Since the introduction of magnetic resonance imaging (MRI) in the early 1980s, its use for tissue characterization has been based on measured T1 and T2 values using the signal intensity on so-called T1-weighted and T2-weighted images. The signal intensities and the underlying T1 and T2 tissue parameters mainly depend on the content of water as modified by the tissue content, including specifically fibrosis, cells, fluid, or protein content, and thus vary among different tissues. However, these parameters do not correlate with the biological nature of a tumor. There is a significant overlap in T1 and T2 characteristics between benign and malignant lesions of the breast; therefore, these fundamental tissue characteristics play no major role in the evaluation of malignant lesions of the breast and in differentiation of breast cancer from other benign lesions. However, unenhanced MRI using T2-weighted images has been shown to be extremely useful for detecting and evaluating breast implant rupture.

The introduction of contrast-enhanced (CE) MRI was a major breakthrough in the diagnosis of breast tumors, based on the observation that gadolinium (Gd)-DTPA enhances virtually all cancers more than minimal glandular breast tissue. However, although the majority of malignant tumors enhance, significant overlap exists between enhancing benign and malignant tissues. Thus, it is generally recommended to combine CE MRI of the breast with x-ray mammography.

To achieve the necessary image quality in MRI of the breast, the use of a dedicated breast coil is mandatory. Both single-breast coils and newer coils that allow imaging of both breasts exist. The advantages of imaging of both breasts in a double-breast coil include the possibility of detecting multicentric carcinoma, the simultaneous evaluation of bilateral unclear breast diseases, and the additional diagnostic information resulting from the comparison of both breasts.

The slice thickness in imaging of the breast should not exceed 4 mm. The optimal slice thickness seems to be approximately 2 mm with an in-plane resolution of 1 mm or less. To allow direct comparison and subtraction of pre- and postcontrast T1-weighted images, it is essential that the patient lie still during the entire examination. Usually the patients are studied in the prone position, which helps to reduce breast motion caused by respiration. Depending on the direction of the phase-encoding gradient, cardiac artifacts that increase after the administration of contrast medium may cross the left breast or both axillae in axial images. Thus, imaging in the sagittal or coronal plane may occasionally be necessary to detect a suspected lesion near the thoracic wall or in the axilla.

Usually a T2-weighted sequence, either spin echo or fast spin echo, is acquired before the CE studies, because T2-weighted images allow differentiation of cysts or fibrous fibroadenomas from other well-circumscribed lesions. For the CE T1-weighted studies, optimally a fast three-dimensional (3D) gradient echo sequence should be used, because these are most sensitive for visualization of paramagnetic contrast medium. To allow later subtraction of CE from unenhanced images, first an unenhanced T1-weighted scan of the breast should be performed followed by the injection of a Gd chelate, usually at a dose of 0.1 to 0.2 mmol/kg body weight. Contrast injection should be followed by a flush of at least 20 ml saline to achieve reproducible administration of the entire amount of contrast medium. Immediately after contrast medium injection, serial acquisitions of the T1-weighted fast 3D gradient echo sequence are performed. The optimal temporal resolution, which is given by the acquisition time of the sequence, is between 1 and 2 minutes. Up to five acquisitions should be performed after the injection of contrast medium.

To eliminate the high signal intensity of fat, which occasionally interferes with the detection of small enhancing lesions, subtraction of the unenhanced images from the CE studies should be performed. This also allows detection of small enhancing lesions. Other techniques that allow elimination of the fat signal include selective fat saturation and selective water excitation. However, with these techniques, signal inhomogeneities may occur because of inhomogeneities of the magnetic field. Thus, the use of image subtraction is a more robust approach for the evaluation of enhancing breast lesions in routine clinical practice.

Imaging studies of the breast in premenopausal patients should be performed between days 6 and 16 of.
the menstrual cycle because focal or diffuse enhancement within normal tissue as a result of hormonal stimulation outside this time interval may obscure recognition of enhancing lesions or mimic malignant changes. The same observation concerning enhancing lesions is true for postmenopausal patients who are receiving hormone replacement therapy.

In addition to qualitative morphologic information achieved on T₁-weighted CE and subtracted images, quantitative image analysis can be performed. If significant enhancement of a breast lesion is observed, quantitative analysis of the dynamic enhancement may provide important additional information.

Findings indicative of malignancy include morphologic observations, such as irregular contours and enhancement that follows the ducts or starts from the periphery, as well as quantitative observations, such as very fast enhancement in the first sequence after contrast media injection followed by a plateau phase or even a washout. Imaging findings that are more indicative of a benign disease include well-circumscribed contours of an enhancing lesion, diffuse patchy enhancement, typical septations within a well-circumscribed lesion, and a slow rise of enhancement on quantitative analysis.

Candidates for CE MRI of the breast include patients with scarring that is difficult to assess in x-ray mammography or ultrasonography after limited surgery, those with silicon implants, and those who have had limited surgery and irradiation. CE MRI of the breast should be performed no sooner than 6 months after therapeutic surgery and irradiation. CE MRI of the breast should be performed during the second or third week of the menstrual cycle, normal breast tissue and nonproliferative dysplasia in middle-aged and older patients show little enhancement. This important imaging finding can be used to exclude malignant disease.

Proliferative dysplasia and adenosis may enhance to a variable degree (Fig. 10-2). In most cases of proliferative dysplasia or adenosis, the enhancement is diffusely distributed with a patchy signal increase within large parts of the breast tissue. In regard to quantitative dynamic analysis, usually a delayed signal intensity increase is observed. In patients with proliferative dysplasia, only absence of enhancement allows exclusion of invasive malignancy with high probability. If diffuse enhancement is present, carcinomas that enhance slowly or diffusely cannot be ruled out. Alternatively, focally enhancing proliferative dysplasia sometimes can mimic malignancy.

Fibroadenoma

Fibroadenomas represent the most common breast tumor. Histologically, these lesions vary from completely fibrosed to adenomatous to myxoid tissue composition. On T₁-weighted images, the signal intensity of fibroadenomas reflects the specific histologic pattern present in an individual fibroadenoma. Whereas fibrous

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FIGURE 10–1. Multifocal invasive ductal carcinoma. Proton density (A) and T₂-weighted (B) images show a high-signal-intensity (SI) mass in the left breast. Additionally, dense tissue in both breasts consistent with proliferative dysplasia can be noted. In the T₁-weighted unenhanced image (C), the mass is low SI.

Illustration continued on following page
One minute (D) and 5 minutes (E) after contrast injection, a strongly enhanced lesion and a more centrally located second tumor are visible. F. The T1-weighted, fat-saturated, contrast-enhanced image also displays both enhancing lesions; however, because of field inhomogeneity, the signal within the field of view is inhomogeneous.
G, The subtraction image clearly displays both lesions and shows the tumors to be rather well-circumscribed. However, in quantitative assessment of contrast dynamics \( (H) \), a strong increase of SI in the first minute after contrast administration is noted, and a washout is demonstrated starting 3 minutes after injection.
Figure 10–2. Proliferative dysplasia. Unenhanced proton density (A), T₂-weighted (B), and T₁-weighted (C) images show dense tissue of both breasts with diffuse delayed enhancement on T₁-weighted contrast-enhanced.
FIGURE 10–2 Continued. (D) and T₁-weighted fat-saturated contrast-enhanced (E) images. The enhancement is best appreciated in the subtracted image (F), and the increasing enhancement suggests proliferative changes. However, magnetic resonance imaging cannot rule out the presence of malignancy in enhancing breast tissue.
fibroadenomas, which consist of densely packed collagen, have a low signal intensity; adenomatous or myxoid fibroadenomas may have increased signal intensity on T2-weighted images. Because other well-circumscribed malignancies such as medullary or mucinous carcinomas have similar signal intensity on T2-weighted images, a distinction between these malignant lesions and adenomatous or myxoid fibroadenomas is not possible. In T1-weighted images, fibroadenomas usually have low signal intensity. On CE MRI, fibrous fibroadenomas enhance very little. Thus, using the findings on enhanced scans, lesions that have low signal intensity on T2-weighted images can be distinguished from malignant disease. However, adenomatous or myxoid fibroadenomas do enhance, and although the enhancement is typically delayed, the distinction from malignant lesions is not reliable (Fig. 10-3). On T1-weighted images, another characteristic finding of a fibroadenoma is a round or oval lobulation in a focal breast lesion. If this lobulation can be demonstrated on T2-weighted images, a fibroadenoma is very likely.

