Imaging of pulmonary arterial hypertension

O. Sanchez¹, M.-P. Revel², S. Couchon², G. Meyer¹

Abstract

Introduction The investigation of pulmonary arterial hypertension (PAH) imposes a rigorous aetiological assessment in which modern imaging techniques play an important role.

Background A plain chest x-ray may show non-specific signs such as cardiomegaly and dilatation of the pulmonary arteries and also provides details of the lung parenchyma. Echocardiography is the essential screening tool to evaluate left ventricular function. Pulmonary ventilation/perfusion scanning is essential to confirm post embolic PAH. Spiral CT has also become an essential examination, yielding a detailed study of the lung parenchyma, the pulmonary vessels and the heart chambers; it is also helpful in determining the aetiology and completes the pre-treatment assessment. Magnetic resonance imaging can be used to calculate several haemodynamic parameters and also provides a morphological study of the cardiac chambers and pulmonary vessels but requires further evaluation.

Viewpoint The improvement in the quality of vascular images and the development of complementary MRI techniques may lead to an increase in the use of this MRI technology in the study of PAH.

Conclusion Imaging plays a fundamental role in the management of patients suffering from PAH.

Key-words: Pulmonary arterial hypertension • Computerised Tomography • Magnetic Resonance imaging • Echocardiography Diagnosis.

¹Pneumology and Intensive Care Department
²Radiology Department
Paris Descartes University, Assistance Publique Hôpitaux de Paris, Hôpital Européen Georges Pompidou, 75015 Paris

Corresponding author: Olivier Sanchez
Service de Pneumologie Soins Intensifs, Hôpital Européen Georges Pompidou, 20 rue Leblanc 75015 Paris, France
olivier.sanchez@egp.aphp.fr

Introduction

Pulmonary arterial hypertension is defined as continuously high blood pressure in the pulmonary vascular bed. In 1998 a new classification to diagnose pulmonary artery hypertension was proposed and subsequently reviewed in 2003 during the 3rd World Health Organisation Symposium in Venice [1]. The reviewed classification reflects the recent progress achieved in our understanding of the pathophysiology of pulmonary vascular diseases, dividing them into 5 categories (Table I) [1]. It recognises that there are similarities between the unexplained form of the disorder (formerly referred to as « primary »), now known as « idiopathic » and PAH associated with a known disease (connective tissue diseases for example). A patient who is diagnosed with PAH must be given a strict aetiological assessment in which imaging studies play a major role. The goal of this article is to describe the main imaging techniques and the different aspects of PAH encountered in clinical practice.

Imaging techniques

Plain chest x-rays

Front and side view chest x-rays are inexpensive and non-invasive as a first-line examination to explore PAH. They give an overall analysis of the pulmonary parenchyma, showing the size of the heart and the pulmonary arterial trunk. They may also contribute information on cardiomegaly or enlargement of the calibre of the pulmonary arteries. The size of the heart can be assessed by measuring the cardiothoracic ratio, which is calculated as a ratio of the transverse diameter of the heart to maximum diameter of the thorax, measured at the angles where the ribs and the diaphragm meet (Fig. 1). In adults, the upper limit of the normal value is 0.5 on a front view chest x-ray with the patient breathing in deeply. The size of the pulmonary arteries should be measured at their hilus (Fig. 1). Pulmonary arteries that measure more than 17 mm in diameter are dilated. Patients with full-blown disease often present with these signs and they indicate that the pressure in the pulmonary vessels is high whatever the cause. The chest x-ray may be normal, which does not eliminate PAH from the diagnosis. On the contrary, in point of fact, because if the patient has dyspnoea and a normal x-ray, this should prompt the physician to research a vascular disorder of the lungs (pulmonary embolism or PAH).

