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Acute Neurological Complications of Coronavirus Disease

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INTRODUCTION

The coronavirus disease (COVID-19) pandemic, caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) virus, has affected hundreds of millions of people globally and led to several million deaths.1 In addition to respiratory sequelae (eg, interstitial pneumonia and acute respiratory distress syndrome), neurologic manifestations have been observed with COVID-19, including encephalopathy, acute cerebrovascular disease, and sensory abnormalities.2,3 The frequency of neurologic symptoms has been observed in up to 36.4% of COVID-19 patients and is more common in patients with severe stages of infection.4

Recognizing the neuroradiological features associated with COVID-19 is crucial, as they have implications on diagnosis and management. This article reviews the various acute neuroradiological patterns that have been observed with SARS-CoV-2 infections (Table 1).

STROKE

Stroke has been observed in 1% to 3% of all hospitalized patients with COVID-19.5,6 From a meta-analysis of published articles detailing MRI neuroimaging findings during the peak of the pandemic, acute and subacute strokes were the most common neuro-radiological abnormality.7 Development of strokes bears important
### Table 1
**Neuroimaging findings in acute coronavirus disease infection**

| Clinical Syndrome          | Imaging Findings (Computed Tomography or MRI)                                                                 | Proposed Pathogenesis                                                                 |
|----------------------------|---------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Stroke                     | • Anterior circulation most common<br>• Multiterritorial involvement<br>• Large vessel occlusions, especially in uncommonly affected vessels: subclavian artery and pericallosal gyrus<br>• Higher prevalence among younger patients and those without traditional risk factors for stroke | • Endothelial cell dysfunction via immune-mediated cytokine storm or direct viral interactions<br>• Indirect propagation of thrombosis and plaque rupture from immune response to the virus |
| Dural vein thrombosis      | • Multifocal involvement: superior sagittal, transverse, and sigmoid sinuses, internal jugular vein<br>• Associated parenchymal hemorrhage, cerebral edema, venous infarcts | • Indirect propagation of thrombosis and plaque rupture from immune response to the virus |
| Arterial dissection        | • Extracranial carotid and vertebral arteries, commonly bilateral<br>• Absence of typical risk factors such as connective tissue disorders or trauma | • Endothelial cell dysfunction via immune-mediated cytokine storm or direct viral interactions |
| Vasculitis                 | • Long segment vessel wall enhancement of multiple arteries<br>• *Focal cerebral arteriopathy*: pediatric patient with focal stenosis, irregular narrowing, concentric contrast enhancement of a large vessel | • Endothelial cell dysfunction via immune-mediated cytokine storm or direct viral interactions |
| Intraparenchymal hemorrhage| • Unifocal or multifocal involvement with extension into subarachnoid and intraventricular spaces<br>• Associated diffuse edema and mass effect<br>• Microhemorrhages: cortical, juxtacortical, deep white matter (WM), perivenular, and corpus callosal involvement | • Dysregulation of blood pressure control through virus-related downregulation of ACE-2 receptors<br>• Endothelial cell dysfunction via immune-mediated cytokine storm or direct viral interactions<br>• Iatrogenic: anticoagulation, ECMO, mechanical ventilation<br>• Hypoxic-induced injury to the blood-brain barrier |
| PRES                      | • CT hypoattenuation, T2/FLAIR signal abnormality, and diffusion restriction in the subcortical WM of posterior temporal and occipital lobes<br>• Associated parenchymal hemorrhages and microhemorrhages | • Endothelial cell dysfunction via immune-mediated cytokine storm or direct viral interaction<br>• Dysregulation of blood pressure control through virus-related downregulation of ACE-2 receptors |
| Leukoencephalopathy       | • Multifocal WM lesions with diffusion restriction and T2/FLAIR hyperintensity, predominantly in the posterior WM<br>• Central restricted diffusion greater for COVID-19 lesions | • Endothelial cell dysfunction via immune-mediated cytokine storm or direct viral interactions |

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implications in the clinical course of the COVID-19 patient. Their detection signifies poor prognosis with reported rates of mortality up to 50%. Severe disability has been seen in COVID-19 survivors with ischemic strokes upon discharge, significantly greater than those with non-COVID-19-related ischemic strokes. Moreover, studies have shown that COVID-19 represents a significant independent risk factor in stroke development among hospitalized patients, even greater than traditional comorbidities such as cardiovascular disease and obesity.

Certain neuroradiological characteristics are linked to COVID-19-related strokes. These features include multiterritorial involvement, involvement of atypical vessels, and large vessel occlusions.

**Stroke Distribution**

Strokes in COVID-19 patients more commonly involve the anterior circulation compared with the posterior circulation. Multivascular distribution is a common feature, observed in up to 40% of cases. This rate is higher than that observed in the prepandemic era (10.7%). The high prevalence of multiterritorial strokes is consistent with the induced prothrombotic environment and increased embolic risk associated with the SARS-COV-2 virus, and had been reported in the previous 2003 outbreak of SARS-COV-1 virus infection. Infection severity is also likely correlated with risk for multiterritorial strokes. In 1 study, multiterritorial strokes were significantly more frequent among hospitalized patients with severe infection compared to outpatients with less severe infections (56.4% vs 33.3%).