Breast Cancer

Breast cancer represents the most common malignant tumor in women and is the leading cause of death in women between the age of 40 and 60 years. Whereas in

**FIGURE 10–3.** Myxoid fibroadenoma. Proton density (A) and T2-weighted (B) images show a well-circumscribed hyperintense lesion of the right breast. C, On the T1-weighted unenhanced image, the lesion shows low signal intensity. In dynamic imaging
FIGURE 10–3 Continued. (D–H, 1 minute to 5 minutes after contrast injection), a strong but delayed enhancement can be noted. The strong enhancement and the distinct borders of the lesion are best displayed in the subtracted image (I), and quantification of contrast uptake shows delayed enhancement (J). However, magnetic resonance imaging does not allow a confident distinction from a well-circumscribed malignancy.

Illustration continued on following page
Breast Implants

The appearance of breast implants on MRI varies because of the many different types. Before imaging, one must know the age and type of implant and whether prior implants were ruptured with open or closed capsulotomy or capsulectomy (Fig. 10-5). X-ray mammography usually only allows detection of fully collapsed rupture if extracapsular silicone is present. Ultrasonography may be very sensitive in showing collapsed or even uncollapsed rupture. In the detection of small amounts of soft tissue silicone, ultrasonography may be even more sensitive than MRI. However, silicone fluid that extends all the way to the skin or calcification in the fibrous capsule of an implant may block the ultrasound signal, rendering further evaluation impossible.

The imaging protocol in MRI of breast implants should consider implant type and date of placement. Typically, first T_2-weighted spin echo sequences should be performed. These allow assessment of the extent of the implant and determination of whether fluid collections are present either around the implant or in soft tissue. If, on these first T_2-weighted images, implant rupture is not clearly identified or ruled out, additional high-resolution sequences should be performed that include water-suppressed T_2-weighted images in both the axial and sagittal planes. The slice thickness of these sequences should not exceed 3 to 4 mm. If a rupture is detected and there is suspicion of free soft tissue silicone in the area of the axilla, the brachial plexus, or even retrosternally, additional sequences with the use of an array coil for imaging of the thorax should be performed to delineate these lesions.

In imaging of breast implants, contour abnormalities may be recognized that represent herniation of either an intact or ruptured implant or a variation of the shape of an intact fibrous capsule. These herniations should not be generally interpreted as a ruptured implant. Collapsed rupture of an implant is indicated by the so-called wavy line sign and C sign. The wavy line sign stands for internal continuous wavy lines in an implant representing an implant shell totally enveloped and surrounded by silicone gel in a single-lumen implant. The C sign is based on the observation that the back patch of an implant shows the shape of the letter C and is fully surrounded by silicone gel. In a fully collapsed implant, the implant shell has a closely layered appearance or may be fully fallen on itself (Fig. 10-6). Uncollapsed rupture may be more difficult to detect. The best sign in detection of uncollapsed rupture is the definitive presence of a small amount of intracapsular silicone gel within an implant fold or folds outside an implant. Silicone detected in soft tissues outside the fibrous capsule of an implant is a very reliable sign of a present or prior implant rupture. Silicone from breast implants found in the soft tissue outside the fibrous capsule of an implant will assume different appearances. If some kind of capsule or scar surrounds the silicone in the soft tissue, it shows a bright signal intensity similar to that of silicone-filled breast implant. However, if there is granuloma formation or infiltration of scar tissue into the silicone deposition, the signal intensity may vary and thus can make a rupture undetectable. Ultrasonography is more sensitive for detecting silicone deposition in lymph nodes (from an implant rupture). In summary, the main indications for MRI of breast implants include determination of rupture of a silicone gel-filled implant and, in the case of a ruptured implant, detection of soft tissue silicone, which should be further evaluated by MRI regarding amount and exact localization.

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Figure 10–4. Invasive carcinoma. Proton density (A), T₂-weighted (B), and T₁-weighted (C) unenhanced images in a 43-year-old woman demonstrate an irregular, spiculated mass of the right breast that shows strong enhancement in the T₁-weighted image after contrast injection (D).
FIGURE 10–4 Continued. E, The irregular spiculated borders of the mass, typical for invasive carcinoma, are best demonstrated in the subtracted image. Quantification of contrast uptake (F and G) shows a strong increase of signal intensity in the first 2 minutes after CM administration with the beginning of washout by 5 minutes after injection.
Figure 10–5. Free silicone after implant rupture and intracapsular water-like fluid. *A* and *B*, $T_2$-weighted fat-saturated images show an intracapsular water-like fluid collection surrounding an intact breast implant of the right breast. Additionally retrosternal soft tissue silicone can be demonstrated (arrow) as a result of prior implant rupture. *C*, $T_2$-weighted image without fat suppression shows the free silicone with high signal intensity. Thus, differentiation on this image from retrosternal fat is difficult.
FIGURE 10–6. Collapsed implant rupture. A–C, T₂-weighted fat-suppressed images cranial to caudal show a collapsed implant shell with extensive soft tissue silicone demonstrating a partial cystic appearance. The so-called wavy line sign is seen in the right breast implant.
MRI excels in the assessment of the mediastinum and hilum. The blood vessels and tracheobronchial tree are both visualized as regions of signal void highlighted by the surrounding fat. Masses in these regions have sufficiently different imaging characteristics to allow their distinction from normal structures and fat. Compared with computed tomography (CT), in which contrast is often needed to identify a mass and to avoid mistaking a blood vessel for a pathologic region, particularly in the pulmonary hilum, MRI provides excellent cross-sectional images of the mediastinum (without contrast), allowing assessment of mediastinal anatomy that is comparable to CT in quality and clarity. The main indications for MRI of the mediastinum and the thoracic inlet are imaging of vascular disorders, staging of non-small cell and small cell bronchiogenic carcinoma, evaluation of mediastinal masses, and staging as well as therapy monitoring in Hodgkin’s and non-Hodgkin’s lymphoma.

MRIs of the thorax are particularly susceptible to motion artifacts. Breathing motion and pulsation of the heart and great vessels can markedly degrade image quality; thus, short measurement times and artifact reduction techniques have to be used when performing MRI of the chest. If imaging of the thoracic inlet and the upper mediastinum above the level of the aortic arch is to be performed, electrocardiogram (ECG) gating and respiratory compensation are not needed, because artifacts in this area are not substantial and high image quality can be obtained with standard T1-weighted and T2-weighted sequences. If imaging below the aortic arch is performed, ECG or pulse oximetry gating is mandatory. If T1-weighted fast spin echo sequences are used for imaging, additional prospective respiratory gating or breath-hold sequences with imaging of only one slice per breath-hold should be performed. New ultra-fast single-shot imaging techniques allow acquisition of high-quality images without breath-holding because acquisition time is typically less than 250 milliseconds. When T1-weighted imaging of the chest below the aortic arch is performed, two different approaches can be used: (1) breath-hold T1-weighted sequences with acquisition of one slice per breath-hold or (2) acquisition of T1-weighted sequences using respiratory compensation techniques such as respiratory-ordered phase encoding (ROPE). The latter technique accomplishes a reduction in respiratory artifacts by reordering the phase-encoding lines of k space. Generally, if respiratory gating techniques are performed, the patient should be instructed to breathe softly and evenly to minimize chest wall movement.