Echocardiography

Trans-thoracic echocardiography is the first line examination to screen for PAH [2]. It can be used to measure the size of the right and left heart chambers, assessing the contractile capacity of the left ventricle, researching valve anomalies and detecting systemic-to-pulmonary shunts associated with congenital heart disorders. The patient’s trans-

Table I.
Classification of pulmonary hypertension (Venice 2003) [1].

| 1. « Proliferative » pulmonary arterial hypertension |
| Idiopathic PAH |
| Familial PAH |
| PAH associated with Diseases of the connective tissues |
| Portal hypertension |
| Infection with the human immunodeficiency virus |
| Anorexigenic or toxic agents |
| Congenital heart disorders with left-right shunts |
| Persistent PAH in neonates |
| PAH with predominant venous or capillary involvement (veno-occlusive disease, capillary haemangiomatosis) |

| 2. « Passive » pulmonary hypertension |
| Left heart disorders |
| Left valve disorders |

| 3. « Hypoxic » pulmonary hypertension |
| Chronic obstructive pulmonary disease |
| Interstitial lung disease |
| Sleep apnoea syndrome |

| 4. « Obstructive » pulmonary hypertension |
| Proximal chronic thromboembolic pulmonary hypertension (CTEPH) |
| Distal CTEPH |
| Non-cruoric pulmonary embolism (tumoral, parasitic, foreign bodies) |

| 5. Miscellaneous |
| PAH associated with sarcoidosis, X histiocytosis, capillary haemangiomatosis and fibrous mediastinitis. |

Fig. 1.
Front view chest x-ray. Patient age 37 with HIV, referred for gradual-onset of dyspnoea. Large bulge in both pulmonary arteries presenting as an enlarged hilus on the right and as a bulge in the middle of the left arch.
tricuspid pressure gradient and pulmonary artery systolic pressure (PAPs) can be calculated on a Doppler flow study of tricuspid regurgitation using Bernoulli’s formula (PAPs = 4v^2 + RAP, in which v is the maximum flow velocity of tricuspid regurgitation and RAP is right atrial pressure assessed by collapsus of the inferior vena cava) [3]. Most studies report a satisfactory correlation (0.57 to 0.93) between transthoracic echocardiography and right heart catheterisation for PAPs measurement [3-5]. Other typical signs of PAH are dilatation of the right heart chambers; these appear larger than the left heart chambers with reversed septal curvature and septal dyskinesia in severe PAH. A PAH screening algorithm based on measuring the maximum velocity of tricuspid regurgitation flow has recently been validated in a broad population of patients with scleroderma [6].

**Ventilation/perfusion scan**

Pulmonary perfusion is explored by injecting technetium 99m (99mTc) labelled macro-aggregates of human albumin into a peripheral vein; the product injected with the radioactive tracer then diffuses within the lungs proportionately to the regional blood flow. Given their size, (10 to 100μm), the albumin molecules become lodged in the pulmonary arterioles as soon as they reach them. The injection is administered in a dorsal decubitus position to cancel out the vertical distribution gradient of pulmonary perfusion. The images are acquired from various angles, immediately after injection. Perfusion anomalies show up on the scintiscan as lacunae or are picked up as more or less ubiquitous hypo-signals. A non-soluble radioactive gas, krypton 81m or an aerosol containing liquid or solid microparticles labelled with 99mTc (Technegas®) is inhaled by the patient for the ventilation study. The images are then acquired from different angles and compared to those obtained in the perfusion study. On normal images the radioactive tracer should be evenly distributed on all the ventilation and perfusion views. Any perfusion anomalies should be carefully analysed, taking into account whether they occur systematically or not (in sub-segments, segments, lobes), assessing their size and whether the ventilation anomalies occur in the same territories. Typically, if the patient has acute or chronic pulmonary embolism a number of perfusion defects will systematically be observed although the patient’s ventilation is normal (fig. 2). The examination should be interpreted on the basis of the criteria validated in the PIOPED study [7].