**Large Vessel Occlusions**

Large vessel occlusions (LVOs) have been observed in up to around 60% of COVID-19 patients with ischemic infarctions. In comparison, arterial occlusions were historically observed in up to 46% of ischemic strokes in the prepandemic era. In 1 study, proximal large vessel occlusions were significantly more common among COVID-19 patients compared with historic controls. The relatively high prevalence of LVOs among COVID-19-related acute ischemic strokes suggests the prothrombotic nature of the SARS-COV-2 virus.

LVOs in COVID-19 patients most commonly involve the anterior circulation, particularly the middle cerebral artery (MCA) and internal carotid artery (Fig. 1). Other locations include the posterior cerebral artery (PCA), basilar artery, vertebral artery, and common carotid arteries. Significant thrombotic burden and occlusions of otherwise uncommonly affected vessels have also been observed in the subclavian artery and the pericallosal artery. Occlusions can appear in tandem, which was seen in up to 40% of patients in 1 case series.

**Strokes in Younger Patients**

Younger age onset of strokes has been observed in COVID-19 patients. In 1 study, 73.3% of patients with large vessel occlusions were younger than 50 years old. Median age of stroke-onset in COVID-19 patients was found to be significantly lower than that of patients without COVID-19 (median age of 63 vs 70). In addition, the mean age of COVID-19 patients with emergency large vessel

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**Table 1 (continued)**

| Clinical Syndrome | Imaging Findings (Computed Tomography or MRI) | Proposed Pathogenesis |
|-------------------|-----------------------------------------------|-----------------------|
| Cranial neuropathy | - Anosmia/dysgeusia: T2/FLAIR signal abnormality in the gyrus rectus and olfactory bulbs <br>- Facial and abducens nerve palsy: affected cranial nerves demonstrating STIR hyperintensity, gadolinium enhancement, and diffusion restriction | - Autoimmune-mediated |

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occlusions was also significantly less than that of patients without COVID-19 (mean age of 59 vs 74 years). Certain clinical factors are shared among younger patients with COVID-19 and stroke, such as the absence of traditional risk factors for stroke (eg, diabetes, hypertension, hyperlipidemia, and coronary artery disease), and minimal to absent respiratory symptoms during the initial stage of the disease course. In 1 study, a significantly higher number of patients younger than 50 years old experienced an ischemic stroke in the absence of any prior respiratory symptoms (50.0%, P=.014).

Pathophysiology of Stroke

The mechanism behind the development of strokes in COVID-19 patients is presumed to be multifactorial. Interaction between the SARS-COV-2 virus with endothelial angiotensin converting enzyme 2 (ACE-2) receptors is thought to result in direct endothelial damage, predisposing to occlusive events. Indirectly, a proinflammatory state induced by a misdirected immune response to the SARS-COV-2 virus can result in propagation of thrombosis and plaque rupture. Inflammatory infiltrates have been found within the intima of surgically removed thrombosis on pathology, consistent with endotheliitis.

It is unclear whether arterial thrombosis is a de novo phenomenon or related to worsening of pre-existing atheromatous plaque. Many COVID-19-related strokes have been observed in patients with prior atherosclerotic disease. However, patients without any significant medical history, especially those younger than the observed population, have presented with strokes and large vessel occlusions. Direct endothelial damage may be the primary mechanism behind occlusive events in these patients. In addition, acute extracranial events, such as pulmonary embolism or cardiac arrests, may be triggers for strokes. In 1 meta-analysis, younger COVID-19 patients (<50 years) had a higher frequency of elevated cardiac troponin, suggesting that acute myocardial injury is a possible risk factor for the development of strokes.

DURAL VEIN THROMBOSIS

Dural vein thrombosis is a relatively rare presentation among COVID-19 patients; in 1 large study, the prevalence was only 0.02% (Fig. 2). When present, sinus vein thrombosis tends to involve multiple sites, most commonly the superior sagittal, transverse, and sigmoid sinuses. Other sites include the cortical veins, vein of Galen, and internal cerebral veins. Complications from the venous thrombosis may also be seen, such as surrounding parenchymal hemorrhage, cerebral edema, and hemorrhagic venous infarcts.

Given the low number of cases, the relationship between the development of dural vein thrombosis and SARS-COV-2 virus has yet to be elucidated. In many case series, dural venous thrombosis and its associated complications were seen in patients with predisposing risk factors, such as hypertension, diabetes, obesity, oral contraceptive pill
the use of OCP, use, and hormonal therapy for cancer. However, sinus thrombosis can present in patients without prior risk factors or inciting events. Its pathogenesis is likely tied to the prothrombogenic state associated with COVID-19.