The selection of coils depends on the area of interest. If the entire mediastinum is to be scanned, a phased-array body coil should be used to achieve sufficient resolution and an adequate signal-to-noise ratio. If tumors of the posterior mediastinum or paravertebral tumors such as neuroblastoma are to be imaged, spine surface coils can be used for evaluation.

Primary Mediastinal Masses

In the diagnosis of primary mediastinal tumors, the age of the patient and the localization of a mass are of special importance. Typical tumors that can be found in the anterior mediastinum are tumors of the thymus (Fig. 10-7), germ cell tumors, mediastinal lymphangiomata, mediastinal goiter, and mediastinal parathyroid adenoma. In the middle mediastinum, mediastinal cysts and esophageal as well as tracheal pathologies are the most common lesions (Fig. 10-8), whereas in the posterior mediastinum typically neurogenic tumors arising from the peripheral nerves, sympathetic ganglia tumors, and thoracic meningoceles account for the majority of lesions. Malignant lymphomas, either Hodgkin’s or non-Hodgkin’s lymphoma, are encountered in all sections of the mediastinum (Fig. 10-9).

In the esophagus and the trachea, MRI is most useful in the preoperative staging of large tumors. Because of its multiplanar imaging capabilities and high tissue contrast, MRI is well suited to evaluate tumor extension and the relationship of the tumor to other surrounding structures.

Secondary Mediastinal Masses

MRI of the mediastinum is useful in detecting secondary mediastinal masses, particularly abnormal lymph nodes. Overall, the sensitivity of MRI in detecting lymph node enlargement is similar to that of CT, although in MRI the differentiation of small lymph nodes from vessels is much easier. However, because of its ability to acquire multiple planes, MRI has proven to be superior to CT in detecting lymph nodes at the hilum. MRI is also useful in detecting mediastinal invasion in the staging of lung cancer. Encasement or invasion of the vasculature (Fig. 10-10), esophagus, and trachea and involvement of the pericardium or myocardium are accurately detected with MRI. Because of the multiplanar imaging capabilities, better performance compared with CT has been reported. However, currently MRI is principally used as a complementary procedure for assessing the mediastinum and hilum and in those patients who have a contraindication to the use of iodinated contrast media or in whom the CT is equivocal, particularly for lesions in the hilum.

Imaging of the Thoracic Inlet

In imaging of peripheral cancers located in the lung apex, MRI, because of its multiplanar capacity, has an obvious advantage over transaxial and reformatted CT images. It is difficult to evaluate this area with CT because of artifacts caused by the surrounding bony
FIGURE 10–7. Malignant thymoma in a 42-year-old woman with myasthenia gravis. T₁-weighted images in sagittal (A), coronal (B), and axial (C) orientations show a lobulated inhomogeneous high-signal-intensity mass of the anterior mediastinum with partially indistinct borders. The mass is partially located within the anterior mediastinal fat and shows extension into the right para-aortic space (arrow).
FIGURE 10–8. Bronchogenic cyst. $T_1$-weighted (A) and $T_2$-weighted (B) axial images show a lobulated high-signal-intensity (SI) mass of the posterior mediastinum located dorsally to the trachea. In the $T_1$-weighted fat-saturated image (C), the high SI of the cyst is not suppressed, indicating high protein content of the fluid consistent with a bronchogenic cyst.
FIGURE 10–9. Hodgkin’s disease. T₂-weighted images in axial (A and B) and sagittal (C) orientations show multiple soft tissue masses with different signal intensities in the mediastinum and the upper thoracic inlet. The size of a lymphoma can be determined very accurately by MRI because of the multiplanar imaging capabilities. Thus, reproducible measurements during therapy can be performed.
FIGURE 10–10. Bronchial carcinoma with mediastinal invasion. T₁-weighted axial images (A–D) cranial to caudal show a low-signal-intensity tumor invading the anterior mediastinum with encasement of the brachiocephalic vein. Additionally, tumor invasion between the ascending and descending aorta is depicted. D. Encasement of the left pulmonary artery is demonstrated with loss of the fat plane between the pulmonary artery and the tumor. E and F. Coronal T₁-weighted images confirm encasement of the pulmonary artery and show extension of the tumor along the left carotid artery.
structures. Unless an adequate bolus of contrast media is given, the effect of the mass on the blood vessels within the thoracic inlet may not be delineated by CT. The high incidence of chest wall involvement with extension to and involvement of the vascular structures, brachial plexus (Fig. 10-11), and spine is the main indication for imaging studies. Because localized chest wall invasion generally is not a contraindication for surgical resection, it is imperative to clearly display the relationship of the tumor to adjacent structures. Contraindications for surgical resection include involvement of the brachial plexus, invasion into the spinal canal, and gross vertebral body involvement as well as encasement of vascular structures. These are clearly displayed by MRI, although oblique sections are sometimes necessary for definitive diagnosis. Because the majority of these tumors undergo radiotherapy, MRI has an important value in radiation planning and follow-up during and after therapy. On T1-weighted images, tumors tend to be isointense to the vasculature and the brachial plexus. However, fat planes are best demonstrated on T1-weighted sequences, which is very important in order to determine plexus or vascular involvement.

Chest Wall

In imaging of tumors of the chest wall, especially when evaluating primary tumors, metastatic lesions, and direct extension of pulmonary tumors, MRI has proven to be more accurate than CT. However, rib destruction is usually best detected by chest x-ray film, and early destruction of vertebral bodies is most easily evaluated by CT. Because MRI, with its superior contrast resolution and multiplanar imaging capabilities, allows delineation of chest wall fat, muscle, and bones, it is the preferred method for evaluating chest wall extension of malignant tumors. Oblique scanning planes parallel or perpendicular to the ribs help to optimize evaluation of chest wall invasion. Differentiation between benign and malignant tumors on the basis of signal intensity characteristics on T1- and T2-weighted images alone is impossible. Only with lipomas, the most common primary chest wall tumor, can tissue-specific characterization be made on MRI. The extension of lipomas, herniation between the intercostal muscles, and subpleural component (if present) are readily demonstrated on MRI. Malignant tumors of the chest wall are rather rare and in most cases originate from the pleura or osseous structures (as in Ewing’s sarcoma). Identification of irregular lesion margins and infiltrative growth are hallmarks of malignancy on MRI.

Pulmonary Parenchyma

The lungs are seen as regions of low (black) signal intensity on MRI. An abnormality within the lung parenchyma causes increased signal intensity. In general, most pulmonary nodules can be seen using either CT or MRI. However, CT usually detects a larger number of small nodules than MRI, but small nodules adjacent to the blood vessels are better displayed on MRI. Small lesions within the lung parenchyma are not as readily identified on MRI as on CT because of the form of acquisition. MRI times are longer, and patients breathe quietly throughout the acquisition of multiple images. Therefore, small lesions can suffer from partial volume averaging during an MRI study because they move in and out of the imaging plane. New ultra-fast imaging sequences allow imaging during breath-holding. In contrast, CT images are obtained during suspended respiration, which decreases the effect of partial volume averaging of small nodules. Additionally, CT examinations using both soft tissue and lung windows improve identification of small pulmonary nodules. In the imaging of tuberculosis or metastases of osteosarcoma, CT can identify even small areas of calcifications that cannot be seen on MRI.