**Thoracic CT-scan**

CT-scans acquire images in consecutive slices and can be useful in the assessment of PAH for several reasons. Firstly, CT is the most suitable examination to research an aetiology because unlike MRI it gives a good overall assessment of the pulmonary parenchyma. A cardiac-gated CT-scan (synchronized with an ECG) also can also provide helpful information on the impact of pulmonary hypertension on right ventricular function, although at the cost of extra radiation exposure for the patient, which can be avoided with MRI [8]. A 4 to 64-row multi-detector, multi-slice CT-scan with injection of a contrast medium provides the best assessment of pulmonary vascularisation. The thickness of the slices acquired (0.625 mm) and the speed of acquisition obtained with the more recent scanners (less than 10 seconds without cardiac gating) yield a study that is acceptable down to the arterial sub-segment level [9]. However, a reconstruction thickness of 1 mm is sufficient to analyse the pulmonary vessels. The injection rationale differs very little, whatever the scanner used; however, the volume of contrast medium can be reduced from 120 to 90 ml on the more recent machines. Ideally, the contrast medium should be injected at a rate of 4 ml/second. The contraindications are renal insufficiency, a case history of allergy to iodine and severe pulmonary arterial hypertension. The sudden increase in the circulating blood volume due to a bolus injection of 100 ml of contrast medium can lead to decompensation in a patient with severe PAH; however, if it is generally felt that the examination is essential (to eliminate an acute embolism) the volume injected should not exceed 90 ml.

**Post-processing**

Once the images are acquired they can be processed and post-processing plays an important role in assessing PAH. Multiplanar reformation (MPR) for example will show whether a hyposignal picked up along the margin of a vessel...
is an extrinsic structure such as a nest of cells or a lymph gland or an intrinsic feature such as a clot inside the wall. MIP (maximum intensity projection) reconstructions yield angiogram type images, which give an analysis of the distal portion of the vascular structures to research for stenosis or any sudden change in calibre (fig. 3). MinIP (minimal intensity projection) reconstructions are more sensitive in detecting differences in density in the pulmonary parenchyma consecutive to perfusion disorders (fig. 4).

In relation to high pulmonary arterial pressure an increase in the diameter of the pulmonary arteries and in the size of the right heart chambers are non-specific signs (fig. 5). Above 29 mm an increase in the calibre of the pulmonary trunk has a positive predictive value of 83% and a negative predictive value of 28% according to a study assessing the prevalence of pulmonary hypertension in ARDS [10]. Above 33.2 mm the sensitivity is 58% and the specificity is 95% [11]. The ratio of the diameter of the pulmonary trunk to the aorta has been reported as being a better sign, with a higher correlation with mean pulmonary pressures in patients under the age of 50 (r = 0.77 versus r = 0.59) [12]. When the pulmonary trunk is larger than 29 mm and the patient has an upper segment arterio-bronchial ratio above 1 in at least 3 lobes the specificity is 100% when screening patients with chronic disease of the pulmonary parenchyma for PAH; however, this study does not find any correlation between the degree of PAH and the diameter of the pulmonary trunk [13]. Some authors have suggested that arterial compliance is a major factor, determining the degree of dilatation in response to an elevation of pulmonary pressure [14]. No correlation was found between pressure and diameter in patients with respiratory disease, whereas there was a correlation between dilatation of the pulmonary trunk and pulmonary resistance in idiopathic and postembolic PAH. In yet another study, the combined cross-sectional surface of the pulmonary trunk and the left pulmonary artery related to body mass index had a high correlation with mean pulmonary pressure (r = 0.87), but it was only possible to predict mean pulmonary pressures that were accurate to 5 mmHg in 50% of the cases of chronic pulmonary disease and 8% of the cases caused by vascular
disorders [15]. To summarize, one can state that an analysis of the calibre of the arteries can be used to screen for PAH and it is highly specific if they are clearly enlarged, but that the correlation between pulmonary size/pressure alone is insufficient and depends on the cause of pulmonary arterial hypertension (vascular, primary or secondary to disease of the parenchyma). An increase in the right/left ventricle ratio, which should normally be below 1, is also a non-specific sign of PAH.