**ARTERIAL DISSECTION**

Arterial dissections are rarely observed among COVID-19 patients, typically occurring in the extracranial carotid and vertebral arteries, and often bilaterally. One report noted extension of the dissection from the distal cervical part to the petrous segment of the internal carotid arteries. Patients were also noted to lack typical risk factors for dissection, such as connective tissue disorders, or inciting events, such as trauma (Fig. 3).

Although the mechanism remains unclear, endothelial damage propagated by the cytokine storm and direct infection by the SARS-COV-2 virus likely play a role. Dissections at other sites, such as the aorta and coronary arteries, have been observed in the context of COVID-19 and likely follow a similar pathogenesis.

**VASCULITIS AND FOCAL CEREBRAL ARTERIOPATHY**

Acute vasculitis is a rare neuroradiologic manifestation observed in COVID-19 patients. Typical imaging features include long segment vessel wall enhancement of multiple arteries. In 1 case of a 64-year-old patient, vasculitis was observed in MCAs, anterior cerebral arteries (ACAs), vertebral arteries, and the basilar artery, and was associated with multiterritorial infarcts.

In pediatric COVID-19 patients, several cases of focal cerebral arteriopathy of childhood-inflammatory type have been reported. Imaging findings include focal stenosis and irregular narrowing of a large vessel, such as the M1 segment, with associated wall thickening and concentric contrast enhancement. In lieu of typical cardiovascular factors and pre-existing disease, focal cerebral arteriopathy may represent a possible mechanism for which strokes can develop in children. One case of stroke has been observed in a COVID-19 patient as young as 5 years old.

**INTRACEREBRAL HEMORRHAGE**

Intracranial hemorrhage is a neurologic complication seen in approximately 0.2% of COVID-19 patients. It has been observed in up to 42% of patients with abnormal neuroradiological findings. Typical imaging features of intracranial hemorrhage include massive intraparenchymal hemorrhage, usually with extension into the subarachnoid and intraventricular spaces, multifocal intraparenchymal hemorrhages, and microhemorrhages. Diffuse edema is often associated with foci of hemorrhage, and may contribute to significant mass effect with increased risk of brain herniation. Rarely, acute parenchymal hematomas can involve the bilateral basal ganglia. The mechanism behind
this distribution of hemorrhage is hypothesized to be disrupted drainage of the basal ganglia secondary to occlusion of the great cerebral vein.

Intracranial hemorrhage may result spontaneously, which typically occurs in critically ill patients with severe infections and multiorgan failure. Hemorrhage can also result secondarily from other pathologic processes, such as hemorrhagic transformation of ischemic strokes, rupture of dissecting aneurysms and pseudoaneurysms, hemorrhagic infarction associated with venous sinus thrombosis, reversible cerebral vasoconstriction syndrome, posterior reversible encephalopathy syndrome (PRES), and iatrogenic causes.

Pathophysiology of Hemorrhage

The pathophysiology for the development of intracranial hemorrhage is multifactorial. COVID-19 is associated with coagulopathies, such as thrombocytopenia and disseminated intravascular coagulation, which increase the risk for hemorrhage. More directly, SARS-COV-2 virus is known to bind to the angiotensin-converting enzyme 2 (ACE-2) receptor in order to enter host cells. ACE-2 receptors are expressed on various organs, including cerebrovascular endothelial cells, and are integral components of the renin-angiotensin pathway. SARS-COV-2-induced downregulation of ACE-2 receptors can result in dysregulation of blood pressure control and lead to blood pressure spikes, potentially causing arterial wall rupture and hemorrhage in the brain. Alternatively, the mechanism of diffuse thrombotic microangiopathy has been proposed. Diffuse thrombosis and vascular endothelial damage can lead to breakdown of the blood-brain barrier, facilitating the development of microhemorrhages that eventually coalesce into large intraparenchymal hematomas.

Iatrogenic causes most likely play a role in the pathogenesis of intracranial hemorrhage. Anticoagulation therapy has been determined to be the cause of a substantial number of cases of intracranial hemorrhage in COVID-19 patients. In 1 study, most parenchymal hemorrhages were attributed to anticoagulation (60%), whereas a few cases were related to indeterminate mechanisms (30%). Other case series indicated that all patients with observed hemorrhagic transformation of ischemic strokes were on anticoagulation therapy. Characteristic imaging features can help distinguish coagulopathic intracranial hemorrhages from other etiologies. The presence of a fluid-blood level, represented by a meniscus separating dependent hyperattenuating blood products from lighter hypoattenuating serous fluid, is a highly specific finding for anticoagulation or antiplatelet therapy in COVID-19 patients.

High prevalence of intracranial hemorrhage has been reported in COVID-19 patients on extracorporeal membrane oxygenation (ECMO) therapy. In 1 case series, up to 41.7% of COVID-19 patients on veno-venous ECMO therapy had subarachnoid,
intraparenchymal, or intraventricular hemorrhage. ECMO therapy is associated with derangements of hematologic and coagulation pathways, resulting from continuous contact between the patient’s blood and extracorporeal circuit. These factors, possibly compounded by the coagulopathic environment associated with the SARS-COV-2 virus, promote the development of hemorrhagic complications.