Thoracic Aorta

Disease of the thoracic aorta is best evaluated by MRI. Because of its multiplanar imaging capabilities, studies can be optimally tailored to the different diseases that may need further evaluation. The basic examinations in imaging of the thoracic aorta consist of ECG-gated multislice acquisitions, ECG-gated breath-hold single-slice imaging, multiphase cine imaging, and velocity mapping dynamic imaging. First, transaxial scans should be performed from the thoracic inlet to the level of the diaphragm followed by a left anterior oblique study, which follows the axis of the aortic arch and descending aorta. In certain cases, it is also necessary to perform transaxial slices perpendicular to the aorta to achieve further information about diseases of the aortic wall. Furthermore, MRI using cine techniques allows reliable quantification of blood flow, ejection fraction, stroke volume, and quantification of regurgitation in aortic valve insufficiency.

Gd-enhanced 3D magnetic resonance angiography (CE MRA) is a newer technique that provides high-resolution 3D data sets very quickly and is well suited for depicting intrathoracic vessels. Because of the 3D nature of the data set, CE MRA provides volumetric data that can be processed for multiplanar reformations and maximum intensity projections. Vascular visualization using CE MRA relies on the T1 shortening of blood by Gd-based contrast during the intravascular transit. It is important to note that this technique requires the combination of an intravenously administered Gd chelate-contrast bolus with the image acquisition. A major advantage of this technique compared with time of flight or phase contrast angiography is the less pronounced sensitivity to flow-related artifacts and thus the more reliable visualization of vascular structures. Another important issue is the acquisition of the whole data set in a single breath-hold, thus avoiding respiratory artifacts. The sequences used for CE MRA depend on the different MRI systems; however, generally the fastest possible 3D imaging sequence, typically a fast 3D gradient echo scan, should be used. Preferential arterial images can be achieved by selective timing of the contrast bolus arrival to the acquisition of the central k-space data.
Figure 10-11. Pancoast tumor (superior pulmonary sulcus tumor) in a 52-year-old woman with progressive atrophy of the left upper extremity. A and B, Coronal short TI inversion recovery images demonstrate a small high-signal-intensity (SI) superior sulcus tumor along the lower brachial plexus. C and D, On coronal T1-weighted images, the tumor has low SI. Decreased SI can be noted within the involved brachial plexus (arrow) on the left as compared with the contralateral, normal side.
FIGURE 10–11 Continued. Axial T₁ (E and F) and T₂-weighted (G and H) images also demonstrate the direct contact between the tumor and the lower brachial plexus, with inhomogeneous enhancement of the tumor and parts of the brachial plexus on T₁-weighted contrast-enhanced images (I and J), indicating infiltration of the lower brachial plexus.
Aneurysms

In the evaluation of patients with an aortic aneurysm, in addition to measuring the true diameter of the vessel and the diameter of the patent lumen, it is extremely important to characterize the location, shape, and extent of the aneurysm and to determine its relationship to branch vessels and any effect the aneurysm may have on adjacent structures. Atherosclerosis is the leading cause of aneurysms involving the thoracic aorta. As a result of weakening of the media secondary to the atherosclerotic process, a progressive increase in the diameter of the aorta involving all layers of the vessel can be observed. Because tortuosity in combination with aortic aneurysm is a common observation, the lateral anterior oblique (LAO) view in most cases does not allow imaging of the entire aorta in one single slice. Different configurations of aortic aneurysms can be found, including fusiform, saccular, and cylindroid. The location of a thoracic aneurysm is an important determinant of the cause. For atherosclerosis it is rare that an aneurysm solely involves the ascending aorta. Rather, these aneurysms also involve the aortic arch and the descending aorta. If an aneurysm involves only the ascending aorta, the differential diagnosis should include cystic medial necrosis, other degenerative processes of the media, and aneurysmatic dilatation caused by aortic valve disease (Fig. 10-12).

In Marfan’s syndrome, the loss of elastic fibers classically leads to a progressive increase in the diameter of the aorta with involvement of the aortic root, the tubular portion of the aorta, and the proximal ascending aorta. As a result of the marked dilatation of the aortic root, secondary aortic insufficiency, aortic dissection, and hemopericardium can be observed and should be recognized on MRI if present. Marfan’s syndrome can also involve the pulmonary arteries and result in an isolated pulmonary artery aneurysm; however, not all patients with Marfan’s syndrome will exhibit aortic root changes or other vascular involvement. Overall, MRI is an excellent noninvasive imaging modality for evaluating pa-

**Figure 10–12.** Aortic regurgitation. A, Contrast-enhanced magnetic resonance angiography shows an increased diameter of the ascending aorta and kinking of the supra-aortic vessels. B, The diameter of the aorta is clearly evaluated in an axial T-weighted image, and (C) flow evaluation of the aorta with a phase contrast acquisition shows the regurgitation volume as the area under the curve for the negative flow component.
tients with Marfan’s syndrome. In aortic valve disease, including both aortic insufficiency (see Fig. 10–12) and aortic valve stenosis, MRI can be used to evaluate stroke volume, ejection fraction, left ventricular hypertrophy, and left ventricular enlargement and to assess quantitatively the velocity across the aortic valve. Because MRI can accurately determine the true diameter of an aneurysm caused by aortic valve disease, and further increases in the aortic diameter can be reliably measured in a noninvasive manner on follow-up, MRI is an excellent tool in monitoring of aortic aneurysms. In general, aneurysms larger than 6 cm in diameter have an increased incidence of aortic rupture and, therefore, require immediate surgery. Unlike x-ray angiography, MRI is also effective in depicting para-aortic processes, including compression of adjacent structures by an aneurysm, para-aortic hematomas, and thrombus formation within an aneurysm, and in detecting mural thrombus.

Aortic Dissection

More than 95% of aortic dissections start in the thoracic aorta, of which 60% to 70% involve the ascending aorta, and only approximately 25% start distal to the left subclavian artery in the region of the ligamentum arteriosum. Aortic dissections are classified by location, and two classifications exist. In DeBakey type I, the dissection begins within the ascending aorta and extends to the descending aorta; in type II, dissections are localized only in the ascending aorta; and in type III, dissections begin just distal to the subclavian artery. Stanford type A dissections involve the ascending aorta, where type B dissections do not. Because dissections of the ascending aorta may affect the aortic valve, coronary arteries, and branching vessels, they represent surgical emergencies and have a very high mortality in the first few hours after onset. Often patients with acute dissection of the ascending aorta are unstable; thus, MRI is not the imaging modality of choice. CT is used for diagnosis followed by immediate surgical intervention. The classic clinical picture in an acute onset of aortic dissection is severe chest pain that radiates to the back, sometimes similar to the clinical picture of ischemic heart disease.

In hemodynamically stable patients, it has been suggested that MRI is the best imaging modality for the evaluation of aortic dissection. If on conventional spin echo images the intimal flap is not clearly displayed, cine MRI usually clarifies the issue. Likewise, differentiation between thrombus and slowly flowing blood in the false lumen can be made by the use of cine MRI techniques (Fig. 10–13). MRI is also highly effective in evaluating branch vessel involvement (Figs. 10–14 and 10–15) and retrograde extension of a dissection with depiction of involvement of the aortic root. Occasionally, it may be difficult to differentiate complete thrombosis of the false lumen of a dissection from an aortic aneurysm or mural thrombus (Fig. 10–16). Indirect signs that favor the diagnosis of a dissection include longitudinal thrombus extension (which is not typically identified in an aneurysm), a noncircular compressed patent lumen, and a change in the position of the thrombus as a result of the spiral configuration of the dissection membrane. MRI is extremely useful in the evaluation of patients after medical or surgical intervention and in the evaluation of periaortic hematomas, infections, and progressive dilatation of the false lumen. In patients who have undergone graft placement, MRI can be used to examine the graft and screen for anastomotic aneurysms.