Cardiac gated CT-scans can be used to assess ventricular ejection fractions and the correlation with the isotopic ventricle is satisfactory (R = 0.91 and 0.89 for the left and right ejection fractions respectively) [16]. Compared with MRI, CT provides a reliable assessment of right ventricle function, although the temporal resolution is clearly lower [17].

Magnetic resonance imaging (MRI)

MRI of the chest has only developed recently in comparison to the other organs. The lower concentration of protons in the pulmonary parenchyma, heart and lung motion and artefacts due to the air/pulmonary tissue interface are as many difficulties that must be overcome to obtain good quality images. Different MRI techniques can be used to assess PAH [8]. Magnetic resonance angiography (MRA) with injection of a paramagnetic contrast medium provides details of pulmonary vascularisation. For the moment the use of hyperpolarised helium is mandatory for ventilation analysis and therefore special dedicated machines must be used. Lastly, various techniques can be used to analyse the magnetisation phase, assessing pulmonary circulation velocities, cardiac output and pulmonary arterial pressure. The contraindications for MRI are limited to metallic intraocular foreign materials [18], claustrophobia and patients with pacemakers, although the last contraindication tends to not apply to the newer models. The main issue related to the use of MRI is that the machines are not always available. The duration of the examination is longer than for a CT-scan and can last up to 45 minutes according to the sequences used.

Non-specific morphological signs

These are right ventricle hypertrophy and an increase in the calibre of the pulmonary trunk artery. There is a linear correlation between mean PAP and the pulmonary trunk/descending aorta ratio measured on cardiac-gated MRI [19]. Hypersignals picked up on the spin echo gated sequences are related to flow artefacts due to sluggish circulation [20] and are present in 92% of the cases of pulmonary hypertension.

Functional evaluation

The data in the literature are somewhat discordant in terms of how reliable MRI is in assessing pulmonary artery pressures resistances. Some articles have shown a difference in circulating velocities and pulmonary artery acceleration time (PAT) in patients with PAH compared to healthy volunteers and found decreased compliance of the pulmonary artery if the patient had PAH [21]. There is a linear correlation between the haemodynamic index calculated on MRI (acceleration time and volume) and the pulmonary artery resistances calculated by right heart catheterisation with a correlation coefficient that can reach 0.89 (ratio of the maximum flow ejection rate to the acceleration volume). The MRI cardiac output values also correlate well with those obtained by right heart catheterisation [22]. More recently, phase contrast MRI flow analysis has proven its value over the more invasive methods of measuring pulmonary resistance [23]. MRI can also be used to assess septal curvature, correlating it with PAPs (r = 0.77). A curvature to the left indicates that the patient’s systolic arterial pressure is at least 67 mmHg [24]. However, some authors did not find sufficient correlation between the pressure values and haemodynamic parameters, especially for acceleration time (correlation coefficient r =-0.26) or morphological parameters (stroke volume index) assessed on MRI, and feel that the non-invasive methods cannot for the moment be used as a substitute for right heart catheterisation [25]. MRI can also
be used to assess right heart function and if the patient has pulmonary hypertension it will reveal a decrease in the cardiac index [23, 26] and hypertrophy of the free wall of the right ventricle [26].

**Pulmonary angiography**

Pulmonary angiography has now been replaced by less invasive examinations to diagnose pulmonary embolism [27]. For this reason it is rarely used today, which necessarily poses the issue of how to maintain good performances. It is an examination that is still indicated when pulmonary embolism is suspected and the other tests are not conclusive or to evaluate whether postembolic PAH is amenable to surgery or not. Strict rules are essential: ideally the patient should be catheterised for angiography via an antebraconial approach to avoid the risk of accidentally puncturing the femoral artery and the contrast medium should be selectively injected into each of the two pulmonary arteries. The right side of the pulmonary arterial tree should be studied on front and side views. The mediastinal artery will be clearly visible on the front view. Side views are essential to visualise the intermediate portion of the trunk and its different branches (median lobular artery, upper segmental artery of the lower lobe and the 4 arterial branches of the basal pyramid). The left side of the arterial tree should be studied on the frontal view and at a left anterior oblique angle or from the side to differentiate the lingular territory from the basal pyramid. A pulmonary angiogram is considered to be normal if 2 orthogonal angles are normal for each pulmonary artery. Positive signs include a pouching defect on an artery that is over 2 mm in diameter or an endoluminal filling defect.