**Microhemorrhages**

Microhemorrhages make up approximately 11.1% of abnormal neuroimaging findings in COVID-19 patients. Distribution patterns are various and include cortical, juxtacortical, subcortical, deep white matter, periventricular, and corpus callosal involvement. Microhemorrhages attributable to COVID-19 can be made by deduction through the exclusion of other etiologies, such as hypertensive coagulopathy, diffuse axonal injury, or cerebral amyloid angiopathy, based on atypical distribution patterns and absence of clinical factors, such as hypertension or trauma. Corpus callosum involvement, particularly the splenium, is a commonly reported finding in multiple case series of COVID-19 patients. Microhemorrhages in the corpus callosum have been previously described in other patient populations, such as in delayed posthypoxic leukoencephalopathy from acute respiratory distress syndrome, high-altitude cerebral edema, and in critical illness-associated microbleeds, in which there is additional involvement of the juxtacortical white matter with sparing of the deep and periventricular white matter. The underlying mechanism is multifactorial, related to hypoxic-induced injury to the blood-brain barrier and impaired cerebral venous return from increased intracranial pressures. COVID-19-related microhemorrhages likely follow similar mechanisms; however, the pervasive use of mechanical ventilation among COVID-19 patients represents a confounding factor. Increased intrathoracic pressures related to ventilator use can reduce cerebral venous return in critically ill patients, which may better explain the development of microhemorrhages than direct effects from the SARS-COV-2 virus.

**Posterior Reversible Encephalopathy Syndrome**

PRES manifestations are typically seen as reversible confluent white matter changes in the posterior cerebrum. These appear as striking areas of hypointensity on noncontrast computed tomography (CT), correlating with findings of T2/fluid attenuated inversion recovery (FLAIR) signal abnormality on MRI. The distribution is typically in the areas associated with PRES, predominantly the subcortical white matter of the posterior temporal and occipital lobes. Corresponding high diffusivity is seen in these regions. Areas of hemorrhage are also described, including small parenchymal hemorrhages visible on CT and microhemorrhages best visualized on gradient echo (GRE)/susceptibility weighted imaging (SWI) imaging. The pathologic mechanism is thought to be related to direct binding of the virus to ACE-2 receptors on neurovascular endothelial cells, leading to breakdown of the blood brain barrier. Blood pressure dysregulation caused by ACE-2 dysfunction is also a possibility. Interestingly, the PRES-like findings of COVID-19 may be associated with lower blood pressure elevations than seen in other PRES etiologies.

**Acute Leukoencephalopathy**

Several ADEM-type lesions have been described secondary to COVID-19. Findings generally include multifocal areas of white matter restricted diffusion with associated T2/FLAIR hyperintensity. These predominate in the posterior white matter, in a similar distribution to PRES-like findings. However, the less confluent distribution of these lesions helps to make the distinction between these pathologies. Of note, the degree of central restricted diffusion is greater in COVID-19 lesions when compared with findings of ADEM seen secondary to other viral infections. Lesions are also reported in the corpus callosum, basal ganglia, brain stem, and cerebellum. Enhancement may be associated with these lesions, as well as multiple microhemorrhages visualized on GRE/SWI imaging. Upon follow-up imaging after the acute episode, lesions may persist as white matter changes.
demonstrate more confluence on T2/FLAIR as well as development of cavitation and volume loss. More severe manifestations have also been described with imaging findings similar to AHLE. A case report of a patient with severe acute respiratory syndrome and altered mental status described more central expansile T2/FLAIR hyperintensity involving the basal ganglia and thalami. There was more frank evidence of hemorrhage than seen in less severe ADEM-like cases. Predominantly peripheral enhancement was also seen.

The underlying pathologic mechanism shares some similarity to the PRES-like syndrome, including suspected ACE-2-related endothelial dysfunction. Cytokine storms with elevated bloodstream cytokines and interleukins may also play a central role. On pathology, a range of lesions are identified, including those that share features of ADEM and AHLE. It may be that acute leukoencephalopathy in the setting of COVID-19 represents a spectrum of disorders rather than 1 entity.