Pulmonary Arteries

Since its introduction, there has been interest in the use of MRI for evaluating the pulmonary arteries for pulmonary embolism or thrombus. Standard MRI techniques are limited in their ability to evaluate the pulmonary arterial tree because they lack the ability to study the peripheral vasculature. In normal pulmonary arteries, signal void appears within the vessels on standard spin echo pulse sequences. MRI detects central thrombus as an intraluminal signal within the pulmonary

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Figure 10-14. Abdominal aortic dissection. Contrast-enhanced magnetic resonance angiography clearly displays dissection of the abdominal aorta with retrograde filling of the false lumen by a re-entry at the level of the iliac arteries. Note that all abdominal vessels except the right renal artery arise from the true lumen.
FIGURE 10–15. Chronic type B dissection in a 64-year-old man. Whole-volume MIP projection (A) and targeted subvolume MIP projection (B) of contrast-enhanced magnetic resonance angiography data set clearly display the aortic dissection beginning just distal to the left subclavian artery. However, the dissection membrane is better appreciated in the subvolume MIP.
Intramural bleeding with subsequent type B aortic dissection in a 52-year-old man with sudden onset of thoracic pain. A, T₁-weighted axial imaging at initial presentation shows thickening of the aortic wall with intermediate to high signal intensity. B, Axial cine imaging at this time only shows the thickening of the wall but no intimal flap. One year later, the patient presented for routine follow-up without history of another pain episode.
Figure 10–16 Continued. At this time, an intimal flap is clearly demonstrated in T$_1$-weighted (C) and cine (D–F) imaging. G, Maximum intensity projection of the contrast-enhanced magnetic resonance angiogram clearly depicts the spiral course of the dissection membrane.
arteries; however, using standard techniques, MRI is not the modality of choice for detecting pulmonary emboli. In a patient for whom there is an absolute contraindication to iodinated contrast and an equivocal ventilation-perfusion scan, MRI plays an important role by demonstrating emboli. If MRI with standard techniques is to be used for pulmonary artery evaluation, it is important to note that the technique is better suited for detecting central rather than peripheral emboli. The varying flow direction within the pulmonary arteries as well as potentially diminished flow may lead to incomplete washout and to erroneous simulation of thrombus as a result of missing signal void. More recently, Gd-enhanced MRA has been used for imaging patients with suspected pulmonary embolism. It is especially helpful for imaging patients with ambiguous pulmonary ventilation and perfusion scintigraphy and patients with contraindications to the use of iodinated contrast. Several studies report high sensitivity and specificity for CE MRA in detecting pulmonary embolism up to the subsegmental branches. Three-dimensional CE MRA is also particularly useful for identifying systemic pulmonary circulation connections (e.g., shunt lesions). Typically, CE MRA depicts these anomalous connections, because they generally fill with contrast (Fig. 10-17). The evaluation of the data set using multiplanar reformation and targeted maximum intensity projections gives very high sensitivity for detecting these lesions. In imaging of the pulmonary veins, CE MRA may be helpful in evaluating anomalous pulmonary venous return in patients with congenital heart disease.

HEART

Congenital Heart Disease

Since the late 1980s, MRI has developed into a clinically useful tool to study the heart, in particular for congenital malformations. The effectiveness of MRI in diagnosing congenital heart diseases (CHD) is widely recognized, but its appropriate role in imaging of CHD in relation with echocardiography and cardioangiography is still evolving. The anatomy of CHD either pre- or postoperatively can vary from simple to very complex. Many CHD types require intervention, either corrective or palliative, and with improvement of various surgical and intervention techniques survival rate has increased dramatically. This has resulted in a growing number of postoperative patients who generally require extensive follow-up. Because residual sequelae and complications determine the long-term outcome of corrected or palliated CHD, timely detection and quantification of morphologic and functional abnormalities require accurate and preferably noninvasive imaging methods.

Echocardiography is currently used as the initial noninvasive imaging study for almost all patients with known or suspected CHD. It is unlikely that MRI will replace echocardiography as the first diagnostic procedure because of the portability, universal availability, and low cost of echocardiography. It is superior to MRI in depicting cardiac valves, real-time cardiac motion, and small intracardiac shunts. However, MRI can demonstrate cardiovascular anatomy without the limitation of acoustic windows or ultrasound penetration of the body. Furthermore, MRI can provide tomographic images in any imaging plane and with a wide field of view. Clearly, in many cases, the diagnostic capabilities of MRI and echocardiography are complementary rather than competitive.

Angiocardiography has been the gold standard for evaluation of cardiac anatomy and function. Important information such as intracardiac pressures, pulmonary vascular resistance, and oxygen saturation can be obtained as with no other modality. However, catheterization has a known complication rate, requires the use of ionizing radiation and intravascular administration of
iodinated contrast media, and thus is particularly undesirable for repeated applications in young patients.

Conventional echocardiography-gated spin echo sequences are still the basis for evaluation of cardiac anatomy. In most cases, $T_1$-weighted imaging should be performed. Adjunct $T_2$-weighted sequences are necessary only if inflammation or myocardial tissue abnormalities are suspected. Respiratory artifacts can be reduced using prospective imaging algorithms that improve image quality significantly and do not prolong imaging time. High-field-strength systems (1.5 T) have some clear advantages over lower strength systems, because improved spatial resolution and shorter imaging times are very important. This is especially true in imaging in children because occasionally very thin sections (3 mm) are needed to evaluate the anatomy effectively. In contrast to spin echo imaging, gradient echo imaging is a faster technique that allows evaluation of the same section with a high repetition rate at different times after the trigger signal, which enables reconstruction of a cine loop of this particular section. Turbulent flow, stenosis, regurgitation, and shunt flow in this type of imaging can be detected as a jet of signal void. Cine gradient echo MRI can also be used to assess left ventricular and right ventricular function in terms of volume and myocardial mass.

In a typical imaging protocol, first a scout image is obtained to determine the location of subsequent transverse sections. After coronal images are obtained, multislice transverse images are acquired from the top of the aorta to the diaphragm using spin echo sequences. Typically, in these initial studies, a slice thickness of 5 mm should be used. However, if small structures that need additional evaluation are detected, a specially targeted sequence with a smaller slice thickness (3 mm) should be used. These first transverse images are supplemented by sagittal and coronal images. Additionally, oblique images may be needed (e.g., to demonstrate the aortic arch or the descending aorta). Short-axis or four-chamber views of the heart may be acquired with cine MRI technique to quantify ventricular volume, ejection fraction, and shunts.

The main clinical indications for MRI in CHD are:

1. Evaluation of thoracic aortic anomalies
2. Assessment of presence, central connections, and size of the pulmonary arteries in tetralogy of Fallot, pulmonary atresia, and right-sided obstructive anomalies
3. Evaluation of intracardiac and extracardiac morphology of complex ventricular anomalies
4. Examination of pulmonary venous connections and other pulmonary venous anomalies
5. Assessment of septal defects
6. Monitoring of patient status after various surgical procedures
7. Identification of systemic venous anomalies

In evaluation of the aorta, MRI has been found to be effective for definitive diagnosis of a number of different congenital anomalies.

MRI can demonstrate aortic arch anomalies such as, for example, double aortic arch and aberrant left subclavian artery (Fig. 10-18). The most frequently encountered congenital anomaly of the thoracic aorta is coarctation (Fig. 10-19). MRI is very effective for evaluating...
coarctation initially and after treatment. The transverse and the sagittal or LAO view should be used when this diagnosis is suspected. The stenosed aortic segment is often most clearly identified using the LAO equivalent plane because this plane is perpendicular to the coarctation. However, because of the tortuosity of the aorta in the prestenotic segment, occasionally the complete aortic coarctation cannot be displayed in one single slice.