**Anomalies found in different types of pulmonary hypertension**

**« Proliferative » form of PAH**

**Idiopathic and familial forms of PAH associated with anorexigenic drugs**

This is a rare disorder affecting mainly women (sex-ratio 1.7 females for 1 male) for which the prevalence is assessed to be two new cases per million inhabitants in France [28]. Its frequency peaks between the age of 20 and 40, although it occurs at all ages [29]. One of the main symptoms is dyspnoea but as this is a non-specific sign it can often be confusing and delay the diagnosis, which is frequently made at a late stage. A chest x-ray will show up anomalies due to increased pressure in the pulmonary vascular bed (cardiomegaly, dilated pulmonary arteries) (fig. 1), although a normal x-ray does not eliminate the diagnosis which is based on measuring the pulmonary pressures on an echocardiogram and using right heart catheterisation. The pulmonary ventilation/perfusion scan may well be normal but will nevertheless show the classic signs of an antero-posterior gradient that can sometimes be deceptive but does not suggest chronic thromboembolic disease. A CT-scan of the chest will show highly suggestive cardiovascular changes in the mediastinal window, including hypertrophy of the right ventricle and an increase in the calibre of the pulmonary arteries (ratio of the diameter of the PA to the ascending thoracic aorta > 1) (fig. 5). Pericardial effusion is observed in severe cases of PAH. The pulmonary parenchyma is normal as a rule. Micro-nodes have been described; these are caused by cholesterol granuloma [30] but can be distinguished from the findings described in veno-occlusive disease because there are no septal lines nor mediastinal lymph nodes. Signs of mosaic perfusion have also been reported, mimicking postembolic PAH [31], but the ground glass areas are not systematically found. No clots are observed along the margins, except very proximally, particularly between the lobes. If clots are found, they will be sedimentary thrombi of the type usually observed in full-blown, older cases of PAH.

The pulmonary angiogram will show a classic “dead-tree” picture showing very narrow peripheral vascular structures with no signs of postembolic PAH (irregular structure, amputated vessels).

**PAH associated with connective tissue disorders**

PAH is a serious and potentially fatal complication of systemic diseases, especially connective tissue disorders such as scleroderma, particularly when it presents in the limited cutaneous form (formerly known as CREST (subcutaneous Calcifications, Raynaud’s syndrome, Oesophageal dysmotility, Sclerodactyly, Telangiectasia) syndrome [32]. It can be caused by specific fibrotic involvement of the lungs, but it can also occur without any significant interstitial pulmonary disease. In this case isolated involvement of the pulmonary vessels can be the cause of high pulmonary pressures. Clinically, this form of the disorder is generally severe and the prognosis is poor [32, 33]. X-rays and a CT-scan of the chest will reveal anomalies similar to those described previously. The findings usually show a picture of moderate interstitial disease in the pulmonary parenchyma combining, honeycomb and ground glass lesions and thickening of the septal lines involving the base of the lungs (fig. 6).

**PAH associated with congenital heart disorders with right-left shunt**

In 1897, Vicktor Eisenmenger reported the case of a patient with a large, interventricular septal defect and severe PAH. The term Eisenmenger’s syndrome commonly covers any case of PAH induced by shunts that entail the communication of the pulmonary and systemic circulation such as patent ductus ateriosis, interatral septal defect, truncus arteriosus, aortopulmonary window and other, more complex
heart malformations such as so called single ventricles with no pulmonary protection [1]. In the early stages of the disease the high-pressure systemic blood-flow (left-right shunt) causes lesions that remodel the pulmonary vascular bed, gradually but continually, increasing the pulmonary vascular resistance values until a two-way or reversed (right-left) shunt is created when they exceed the systemic resistance values. The chest x-ray shows cardiomegaly and dilatation of the main pulmonary trunk artery and its proximal branches. Echocardiography is the main examination used to diagnose this disorder and visualise the malformation causing the right-left shunt. In some cases it can be more difficult to find, even with an angioscan and, above all, cardiac MRI will be the examinations of choice (fig. 7).