**NEUROPATHIES**

**Anosmia/Dysgeusia**

Sudden onset and persistent alterations of taste and smell have been frequently reported in the setting of COVID-19 respiratory illness. In fact, loss of smell is reported as a helpful symptom in initial diagnosis of COVID-19. Several case reports and case series describe abnormal imaging findings in the anterior cranial fossa/olfactory bulbs seen in the early stages of infection (Fig. 6). An initial case report described T2/FLAIR signal abnormality in the gyrus rectus and olfactory bulbs at 3 days following presentation. At 28 days, the cortical edema had resolved, and atrophy was
demonstrated in the olfactory bulbs.\textsuperscript{74} A follow-up case series identified intrinsic T1 hyperintensity and possible enhancement in the olfactory bulbs in 5 patients. Earlier work has shown central nervous system involvement via olfactory bulb invasion in experimental mouse models. This phenomenon has also been described in other viral infections.\textsuperscript{75} More recent case series evaluating patients with persistent anosmia at least 1 month after presentation described variable findings of volume loss, morphologic change, and signal abnormality.\textsuperscript{76} The pathologic mechanism is not yet completely understood. One possibility is injury of olfactory epithelial cells bearing ACE-2 receptors. Direct nerve invasion with retrograde tracking along the olfactory pathway has also been suggested, as seen in herpes simplex virus (HSV) infections; however, it remains unproven.\textsuperscript{76}

Other Cranial Neuropathies

Other cranial neuropathies have been observed in COVID-19, such as palsy of the facial nerve\textsuperscript{77–79} and abducens nerve.\textsuperscript{77} These manifestations can occur as the initial symptom or develop more subacutely, usually up to 2 weeks from the initial onset of COVID-19 symptoms. Patients typically present with mild or absent respiratory or constitutional symptoms.

Characteristic imaging features include short-T1 inversion recovery (STIR) hyperintensity with gadolinium enhancements of the affected cranial nerve. Diffusion restriction may also be observed.\textsuperscript{77} In facial nerve palsies, enhancement of the facial nerve may actually be normal and reflect anatomy, such as the circumneural venous plexus.\textsuperscript{77} However, presence of asymmetric enhancement and correlation with clinical symptoms can increase confidence that the enhancement is actually pathologic.

As with olfactory neuropathies, the pathogenesis of these other cranial neuropathies is not well understood, but may be similar to that of neurotropic viruses, such as HSV and varicella zoster virus (VZV), in which direct viral invasion of the nerve can lead to axonal spread and subsequent inflammation and demyelination.\textsuperscript{80} Immune-mediated injury of the nerve from proinflammatory cytokines may additionally play a role.\textsuperscript{77}

SUMMARY

COVID-19 infections are associated with a myriad of acute neuroradiological features, many of which necessitate careful and prompt diagnoses. Cerebrovascular disease is a predominant complication of COVID-19 infection, attributing to the prothrombotic environment engendered by the SARS-COV-2 virus. Acute and subacute strokes, the most common neuroradiological findings, share typical features, including multiterritorial distributions, involvement of atypical vessels, and prevalence among younger patients. Appearances of intracerebral hemorrhages are more variable, although predilection for the cerebral hemispheres and corpus callosum are salient features. COVID-19-related leukoencephalopathies share similar
imaging patterns with white matter diseases observed in other infections, such as PRES, ADEM, and AHLE. Acute cranial nerve neuropathies, such as anosmia and dysgeusia, can present with pathologic enhancement and nerve atrophy. Radiologists and clinicians alike should be aware of the typical neuroimaging features of COVID-19 infections as these findings can play a significant role in patient management and treatment outcomes.

**CLINICS CARE POINTS**

- Given that neurological manifestations in COVID-19 patients can be associated with poor prognosis, radiologists and clinicians should have a lower threshold to pursue neuroimaging in these patients
- Promptly recognizing characteristic imaging features of COVID-19-related strokes and intracranial hemorrhages can allow for earlier intervention and improved patient outcomes

**DISCLOSURE**

The authors have nothing to disclose.

