance of obstetric ultrasound examinations. *J Ultrasound Med.* 2010;29:157–166. American College of Obstetricians and Gynecologists. Ultrasonography in pregnancy. *Obstet Gynecol.* 2009;113:451–461. ACOG Practice Bulletin No. 101. Australasian Society for Ultrasound in Medicine. *Policies and Statements, D2: Guidelines for the Mid Trimester Obstetric Scan.* http://www.asum.com.au/open/P&S/D2_policy.pdf. National Collaborating Centre for Women's and Children's Health. *Antenatal Care: Routine Care for the Healthy Pregnant Woman.* 2nd ed. London, England: RCOG Press; 2008.

references to anomalies are made to underscore the pertinence of a good anatomic evaluation. Each image used in this chapter was obtained using two-dimensional (2D) ultrasound. Three-dimensional (3D) ultrasound can be a useful adjunct to 2D ultrasound in select circumstances and will be discussed in Chapter 2. All stated gestational ages are according to last menstrual period dating.

EARLY FIRST TRIMESTER SCAN (5 TO 10 WEEKS' GESTATION)

The embryonic stage, ending at 10 weeks' gestation, is a time of very rapid change in the small, developing conceptus.[45] Ultrasound before 11 weeks' gestation is not typically regarded as a routine part of pregnancy assessment. When performed, the examination is generally limited to determination of the location and number of gestations present, determination of chorionicity in cases of multiple gestations, assessment for viability, and estimation of gestational age.[46] Although the anatomy of embryo is not typically examined in detail, a variety of severe congenital anomalies (e.g., severe amniotic band syndrome, body-stalk anomalies, and conjoined twins) may be identified even at this point. A finding that is commonly seen in the early first trimester and that deserves special mention is physiologic herniation of the midgut into the root of the abdominal cord insertion (Fig. 1.1).[47] This finding is considered normal until the early portion 12th week of gestation and should not be mistaken for an omphalocele.

Most examinations at this stage are performed for a specific clinical indication such as pain or vaginal bleeding associated with a positive pregnancy test. Systematic evaluation is needed to accurately distinguish between a viable intrauterine pregnancy, a miscarriage, or an ectopic pregnancy. Ultrasound findings are frequently best interpreted in combination with quantitative maternal serum hCG (human chorionic gonadotropin) with or without progesterone levels. Serial examinations may be needed to reach a diagnosis. The transvaginal approach should be used in all circumstances where a viable intrauterine pregnancy is not obvious on transabdominal assessment. The uterus and adjacent structures should be assessed in both longitudinal and axial sections, taking care to pass completely from side to side and from fundus to cervix to determine the number and location of gestational sacs and embryos. In the early first trimester, the transvaginal approach is ideal to detect any adnexal pathology or free fluid.

Using transvaginal ultrasound, the presence of an intrauterine gestational sac can be consistently demonstrated by the

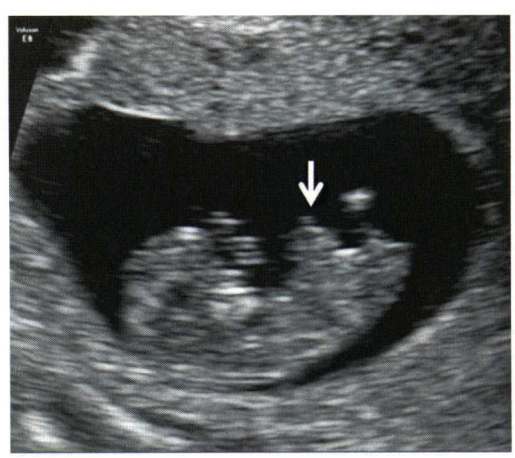

FIGURE 1.1: Sagittal view of a 10- to 11-week fetus demonstrating a physiologic midgut herniation *(arrow)*.