**Veno-occlusive disease and pulmonary capillary haemangiomatosis**

Pulmonary veno-occlusive disease (PVOD) and pulmonary capillary haemangiomatosis (PCH) are rarer causes of PAH [1]. On the contrary to idiopathic PAH they predominantly feature involvement of the veinules or capillaries, causing chronic interstitial oedema and pulmonary haemosiderosis. However, there are many features that are similar to idiopathic PAH in the clinical and hemodynamic presentation (normal pulmonary artery occlusion pressure), which can make the diagnosis difficult. This form is particularly serious because when it is treated by vasodilators, the treatment itself can in some cases incur a risk of sometimes fatal aggravation of the pulmonary oedema [34]. A formal diagnosis can only be made by biopsy, which is never entirely risk-free in these patients. Therefore, since a non-invasive diagnostic approach is essential, a thoracic...
CT-scan is called for. Resten et al compared the thoracic CT-scans of 15 patients who suffered from histologically confirmed PVOD or PCH and 15 patients with idiopathic PAH [35]. They demonstrated that an association of thickening of the interlobular septa, centrolobular nodules, enlarged mediastinal lymph nodes and pleural effusion on a CT-scan are anomalies that are highly suggestive of PVOD or PCH [35] (fig. 8) when the pulmonary veins and the right atrium are not dilated. This permits a differential diagnosis with the signs observed in the case of mitral stenosis or myxoma of the left atrium. The signs of PVOD picked up on the CT-scan are caused by high pressures in the veins. A patient who presents with PAH and has these abnormal findings on the CT-scan should be given a broncho-alveolar lavage to check for hidden alveolar haemorrhage with siderophages [36] to complete the evaluation.

« Passive pulmonary hypertension »

Pressures above 15 mmHg in the pulmonary veins due to cardiomyopathy or left valve disease induce a passive elevation of the pressure in the entire pulmonary circulation. A chest x-ray will show vascular redistribution towards the apex of the lungs, Kerley’s septal lines and yield a general picture of pulmonary oedema associated with cardiomegaly. Isolated dilatation of the left atrium is sometimes seen in mitral stenosis. Cardiac ultrasonography is the examination of choice to analyse the valvular structures and assess the contractile capacity of the left ventricle. Some details on the thoracic CT-scan can suggest a post-capillary cause, namely signs of diffuse interstitial oedema presenting as a ground glass picture, predominantly in the sloping central areas, combined with a smooth, regular thickening of the interlobular septa and hazy centrolobular nodules. All these signs bear witness to high venous pressures. Very often these signs are also accompanied by enlarged lymph nodes in the mediastinum and pleural effusion. An analysis of the size of the left atrium and the calibre of the central pulmonary veins will be highly suggestive of mitral valve disease if both are enlarged.