**REFERENCES**

1. COVID-19 Map. Coronavirus Resource Center - John Hopkins University n.d., Available at: https://coronavirus.jhu.edu/map.html. Accessed September 9, 2021.
2. Vogrig A, Gigli GL, Bnà C, et al. Stroke in patients with COVID-19: Clinical and neuroimaging characteristics. Neurosci Lett 2021;743:135564.
3. Helms J, Kremer S, Merdji H, et al. Neurologic features in severe SARS-CoV-2 Infection. N Engl J Med 2020;382:2268–70.
4. Mao L, Jin H, Wang M, et al. Neurologic manifestations of hospitalized patients with coronavirus disease 2019 in Wuhan, China. JAMA Neurol 2020;77:683–90.
5. Chou SH-Y, Beghi E, Helbok R, et al. Global incidence of neurological manifestations among patients hospitalized with COVID-19-a report for the GCS-NeuroCOVID consortium and the ENERGY consortium. JAMA Netw Open 2021;4:e2112131.
6. Yaghi S, Ishida K, Torres J, et al. SARS-CoV-2 and stroke in a New York healthcare system. Stroke 2020;51:2002–11.
7. Gulko E, Oleksk ML, Gomes W, et al. MRI brain findings in 126 patients with COVID-19: initial observations from a descriptive literature review. AJNR Am J Neuroradiol 2020;41:2199–203.
8. Jain R, Young M, Dogra S, et al. COVID-19 related neuroimaging findings: a signal of thromboembolic complications and a strong prognostic marker of poor patient outcome. J Neurol Sci 2020;414:116923.
9. Ntaios G, Michel P, Georgiopoulos G, et al. Characteristics and outcomes in patients with COVID-19 and acute ischemic stroke: the Global COVID-19 stroke registry. Stroke 2020;51:e254–8.
10. Belani P, Schefflein J, Khira S, et al. COVID-19 is an independent risk factor for acute ischemic stroke. AJNR Am J Neuroradiol 2020;41:1361–4.
11. Katz JM, Libman RB, Wang JJ, et al. Cerebrovascular complications of COVID-19. Stroke 2020;51:227–31.
12. John S, Kesav P, Mifsud VA, et al. Characteristics of large-vessel occlusion associated with COVID-19 and ischemic stroke. AJNR Am J Neuroradiol 2020;41:2263–8.
13. Radmanesh A, Raz E, Zan E, et al. Brain imaging use and findings in COVID-19: A single academic center experience in the epicenter of disease in the United States. AJNR Am J Neuroradiol 2020;41:1179–83.
14. Yoon BC, Buch K, Lang M, et al. Clinical and neuroimaging correlation in patients with COVID-19. AJNR Am J Neuroradiol 2020;41:1791–6.
15. Kaesmacher J, Mosimann PJ, Giarrusso M, et al. Multivessel occlusion in patients subjected to thrombectomy: prevalence, associated factors, and clinical implications. Stroke 2018;49:1355–62.
16. Umapathi T, Kor AC, Venketasubramanian N, et al. Large artery ischaemic stroke in severe acute respiratory syndrome (SARS). J Neurol 2014;251:1227–31.
17. Katz JM, Libman RB, Wang JJ, et al. COVID-19 severity and stroke: correlation of imaging and laboratory markers. AJNR Am J Neuroradiol 2021;42:257–61.
18. Hernández-Fernández F, Sandoval Valencia H, Barbera-Aponte RA, et al. Cerebrovascular disease in patients with COVID-19: neuroimaging, histological and clinical description. Brain 2020;143:3089–103.
19. Khira S, Schefflein J, Mahmoudi K, et al. Association of coronavirus disease (COVID-19) with large vessel occlusion strokes: a case-control study. AJR Am J Roentgenol 2021;216:150–6.
20. Rennert RC, Wall AR, Steinberg JA, et al. Epidemiology, natural history, and clinical presentation of large vessel ischemic stroke. Neurosurgery 2019;85:S4–8.
21. Beyrouti R, Adams ME, Benjamin L, et al. Characteristics of ischaemic stroke associated with
COVID-19. J Neurol Neurosurg Psychiatry 2020;91:889–91.
22. Franceschi AM, Arora R, Wilson R, et al. Neurovascular complications in COVID-19 infection: case series. AJNR Am J Neuroradiol 2020;41:1632–40.
23. Morassi M, Bagatto D, Cobelli M, et al. Stroke in patients with SARS-CoV-2 infection: case series. J Neurol 2020;267:2185–92.
24. Majidi S, Fifi JT, Ladner TR, et al. Emergent large vessel occlusion stroke during New York City’s COVID-19 outbreak. Stroke 2020;51:2656–63.
25. Cavallieri F, Marti A, Fasano A, et al. Prothrombotic state induced by COVID-19 infection as trigger for stroke in young patients: a dangerous association. eNeurologicalSci 2020;20:100247.
26. Fridman S, Bullrich MB, Jimenez-Ruiz A, et al. Stroke and anticoagulation in COVID-19. J Neurol 2020;267:2218–24.
27. Mohamud AY, Griffith B, Rehman M, et al. Intraluminal carotid artery thrombus in COVID-19: another danger of cytokine storm? AJNR Am J Neuroradiol 2020;41:1677–82.
