the reconstructed LA from the imaging scan before the index procedure, enables a precise localization of the occluded PV.[1257] Baseline CT angiography or MRI is more helpful in defining the PV anatomy.

Many PV stenoses are rigid and difficult to dilate. Even after acutely successful angioplasty, PV restenosis occurs in up to 50% of cases.[1250,1254,1255,1258] Percutaneous treatment of PV stenosis with stenting is associated with reduced risk of restenosis when compared with balloon angioplasty, particularly with the use of larger diameter and drug-eluting stents.[1250,1254,1255,1258] Nevertheless, even after stenting, restenosis rates are high.[1254,1255,1259] There are only limited data on the role of surgical treatment of PV stenosis. Connecting the patch to the proximal end of the stenosis is challenging because this end is buried in the lung parenchyma. Given this difficulty and the excessive risk, there is no evidence for recommending surgical treatment in patients with recurrent PV stenosis after AF ablation. Even for patients with recurrent severe and persistent problems due to restenosis despite interventional treatment, recurrent infection and hemoptysis are uncommon and manageable, and the need for lobectomy or pneumonectomy is very rare.[1254] Therefore, repeat percutaneous intervention is the treatment of choice for cases of PV restenosis after angioplasty.

11.3.6. Phrenic nerve palsy

Phrenic nerve palsy is a significant complication of AF ablation and results from direct PN injury. The right PN is most commonly affected because it descends in close proximity to sites of ablation in the SVC and both right-sided PVs. It courses slightly further from the right inferior PV, so that injury during treatment of this vein is less common than that occurring with RSPV ablation. Injury of the left PN may also occur during ablation of the LAA due to its course anterior to the base of the LAA (*Section 3.9.*).

Phrenic nerve palsy is observed with all technologies of thermal AF ablation, but the vast majority of cases occurs after cryoablation.[244,294,1206,1260] With cryoballoon ablation, most PN injuries are transient and resolve before the end of the procedure.[1261] Based on recent PFA registries, the occurrence of PN palsy following ablation with the pentaspline, multielectrode PFA catheter is exceedingly rare.[643,644]

In patients with persistent PN palsy, recovery of nerve function may occur within weeks and in the vast majority by 12 months, although 18–24 months might be required in some patients.[1248,1262] In a large multinational registry enrolling 17 356 patients undergoing cryoballoon-based PVI, PN injury recovered in 97.0% of patients at 12 months, with only 0.1% of the overall population showing permanent PNI.[1261] In recent large surveys, the reported incidence of permanent PN palsy ranges from 0.08 to 0.1%.[1066,1198,1261]

Several mechanisms have been proposed to explain the increased incidence of PN injury after balloon-based AF ablation. First, wedging or exerting force to direct the balloon into the RSPV for complete PV occlusion can distort the anatomy and decrease the distance between the RSPV endocardium and the right PN.[227] Second, a small balloon size relative to PV diameter can increase the likelihood of distal ablation in the vein. Studies have shown a higher risk of PN injury associated with the smaller 23 mm balloon compared with the larger 28 mm balloon, the latter resulting in more proximal energy application.[239,1248] The smaller balloon is potentially advanced further within the PV, causing distortion of the anatomy, creating a higher susceptibility to PN thermal injury. Third, the use of additional freeze cycles can increase the risk of dose-dependent nerve palsy.[1169] Phrenic nerve palsy can also occur during antral ablation using RF energy. This likely results from thermal injury to the PN as it courses anterior to the right PVs. Another common scenario of PN palsy is during electrical isolation of the SVC using point-by-point RF ablation (*Section 3.9.*).

Phrenic nerve palsy can be asymptomatic but typically causes dyspnea, tachypnea, cough, hiccups, and thoracic pain (Figure 13). The diagnosis is suggested when newly elevated hemidiaphragm with or without atelectasis of the ipsilateral lung base is observed on postprocedural chest x-ray. When suspected, diaphragm excursion should be evaluated using fluoroscopy (sniff test) or ultrasound to confirm the diagnosis.

A number of strategies have been employed to prevent PN palsy. These include limiting ablation to antral regions with various balloon maneuvers; preablation high-output pacing to establish whether the PN can be captured from the proposed ablation site before energy delivery; PN mapping with anatomic tagging of its course using an EAM system to guide safe deployment of ablation lesions; and monitoring of diaphragmatic excursion with abdominal palpation, fluoroscopy, or intracardiac ultrasound while pacing the PN from the SVC or subclavian vein during ablation.[1263] Monitoring the effects of right PN pacing is now considered a standard part of cryoballoon ablation and should also be considered during RF energy delivery at the anterior part of the rights PVs and during SVC isolation (Figure 6). Finally, diaphragmatic electromyography for direct monitoring of diaphragmatic compound motor action potentials during ablation is a technique for early detection of PN palsy that has been reported to reduce incidence of palsy.[1264,1265] Compound motor action potentials are recorded using body surface electrodes, esophageal electrodes, or a diagnostic catheter positioned in the hepatic vein. A decrease in the amplitude of the myopotential by 30% is more sensitive than abdominal palpation for predicting the subsequent reduction in diaphragmatic excursion and PN palsy.[1266] Energy delivery should be interrupted immediately at the first sign of PN injury.

There is no active treatment known to facilitate PN healing. In highly symptomatic patients, physical therapy of intercostal muscles and scalenes can improve breathing. In patients with permanent nerve palsy, surgical treatment