MRI can clearly depict the luminal diameter of the coarctation site as well as poststenotic dilatation and dilated collaterals. Additionally, CE MRA can be performed with maximum intensity projection reconstructions to give a detailed overview of the anatomy for planned surgery. After treatment, MRI can be used to demonstrate the diameter at the site of repair, postoperative mediastinal hematoma, and false aneurysms devel-
Pulmonary atresia is depicted on transverse MRI as a solid layer of muscle in the region of the right ventricular outflow tract at the base of the heart. Additional images oriented along the right ventricular outflow tract can be used to evaluate the atretic segment further. The solid layer of muscle found in pulmonary atresia represents the blind-ended infundibulum, and the length of the atresia may be shown to be extensive or focal at the valve level. The most useful information provided by MRI in patients with pulmonary atresia is the state of the main and central pulmonary arteries distal to the atresia.

In the evaluation of tetralogy of Fallot (Fig. 10-20), transverse scans depict the ventricular septal defect and the infundibular, annular, and pulmonary arterial stenosis. MRI provides information about the size of the main and central pulmonary vessels. The blood supply to the lung is assessed in both axial and coronal images. The aorta in tetralogy of Fallot is typically anteriorly displaced, overriding the ventricular septal defect. In complex anomalies such as transposition of the great arteries (Fig. 10-21) with coexistent septal defect or a double-outlet right ventricle, both the relationship of the great vessels and the anatomy of the outflow tracts can be readily displayed on MRI. This is of special interest for surgical planning. Because of the multiplanar imaging capabilities, MRI can reliably depict the complete anatomy.

The evaluation of pulmonary venous connections and other pulmonary venous anomalies has already been discussed. Regardless, it should be emphasized that MRI can provide important additional information even in combination with pulmonary catheter angiography to clearly depict the sometimes very complicated vascular anatomy. In the evaluation of systemic venous abnormalities, MRI is also a very effective, noninvasive method to depict the complete anatomy. Venous anomalies such as left superior vena cava and interruption of the inferior vena cava withazygos continuation are clearly demonstrated on MRI. Often these venous anomalies are found in combination with other CHDs; thus, their preoperative depiction has a great impact on the therapeutic approach. With regard to imaging of septal defects, MRI has the ability to quantify shunts by measuring left and right ventricular volume from cine MRI or by simultaneous measurement of flow in the ascending aorta and the main pulmonary artery using velocity-encoded cine MRI. The difference calculated between the right and left ventricular stroke volume is the net volume of the shunt for patients with atrial septal defect and patent
FIGURE 10–21. Transposition of the great arteries with right-sided aorta and functional single ventricle as a result of a large ventricular septal defect. Axial cine images (A–E) show a right-sided descending aorta arising from the right ventricle with depiction of the infundibulum. The superior vena cava is on the left. The pulmonary artery arises posterior to the aorta, and a single ventricle can be identified.
FIGURE 10–21 Continued. Sagittal cine images (F and G) again demonstrate the more ventral ascending aorta and the posterior pulmonary truncus (G, arrow).
ductus arteriosus. The same holds true for patients with partial anomalous pulmonary venous connection.

In summary, MRI is an extremely powerful noninvasive tool for the anatomic depiction of CHD and evaluation of hemodynamics. However, the structural evaluation of cardiac valves is clearly one area in which echocardiography remains superior to MRI. Another drawback for MRI is the relatively long time of examination. A full examination of a patient with CHD may require 30 to 60 minutes; deep sedation is required for infants and small children. Thus, echocardiography currently is used as the initial noninvasive imaging study for almost all patients with known or suspected CHD. New and faster MRI techniques in the future may enable reliable and fast imaging of the heart in children. MRI may become a routine examination in patients with suspected CHD both for initial diagnosis and in follow-up after treatment (Fig. 10-22).

**Acquired Heart Disease**

The high contrast between the moving blood and the myocardium, the high spatial resolution, and the lack of ionizing radiation render MRI a superb technique for myocardial assessment. As a result of ongoing technical developments, MRI is evolving to be the noninvasive gold standard for cardiac structure and function assess-
FIGURE 10–22. Transposition of the great arteries after an arterial switch procedure. A–D, T₁-weighted axial images cranial to caudal show a normal origin of the aorta. The pulmonary artery arises from the right ventricle. A retrosternal conduit between the pulmonary trunk and the right pulmonary artery had to be made during the arterial switch procedure to allow connection of the pulmonary vasculature.

ment. Because cardiac motion is a fundamental problem in MRI of the heart, MRI must be restricted to a constant portion of the cardiac cycle to avoid blurring of the images. Different techniques can be used for evaluating acquired heart disease. These include ECG-gated conventional spin echo images, which can be acquired in either a multislice mode without breath-hold or in a single-slice ECG-gated acquisition mode in breath-hold. These conventional spin echo images give a very good overview concerning the anatomy of the heart combined with high soft tissue contrast and can be used to display, for example, the replacement of muscle by adipose or fibrous tissue, hypertrophic cardiomyopathy, myocarditis (Fig. 10-23), and cardiac masses. Another technique that is generally used to evaluate acquired heart disease is cine gradient echo imaging. In cine imaging, a picture loop of various phases of the cardiac cycle in one single slice is displayed so regional and global wall thickening and functional parameters can be assessed. To evaluate blood flow, phase contrast (PC) methods are applied in which the contrast between stationary and moving tissue is generated as a result of velocity-induced phase shifts of moving spins in a magnetic field gradient. Using this method, the induced phase shift is directly proportional to the velocity, so that PC methods allow quantitative measurement of the velocity of flow. Absolute flow can be calculated by multiplying the linear blood velocity by the cross-sectional area of the blood vessel. Typically, this approach is used to measure flow in the aorta, pulmonary arteries, or ventricular cavities in patients with CHD.

In imaging of acquired heart disease, it is generally preferable to use a phased-array surface coil because higher signal-to-noise ratios with minimum time to repetition and time to echo values can be achieved. In imaging of the coronary arteries, which is still under clinical evaluation, so-called navigator echoes that allow tracking of the diaphragmatic motion are used in combination with 3D image acquisition to depict the anatomy of the coronary arteries without breathing artifacts. To
assess cardiac function further, cine gradient echo imaging with myocardial tagging can be applied. In myocardial tagging, using a saturation band pattern, either a grid or parallel tag lines, a labeled zone of myocardial tissue can be followed anatomically throughout the cardiac cycle. Thus, important insights into regional myocardial mechanics can be achieved by direct visualization of the movement of the myocardium.

The primary planes for cardiac imaging are the transverse, sagittal, and coronal planes. These planes are orthogonal to the thorax but oblique to the axis of the heart. Thus, to achieve similar orientations as used in echocardiography, it is necessary to perform oblique imaging. The oblique long-axis planes of the ventricle are either perpendicular or parallel to the plane of the ventricular septum, producing a horizontal or vertical long-axis plane orientation. Images perpendicular to the long-axis plane orientations of the heart are short-axis planes, which accurately display regional myocardial diameter. To achieve images in the long- and short-axis planes, preliminary imaging in other planes is required. First, an orthogonal imaging plane to the body is acquired. If the sagittal plane is used for these first images, the anterior angulation of the cardiac apex relative to the base is determined. A series of oblique images is then acquired parallel to this plane. From these images, the leftward angulation of the cardiac apex is determined and images parallel to the short axis of the heart can be

Figure 10–23. Myocarditis in a 45-year-old man with sudden onset of cardiac arrhythmia after a viral infection and exclusion of myocardial ischemia. T2-weighted (A) and short TI inversion recovery (B) images show areas of high signal intensity within the myocardium of the left ventricular apex consistent with myocardial edema. C, In the T1-weighted contrast-enhanced sequence, the affected myocardium shows increased contrast uptake. Myocardial biopsy showed acute myocarditis with necrosis of myocytes.
prescribed perpendicular to a line that defines the leftward angulation of the heart. From the basis of the short-axis images, horizontal and vertical long-axis images can then be acquired.