28. Esenwa C, Cheng NT, Lipsitz E, et al. COVID-19-Associated carotid atherothrombosis and stroke. AJNR Am J Neuroradiol 2020;41:1993–9.
29. Siegler JE, Cardona P, Arenillas JF, et al. Cerebrovascular events and outcomes in hospitalized patients with COVID-19: the SVIN COVID-19 Multinational Registry. Int J Stroke 2021;16(4):437–47.
30. Cavalcanti DD, Raz E, Shapiro M, et al. Cerebral venous thrombosis associated with COVID-19. AJNR Am J Neuroradiol 2020;41:1370–6.
31. Gonçalves B, Rigby C, Kurtz P. Thrombotic and hemorrhagic neurological complications in critically ill COVID-19 patients. Neurocrit Care 2020;33:587–90.
32. Khira S, Schefflein J, Pawha P, et al. Neurovascular complications that can be seen in COVID-19 patients. Clin Imaging 2021;69:280–4.
33. Chougar L, Mathon B, Weiss N, et al. Atypical deep cerebral vein thrombosis with hemorrhagic venous infarction in a patient positive for COVID-19. AJNR Am J Neuroradiol 2020;41:1377–9.
34. Poillon G, Obadia M, Perrin M, et al. Cerebral venous thrombosis associated with COVID-19 infection: causality or coincidence? J Neuroradiol 2021;48:121–4.
35. Hughes C, Nichols T, Pike M, et al. Cerebral venous sinus thrombosis as a presentation of COVID-19. Eur J Case Rep Intern Med 2020;7:001691.
36. Patel P, Khandelwal P, Gupta G, et al. COVID-19 and cervical artery dissection- A causative association? J Stroke Cerebrovasc Dis 2020;29:105047.
37. Morassi M, Bigni B, Cobelli M, et al. Bilateral carotid artery dissection in a SARS-CoV-2 infected patient: causality or coincidence? J Neurol 2020;267:2812–4.
38. Romero-Sánchez CM, Díaz-Maroto I, Fernández-Díaz E, et al. Neurologic manifestations in hospitalized patients with COVID-19: the ALBACOVID registry. Neurology 2020;95:e1060–70.
39. Gasso LF, Maneiro Melon NM, Cebada FS, et al. Multivessel spontaneous coronary artery dissection presenting in a patient with severe acute SARS-CoV-2 respiratory infection. Eur Heart J 2020;41:3100–1.
40. Fukushima S, Rosati CM, El-Dalati S. Acute type A aortic dissection during the COVID-19 outbreak. Ann Thorac Surg 2020;110:e405–7.
41. Dixon L, Coughlan C, Karunaratne K, et al. Immunosuppression for intracranial vasculitis associated with SARS-CoV-2: therapeutic implications for COVID-19 cerebrovascular pathology. J Neurol Neurosurg Psychiatry 2020. https://doi.org/10.1136/jnnp-2020-324291.
42. Gulko E, Overby P, Ali S, et al. Vessel wall enhancement and focal cerebral arteriopathy in a pediatric patient with acute infarct and COVID-19 infection. AJNR Am J Neuroradiol 2020;41:2348–50.
43. Mirzaee SMM, Gonçalves FG, Mohammadiard M, et al. Focal cerebral arteriopathy in a pediatric patient with COVID-19. Radiology 2020;297:E274–5.
44. Khira S, Morgenstern PF, Raynes H, et al. Fatal cerebral infarct in a child with COVID-19. PediatrRadiol 2020;50:1479–80.
45. Sharifi-Razavi A, Karimi N, Rouhani N. COVID-19 and intracerebral haemorrhage: causative or coincidental? New Microbes New Infect 2020;35:100669.
46. Dogra S, Jain R, Cao M, et al. Hemorrhagic stroke and anticoagulation in COVID-19. J Stroke Cerebrovasc Dis 2020;29:104984.
47. Daci R, Kennelly M, Ferris A, et al. Bilateral basal ganglia hemorrhage in a patient with confirmed COVID-19. AJNR Am J Neuroradiol 2020;41:1797–9.
48. Al Saiegh F, Ghosh R, Leibold A, et al. Status of SARS-CoV-2 in cerebrospinal fluid of patients with COVID-19 and stroke. J Neurol Neurosurg Psychiatry 2020;91:846–8.
49. Savić D, Alsheikh TM, Alhaj AK, et al. Ruptured cerebral pseudoaneurysm in an adolescent as an early onset of COVID-19 infection: case report. Acta Neuropathol 2020;10:2725–9.
50. Oda K, Kaur G, Gulko E, et al. Reversible cerebral vasoconstriction syndrome and dissection in the setting of COVID-19 infection: case report. Acta Neurochir 2020;162:2725–9.
51. Franceschi AM, Ahmed O, Giliberto L, et al. Hemorrhagic posterior reversible encephalopathy syndrome as a manifestation of COVID-19 infection. AJNR Am J Neuroradiol 2020;41:1173–6.
52. Doo FX, Kassim G, Lefton DR, et al. Rare presentations of COVID-19: PRES-like leukoencephalopathy and carotid thrombosis. Clin Imaging 2021;69:94–101.
53. Polimeni A, Leo I, Spaccarotella C, et al. Differences in coagulopathy indices in patients with severe versus non-severe COVID-19: a meta-analysis of 35 studies and 6427 patients. Sci Rep 2021;11. https://doi.org/10.1038/s41598-021-89967-x.