« Hypoxic » pulmonary hypertension

This category of pulmonary arterial hypertension is caused by chronic hypoxia due to disease in the pulmonary parenchyma (fibrosis or emphysema), alveolar hypoventilation of central origin or a long stay at a high altitude. As a general rule this type of PAH is moderate. However, a minority of patients may develop a more severe form of pulmonary hypertension that is disproportionate to their degree of respiratory insufficiency [37]. In this case a thoracic CT-scan is the best imaging technique to analyse the pulmonary parenchyma. The topography of emphysema features centrolobular or pan-lobular hypo-attenuated areas according to the type of case. The fibrotic areas are specifically organised, mainly sub-pleural, basal and predominantly peripheral, distorting the parenchyma, causing scissors deformities and bronchectasia due to traction.
Chronic thromboembolic pulmonary hypertension (CTEPH) is caused by the formation and persistence of fibrinocruoric clots after one or several attacks of pulmonary embolism, leading to a more or less proximal obstruction of the pulmonary vascular bed [1]. A remodelling of the pulmonary microcirculation very similar to that observed in idiopathic PAH then subsequently develops in the non-occluded territories and combines with the obstruction caused by the fibrous clots, increasing the pulmonary vascular resistance values and gradually leading to right ventricle failure [38]. Some older series report an incidence ranging between 0.1 and 0.5% in patients who survived acute pulmonary embolism [39]. However there are prospective studies following up patients after an attack of acute pulmonary embolism that report much higher incidences ranging between 3.1% at 1 year and 3.8% at 2 years [40]. The prognosis for CTEPH has considerably improved thanks to the development of pulmonary endarterectomy [41]. It is currently the only curable form of pulmonary hypertension. A positive diagnosis is fairly simple and calls for an echocardiogram that will show typical signs of PAH (dilatation of the right ventricle and paradoxical septum). Doppler flow measurements of tricuspid regurgitation will provide an assessment of PAPs. A pulmonary ventilation/perfusion scan is an important examination because it will confirm the post-embolic forms of PAH diagnosed on the echocardiogram. It will also provide evidence of systematic perfusion defects that are usually bilateral (fig. 2) with no associated respiratory anomaly. A pulmonary angiogram will confirm the diagnosis and determine whether the lesions are seated proximally or distally and thus amenable to endarterectomy or not. Ideally the angiogram should be performed in a centre with sufficient experience of this type of examination to make sure that it is technically perfect (See above). There are five main signs on the angiogram that will be more or less marked: (1) a pouching defect may appear in the progression of the contrast medium, revealing that the pulmonary artery is completely obstructed, (2) the wall of the pulmonary artery may be either irregular and/or straighter than normal, (3) there may be sudden changes of calibre in the pulmonary arteries, (4) horizontal cord-like structures may be seen across the arteries, reducing the calibre of the arterial lumen, and (5) the branches of the pulmonary artery may be missing in some segments or lobes with no parenchyma showing up on the angiogram in the corresponding areas (fig. 9). The vascular images obtained with a multi-detector thoracic CT-scan will provide additional information that is complementary to that obtained from the pulmonary angiogram [42] showing the thickening of the pulmonary artery wall and a decrease in the diameter of the arterial lumen in relation to its external diameter on a multiplanar reconstruction or on the axial slices (fig. 9, 10). These images are caused by marginal thrombi, but they are different from those observed in acute pulmonary embolism because they have a high propensity to adhere to the wall once they have developed and become part of the vascular structure. They can cause stenosis to a greater or lesser degree and appear as striated lines along the pulmonary arterial vessels. Heterogeneity in the density of the pulmonary parenchyma, sometimes described as mosaic perfusion, is considered as a non-specific sign observed in different types of pulmonary hypertension [31]. Mosaic perfusion features areas of increased density within which the size of the pulmonary vessels is larger than normal and hypo-attenuated areas containing vessels that are smaller in calibre than normal (fig. 4, 11). The calibre of the vessels can be analysed by comparing them with the diameter of the neighbouring bronchi. Mosaic perfusion can be consecutive to a fixed area of vascular involvement or it may be purely functional and related to a vasoconstriction reflex in badly ventilated areas.