**Normal Myocardium**

The normal left ventricle has a wall thickness of 9 to 11 mm in end diastole. Focal areas of thinning of the myocardium are associated with remodeling after myocardial infarction, whereas a diffuse thickening or thinning may be associated with cardiomyopathy. In both long- and short-axis views, the papillary muscles are clearly visualized. If spin echo sequences are used, the signal of the normal myocardium in T<sub>2</sub>-weighted images is similar to or slightly higher than the signal of the skeletal muscle. On T<sub>1</sub>-weighted images, the signal is usually similar to that of skeletal muscle. Using spin echo imaging, the ventricular and atrial cavities typically have low signal intensity. The normal right ventricle normally shows an end-diastolic thickness of approximately 3 mm, and the trabeculation is much more obvious compared with the left ventricle. The walls of the atria are thin, and if no high-resolution imaging is performed sometimes the atrial septum may not be identified on spin echo images. Quantification of cardiac dimensions such as volume and wall thickening can be made on the basis of cine MRI techniques or of both end-diastolic and end-systolic spin echo images. Because of the ability of MRI to obtain images with good spatial resolution in any tomographic plane, MRI can be rated as the gold standard in evaluation of the left ventricle (Fig. 10-24). The same is true for the right ventricle, in which echocardiography is of limited value because of the difficulties visualizing endocardial borders as well as the complex geometry of the right ventricle. Another important issue in imaging of the heart in acquired heart disease is assessment of the atrial volume. Atrial function augments ventricular function because the atrium acts as a reservoir for delivery of blood to the ventricles. Assessment of the atrial dimensions is important in acquired valvular disease and systemic or pulmonary hypertension (see Fig. 10-24) and acts as an important indicator for diagnosis of these diseases.

**Ischemic Heart Disease**

Signal intensity changes that correlate with myocardial infarction can be visualized on both noncontrast T<sub>1</sub>- and T<sub>2</sub>-weighted images. However, there seems to be a better correlation of the high signal intensity in noncontrast T<sub>2</sub>-weighted images with the size of the infarct compared with the decrease in signal intensity seen on T<sub>1</sub>-weighted images of myocardial infarction. Nevertheless, although increased signal intensity in T<sub>2</sub>-weighted images corresponds to myocardial infarction, it also may correspond to edema formation observed in patients with unstable angina or myocarditis without histologic signs of myocyte necrosis. Another important issue in T<sub>1</sub>-weighted imaging of myocardial infarction is the fact that slow-flowing blood in the trabecular system near the myocardial infarction may lead to an increase in signal intensity, which can make the evaluation of the adjacent endocardial region difficult. In these cases, inversion recovery (IR) sequences in which the signal both from the blood and fat are nulled and which currently, with state-of-the-art MRI machines, can be performed in breath-hold can show better results in quantification of the infarcted area on T<sub>2</sub>-weighted noncontrast studies.

Using CE T<sub>1</sub>-weighted MRI for the assessment of acute myocardial infarction, two basic approaches for imaging of affected areas can be performed. On the one hand, first-pass perfusion MRIs can be achieved; on the other hand, images acquired several minutes after contrast injection can be used to identify areas of increased contrast enhancement representing reperfused myocardial infarction.

If first-pass perfusion MRI is performed, multiple short-axis T<sub>1</sub>-weighted slices with high temporal resolution are acquired during injection of typically a bolus of 0.1 mmol/kg of a Gd chelate. Using this approach, infarcted areas are demonstrated usually as a subendocardial, hypoenhancing zone that extends toward the epicardium.

In images acquired approximately 10 to 15 minutes after contrast injection, these areas become hyperintense in comparison with surrounding normal myocardium if areas of nonviable myocardium are present. This late enhancement represents reperfused infarcts and can be
FIGURE 10–25. Chronic myocardial infarction in a 58-year-old man. Short-axis diastolic (A) and systolic (B) cine images show a decreased thickness of the inferior septum as a result of myocardial infarction. C and D, In myocardial tagging, decreased myocardial wall motion is visualized in the corresponding area.

used for detection and determination of the size of a myocardial infarction. If a comparison with cine MRI and, in particular, cardiac tagging is performed in the affected region (Fig. 10–25), these areas typically demonstrate decreased myocardial wall thickening and a lack of motion of the myocardial tagging lines.

Areas of chronic myocardial infarction are demonstrated as regions of focal wall thinning on MRI both on conventional T₁- and T₂-weighted spin echo sequences and on cine MRI. Typically, an abrupt transition in thickness from normal myocardium to scar in the area of transmural infarction is observed. In chronic infarction, MRI is also very useful in determining the infarct volume. Possible complications, including aneurysm formation and compensatory myocardial hypertrophy (Fig. 10–26), are evaluated with high accuracy.

Cardiomyopathy
Cardiomyopathy represents a diverse group of disorders, including dilated cardiomyopathy, hypertrophic cardio-
myopathy, and restrictive cardiomyopathy. Generally, cardiomyopathies are defined as muscular disorders of the heart. Spin echo imaging may be used to demonstrate the morphologic abnormalities in this group of diseases, and cine MRI may be used to demonstrate the concomitant functional abnormalities.

In dilated cardiomyopathy, MRI demonstrates dilatation of the left ventricle and, in many cases, the right ventricle. Pathologically, underlying myocardial fibrosis is present that accounts for the reduced contractility of the myocardium. Cine MRI and myocardial tagging may be used to show the reduced cross-fiber shortening compared with that of normal individuals. MRI may be used both for diagnosis as well as for monitoring of therapeutic intervention. Despite the thinned wall, there is typically an overall increased myocardial mass.

In hypertrophic cardiomyopathy, MRI has proved to be accurate in defining the extent, location, and severity of hypertrophy of the myocardium and in differentiating obstructive from nonobstructive forms. Because there is considerable variability in ventricular morphology in this group of patients, MRI is mainly used to document the presence of unusual forms. In some patients, hypertrophy exists only in the outflow tract septum, whereas in others the entire septum is hypertrophied. The best imaging planes for hypertrophic cardiomyopathy are short-axis and horizontal long-axis views, because the outflow tract can be assessed optimally in the horizontal axis and quantification is best made in the short axis. If MRI tagging is used to evaluate patients with hypertrophic cardiomyopathy, the circumferential and longitudinal myocardial shortening is typically depressed in hypertrophied segments compared with that in normal myocardium. Abnormalities in diastolic filling of the ventricle can be reproducibly displayed in cine MRI. There is also evidence that the same parameters involving the right ventricle are abnormal in hypertrophic cardiomyopathy as well.

Restrictive cardiomyopathy clinically may have a similar presentation to constrictive pericarditis (Fig. 10-27). Restrictive cardiomyopathy is characterized by enlarged atria with the coexistent finding of relatively normalized ventricles. The lack of increased pericardial thickness as typically seen in constrictive pericarditis hints at the diagnosis of a restrictive disease.