54. Nicholson P, Alshafai L, Krings T. Neuroimaging findings in patients with COVID-19. AJNR Am J Neuroradiol 2020;41:1380–3.

55. Lin E, Lantos JE, Strauss SB, et al. Brain imaging of patients with COVID-19: Findings at an academic institution during the height of the outbreak in New York City. AJNR Am J Neuroradiol 2020;41:2001–8.

56. Wee NK, Fan EB, Lee KCH, et al. CT fluid-blood levels in COVID-19 intracranial hemorrhage. AJNR Am J Neuroradiol 2020;41:E76–7.

57. Masur J, Freeman CW, Mohan S. A double-edged sword: neurologic complications and mortality in extracorporeal membrane oxygenation therapy for COVID-19–related severe acute respiratory distress syndrome at a tertiary care center. AJNR Am J Neuroradiol 2020;41:2009–11.

58. Kowalewski M, Fina D, Stomka A, et al. COVID-19 and ECMO: the interplay between coagulation and inflammation—a narrative review. Crit Care 2020;24:205.

59. Sachs JR, Gibbs KW, Swor DE, et al. COVID-19–associated Leukoencephalopathy. Radiology 2020;296:E184–5.

60. Riech S, Kallenberg K, Moerer O, et al. The pattern of brain microhemorrhages after severe lung failure resembles the one seen in high-altitude cerebral edema. Crit Care Med 2015;43:e386–9.

61. Breit H, Jhaveri M, John S. Concomitant delayed posthypoxic leukoencephalopathy and critical illness microbleeds. Neurol Clin Pract 2018;8:e31–3.

62. Kallenberg K, Dehnert C, Dörfler A, et al. Microhemorrhages in nonfatal high-altitude cerebral edema. J Cereb Blood Flow Metab 2008;28:1635–42.

63. Fanou EM, Coutinho JM, Shannon P, et al. Critical illness–associated cerebral microbleeds. Stroke 2017;48:1085–7.

64. Reichard RR, Kashani KB, Boire NA, et al. Neuropathology of COVID-19: a spectrum of vascular and acute disseminated encephalomyelitis (ADEM)-like pathology. Acta Neuropathol 2020;140:1–6.

65. D’Amore F, Vinacci G, Agosti E, et al. Pressing issues in COVID-19: probable cause to seize SARS-CoV-2 for its preferential involvement of posterior circulation manifesting as severe posterior reversible encephalopathy syndrome and posterior strokes. AJNR Am J Neuroradiol 2020;41:1800–3.

66. Conte G, Avignone S, Carbonara M, et al. COVID-19–associated PRES-like encephalopathy with perivascular gadolinium enhancement. AJNR Am J Neuroradiol 2020. https://doi.org/10.3174/ajnr.A6762.

67. Kishfy L, Casasola M, Banankhah P, et al. Posterior reversible encephalopathy syndrome (PRES) as a neurological association in severe COVID-19. J Neurol Sci 2020;414:116943.

68. Rogg J, Baker A, Tung G. Posterior reversible encephalopathy syndrome (PRES): another imaging manifestation of COVID-19. InterdiscipNeurosurg 2020;22:100808.

69. Khira S, Delman BN, Belani P, et al. Imaging features of acute encephalopathy in patients with COVID-19: A Case Series. AJNR Am J Neuroradiol 2020;41:1804–8.

70. Lang M, Buch K, Li MD, et al. Leukoencephalopathy associated with severe COVID-19 infection: sequela of hypoxemia? AJNR Am J Neuroradiol 2020;41:1641–5.

71. Kandemirli SG, Dogan L, Sarikaya ZT, et al. Brain MRI findings in patients in the intensive care unit with COVID-19 infection. Radiology 2020;297:E232–5.

72. Agarwal S, Conway J, Nguyen V, et al. Serial imaging of virus-associated necrotizing disseminated acute leukoencephalopathy (VANDAL) in COVID-19. AJNR Am J Neuroradiol 2021;42:279–84.

73. Poyiadji N, Shahin G, Noujaim D, et al. COVID-19–associated acute hemorrhagic necrotizing encephalopathy: imaging features. Radiology 2020;296:E119–20.

74. Politi LS, Salsano E, Grimaldi M. Magnetic resonance imaging alteration of the brain in a patient with coronavirus disease 2019 (COVID-19) and anosmia. JAMA Neurol 2020;77:1028–9.

75. Poyiadji N, Shahin G, Noujaim D, et al. COVID-19–associated acute hemorrhagic necrotizing encephalopathy: imaging features. Radiology 2020;296:E119–20.

76. Kandemirli SG, Dogan L, Sarikaya ZT, et al. Brain MRI findings in patients in the intensive care unit with COVID-19 infection. Radiology 2020;297:E232–5.

77. Correà DG, Hygino da Cruz LC Jr, Lopes FCR, et al. Magnetic resonance imaging alteration of the brain in a patient with coronavirus disease 2019 (COVID-19) and anosmia. Acad Radiol 2021;28:28–35.

78. Goh Y, Beh DLL, Makmur A, et al. Pearls & oysters: facial nerve palsy in COVID-19 infection. Neurology 2020;95:364–7.

79. Lima MA, Silva MTT, Soares CN, et al. Peripheral facial nerve palsy associated with COVID-19. J Neurovirol 2020;26:941–4.

80. Eviston TJ, Croxson GR, Kennedy PGE, et al. Bell’s palsy: aetiology, clinical features and multidisciplinary care. J Neurol Neurosurg Psychiatry 2015;86:1356–61.