**Fig. 9.**
A: Right pulmonary angiogram, left oblique 30° angle in a patient who presented with severe postembolic PAH. The arterial wall is clearly irregular in the lower right lobe and one of the branches of the right basal pyramid (arrow) fits with a marginal thrombus on the MIP reconstruction of the coronal slice on the angio-CT (B).
In the latter case the heterogeneity will increase during the expiratory phase, whereas this will not occur if the cause is vascular. Although it is described as non-specific of CTEPH, a pulmonary density that presents a mosaic aspect is highly suggestive of CTEPH, particularly when it is systematically found in one or several of the secondary pulmonary lobules. These findings are observed in 74% of the patients with CTEPH, in 12% of the patients with cardiac PAH and in only 5% of the patients who present with PAH consecutive to pulmonary involvement [31]. Systemic hypervascularisation is most frequently observed in CTEPH [43]. This type of hypervascularisation affects the bronchial arteries (fig. 10, 12) and also other systemic arteries such as the phrenic (fig. 12), intercostal or internal mammary arteries. The diagnosis is based on the abnormal visibility of these arteries rather than on a strict diameter criterion that is considered to be abnormal above 1.5 mm [43]. It is easier to show up these systemic arteries that are usually small in size with multi-slice technology and post-processing techniques such as MIP or volume rendering are also particularly useful [43]. In full-blown cases with major dilatation of the pulmonary artery, thrombi may form in situ upstream from an obstruction where the circulation is sluggish; these are known as sedimentary thrombi. They are the result and not the cause of CTEPH and are more particularly observed in the bend of the right interlobular artery. On the contrary to embolic thrombi, they are observed more readily in the proximal portion of the artery. Tumoral emboli of the pulmonary artery can be caused by cancer (kidney, thyroid, stomach, etc.) or by the migration of an embolus or endoluminal extension of the tumour through the vena cava and the right heart chambers. The clinical presentation may mimic that of cruric post-embolic pulmonary hypertension but if the patient has no case-history of venous thromboembolic disorders and does not improve under anti-coagulants, the signal picked up on the angioscan (fig. 13) or the angioMRI and a strongly positive positron emission CT-scan (PET-scan) after injection of18 fluoro-deoxy-glucose (18-FDG) picking up the endoluminal material will be highly suggestive of the diagnosis.

*Fig. 10.*
Angio CT-scan of the chest in a patient aged 70 who presented with severe postembolic PAH 20 years after an attack of acute pulmonary embolism. A: Hypodense (hyposignal showing a) marginal thrombus (arrow) positioned proximally in the trunk of the right pulmonary artery. B: Sagittal slice on the MIP reconstruction showing the marginal thrombus in the right pulmonary trunk artery. C: Coronal slice of the MIP reconstruction showing major hypertrophy of the bronchial arteries yielding a serpiginous vascular network.

*Fig. 11.*
Parenchymatous window of an angioscan of the chest in postembolic PAH. A: The density of the parenchyma seems homogeneous. B: MiniMIP processing unveils heterogeneous perfusion. The clear borders that appear systematically and the fact that there is no increase in the expiratory phase are a strong argument in favour of a postembolic cause.
Beneath the segment level the images obtained with MRA were not sufficiently accurate [44]. In this study, the most proximal marginal thrombi on the MRA were located at the beginning of the surgical dissection plane used in pulmonary endarterectomy. However, the patients included in this study had all been selected a priori as suitable candidates for surgery, so this does not enable us to draw any conclusions as to whether MRA can distinguish between the proximal forms that are amenable to surgery and the distal forms that are not. Recently, Nikolaou et al evaluated MRA in 29 patients with either post-embolic or idiopathic PAH [45]. The difference between idiopathic or post-embolic PAH was correctly diagnosed in 24 patients out of the 29 included.

Studying pulmonary microcirculation by analysing pulmonary perfusion on MRI may become one of the essential parameters in assessing patients with CTEPH. Being able to show that perfusion defects in territories fit with proximal obstruction of the pulmonary arterial vascularisation could provide the surgeon with crucial information on the likelihood of performing pulmonary endarterectomy successfully. Conversely, when the non-perfused areas do not fit with obstructed vessels, these findings may show the remodelling of the pulmonary microcirculation in such patients. In this case, the patient will be less likely to recover after endarterectomy. The preliminary analysis reveals promising results but a more detailed study will be essential [45, 46].

**Conclusion**

Over the past few years imaging techniques have progressed enormously and now play a prominent role in managing the diagnosis and treatment of patients with pulmonary arterial hypertension. An algorithm summarising the use of the different imaging techniques used to treat patients who present with suspected pulmonary arterial hypertension is proposed (fig. 14).
References