In dysrhythmogenic right ventricular dysplasia, pathologically a replacement of muscle by adipose or fibrous tissue and enlargement of end-diastolic diameter are present. Typically, fat extends from the epicardial surface into the interstitium and displaces myocardial fibers. MRI has shown promising results in clarifying the diagnosis of right ventricular dysplasia. MRI can provide information as well about cardiac function, regional wall motion, and direct visualization of the anatomy of the right ventricular free wall. Typically, T₁-weighted images should be used to identify fatty infiltration because they give a high contrast between normal myocardium and adipose tissue. To differentiate right ventricular dysplasia, which has a high risk of sudden death, from right ventricular outflow tract tachycardia, which typically...
shows a more benign course, MRI may be helpful in localizing dyskinesia to the right ventricular outflow tract in cine MRI.

Valvular Disease

Using ECG-gated spin echo imaging, MRI most commonly is used to assess the secondary changes that occur in combination with valvular disorders of the aortic, pulmonary, and mitral valves. Using cine MRI, the regurgitation jet in valve insufficiency as well the jet observed in stenosis of a valve can be visualized as a region of signal void (Fig. 10-28). Unfortunately, the size of this signal void does not correlate with the degree of regurgitation or stenosis. However, cine MRI can be used for quantification of the volume of regurgitation in patients with only one affected valve (Figs. 10-12 and 10-29). The regurgitation volume can be assessed by the difference between right and left ventricular stroke volumes as calculated from serial MRIs covering the ventricles acquired in both diastole and systole. However, this is very time consuming; thus, velocity-encoded techniques are favored to measure regurgitant flow. Using this approach, images are obtained parallel to the annulus of the affected valve, and with PC techniques the total flow during the cardiac cycle can be calculated as the product of the valve area and the velocity. Thus, retrograde flow can be quantified. MRI is useful as well in detecting and quantifying acquired valvular disease and in differentiating among congenital anomalies such as subvalvular stenosis in pediatric patients. Combining measurement of the cross-sectional area of the aorta with the functional assessment of the aortic valve gives a complete overview of the disease and allows reproducible follow-up in cases with equivocal findings concerning indication for surgery.

Pericardium

In normal patients, the pericardium in $T_1$-weighted images is less than 2 mm thick. Overall, the pericardium is somewhat better visualized during systole and can be easily identified on $T_2$-weighted images anterior to the right ventricle (see Fig. 27). In contrast, posterolateral to the left ventricle the normal pericardial signal is often not seen against the low-signal-intensity lung parenchyma. Although echocardiography is the primary modality for identifying pericardial abnormalities, MRI has an established role in the evaluation of the pericardium. Typical indications include patients in whom clinical findings are inconsistent with echocardiographic diagno-
FIGURE 10–29. Pulmonary regurgitation in a 34-year-old, otherwise healthy man. A systolic ejection murmur was detected during routine check-up. A, Systolic cine imaging longitudinal to the right ventricular outflow tract shows turbulence across the pulmonary valve and marked dilatation (arrow) of the pulmonary truncus. B, In diastole a retrograde jet is noted across the pulmonary valve. C, Flow evaluation of the pulmonary flow with phase contrast acquisition shows the regurgitation volume as the area under the curve for the negative flow component.

sis, patients with inadequate echocardiographic evaluation, and patients in whom a more precise evaluation is necessary. However, for identification of calcific pericarditis, CT is the method of choice.

Pericardial Effusion

In contrast to what is seen with fluid collections elsewhere in the body, the signal intensity of a pericardial effusion on T₁-weighted images is frequently lower than that of simple fluid. Flow effects in the pericardium in patients with a large simple effusion may also lead to inhomogeneous signal intensity, with areas of both high and intermediate signal. These alterations of the signal are probably caused by a loss of phase coherence within the pericardial fluid from fluid motion. Pericardial perforations may be serous, bloody, or lymphatic. Hemorrhagic effusion is characterized by high signal intensity on T₁-weighted spin echo images in contrast to the low signal intensity of nonhemorrhagic fluid. Typically, it is easier to identify nonhemorrhagic effusions on T₁-weighted images because pericardial fat has a high signal intensity; thus, serous or lymphatic effusions are distinguished by their low signal intensity compared with normal myocardium and pericardial fat. Effusions may be generalized or loculated, and associated pericardial inflammation may be separately recognized as a thickened pericardium with a higher signal intensity than pericardial effusion on T₁-weighted images.

In pericardial thickening, MRI detects a widened pericardial line of low signal intensity on T₁-weighted images. Calcifications may appear as focal areas of decreased signal with irregular borders. In constrictive pericarditis, a thickness of more than 4 mm indicates pericardial thickening. However, pericardial thickening can also be observed in the absence of constrictive pericarditis; thus, the diagnosis should always include a con-
Figure 10–30. Myxoma of the left atrium in a 43-year-old man with unspecific clinical symptoms. A, The sagittal T2-weighted image demonstrates a tumor of the left atrium, which, in oblique coronal images (B and C), is located in the area of the right pulmonary vein. D, The axial T1-weighted image clearly shows the tumor. E, In cine imaging, systolic movement toward the mitral valve is demonstrated.
FIGURE 10–31. Myxoid sarcoma of the tricuspid valve in a 42-year-old woman with increasing dyspnea. T2-weighted coronal (A) and sagittal (B) images show an inhomogeneous hyperintense mass in the right ventricle protruding into the pulmonary artery. C–E, In axial cine imaging, enlargement of the right atrium can be noted with systolic (E) prolapse of the tumor across the tricuspid valve.
sideration of clinical symptoms. The main issue in MRI for constrictive pericarditis is the differentiation from restrictive cardiomyopathy. In this clinical setting, pericardial thickening in combination with a small, tubular right ventricle and a dilated right atrium favors the diagnosis of constrictive pericarditis.

**Cardiac Masses**

ECG-gated spin echo sequences have proven effective in demonstrating the presence, location, and extent as well as in certain instances the nature of a cardiac mass. Primary cardiac tumors are rare. Approximately 80% are benign and can be effectively treated with surgical resection. Secondary malignant tumors involving the heart are somewhat more common, resulting from metastatic disease to the myocardium and pericardium or direct invasion of a tumor from adjacent lung or mediastinal structures.

The most frequent intracardiac mass is thrombus, which is usually located within the left atrium or left ventricle. The most frequent primary benign tumors are myxoma and lipoma; the former is usually located in the left atrium (Fig. 10-30) and the latter in the right. MRI can be used to distinguish these tumors from mural thrombus, which may occur in a similar location, by identifying a pedicle that attaches the tumor to the atrium in the case of a myxoma and by the homogeneous high signal intensity of the mass in the case of a lipoma. Definite tissue specific diagnosis of a cardiac tumor can only be made in cases of lipoma that typically show the same high signal intensity in T1-weighted images as subcutaneous or pericardial fat. Occasionally, in the case of a myxoma, prolapse of the tumor across the mitral valve can be observed in diastole that can be identified on cine MRI. Other benign and malignant cardiac tumors include rhabdomyomas and rhabdomyosarcomas, angiosarcomas, myxoid sarcomas (Fig. 10-31), fibromas, and melanomas. Observations that favor the diagnosis of a malignant tumor include a wide base of attachment, which, in contrast to the pedicle in myxoma, is more indicative of a malignant infiltrative tumor, and the observation of a hemorrhagic pericardial effusion in combination with a cardiac mass.

In secondary tumors of the heart, cardiac involvement may be caused by direct spread of mediastinal or lung tumors or extension of tumors of the upper abdomen through the inferior vena cava into the right atrium (e.g., in cases of tumor thrombus with renal cell carcinoma). In imaging of metastases to the pericardium, myocardium, or the cardiac chambers, MRI has been proved effective in demonstrating these tumors. However, in most cases, myocardial metastases represent end-stage metastatic disease, and there is only limited effect on therapeutic management of the patient.