Early postmortem brain MRI findings in COVID-19 non-survivors

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Abstract

Objectives
The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is considered to have potential neuroinvasiveness that might lead to acute brain disorders or contribute to respiratory distress in patients with coronavirus disease 2019 (COVID-19). This study investigates the occurrence of structural brain abnormalities in non-survivors of COVID-19 in a virtopsy framework.

Methods
In this prospective, monocentric, case series study, consecutive patients who fulfilled the following inclusion criteria benefited from an early postmortem structural brain MRI: death <24 hours, SARS-CoV-2 detection on nasopharyngeal swab specimen, chest CT scan suggestive of COVID-19, absence of known focal brain lesion, and MRI compatibility.

Results
Among the 62 patients who died of COVID-19 from March 31, 2020, to April 24, 2020, at our institution, 19 decedents fulfilled the inclusion criteria. Parenchymal brain abnormalities were observed in 4 decedents: subcortical microbleeds and macrobleeds (2 decedents), cortico-subcortical edematous changes evocative of posterior reversible encephalopathy syndrome (PRES; 1 decedent), and nonspecific deep white matter changes (1 decedent). Asymmetric olfactory bulbs were found in 4 other decedents without downstream olfactory tract abnormalities. No brainstem MRI signal abnormality was observed.

Conclusions
Postmortem brain MRI demonstrates hemorrhagic and PRES-related brain lesions in non-survivors of COVID-19. SARS-CoV-2–related olfactory impairment seems to be limited to olfactory bulbs. Brainstem MRI findings do not support a brain-related contribution to respiratory distress in COVID-19.

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Go to Neurology.org/N for full disclosures. Funding information and disclosures deemed relevant by the authors, if any, are provided at the end of the article.
Infection by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), called coronavirus disease 2019 (COVID-19) by the World Health Organization, is associated with an ongoing worldwide outbreak of atypical and severe pneumonia. SARS-CoV-2 uses human cell receptor angiotensin-converting enzyme 2 (ACE2) as cellular entry point. ACE2 is expressed in airway epithelia, lung parenchyma, vascular endothelium, heart, kidneys, and small intestine, which explains most of the COVID-19 symptoms. ACE2 is also present in glial cells and neurons of mammalian brain, especially in brainstem nuclei involved in cardiorespiratory function. SARS-CoV-2 is therefore considered to have potential neuroinvasiveness that might lead to acute brain disorders or contribute to respiratory distress in patients with COVID-19. SARS-CoV-2 might enter the CNS through hematogenous dissemination or neuronal retrograde route via, for example, olfactory bulbs or medullary neurons. The anosmia frequently observed in SARS-CoV-2–infected patients supports the neural retrograde hypothesis. The neuroinvasiveness of SARS-CoV-2 is also supported by case reports of meningoencephalitis, intracerebral hemorrhage, ischemic strokes, and secondary acute necrotizing encephalopathy associated with SARS-CoV-2 infection. Central neurologic symptoms (e.g., headache, stroke, impaired consciousness) are also observed in 25% of patients with COVID-19. Still, brain MRI data are scarce in patients with COVID-19 due to difficulties in obtaining such an examination in infected unstable patients during the COVID-19 outbreak.

This prospective, monocentric, postmortem brain MRI case series investigated the occurrence of structural brain abnormalities in non-survivors of COVID-19 in a brain virtopsy framework performed early (<24 hours) after death. We specifically searched for signs of acute brain injury (e.g., stroke, encephalitis) and MRI signal abnormalities along the olfactory tract and brainstem.

**Methods**

**Study design and participants**

From March 31, 2020, to April 24, 2020, consecutive deceased who fulfilled the following inclusion criteria were included: death <24 hours, SARS-CoV-2 detection (direct antigen detection or reverse transcriptase PCR) on nasopharyngeal swab specimen, chest CT scan suggestive of COVID-19 without alternative diagnosis, absence of known focal brain lesion, and MRI compatibility. Clinical data were retrieved from decedents’ medical records and reviewed by clinicians (F.S.T., S.H., J.C.G., G.N., O.D.).

After death, decedents were directly placed in an MRI-compatible mortuary bag, brought to the morgue, and placed in dedicated mortuary refrigerators (2°C–3°C).

**Standard protocol approvals, registrations, and patient consents**

This study was carried out at the CUB Hôpital Erasme (Brussels, Belgium) after approval by the institutional Ethics Committee (reference: P2020/204, SRB2020121), which did not request informed consent from legal representatives.

**Clinical definitions**

Bilateral chest infiltrates associated with a \(\text{Pao}_2/\text{FiO}_2 < 300\) in ambient oxygen conditions or oxygen saturation <90% during administration of at least 50% oxygen fraction (\(\text{FiO}_2\)) were identified as severe respiratory failure. Acute kidney injury was defined according to the Kidney Disease Improving Global Outcomes criteria. Hypoxic hepatitis was defined as an increase in aspartate or alanine transaminases >20 times the upper normal range (\(\leq 50\) IU/L), that is, >1,000 IU/L in the setting of acute cardiovascular failure and in the absence of another cause of cell necrosis. Disseminated intravascular coagulation (DIC) was defined according to standard criteria. Acute cardiac injury associated with COVID-19 was identified according to recently proposed definitions.

**MRI data acquisition**

Postmortem structural brain MRIs were performed on a 3T hybrid PET–magnetic resonance (MR) scanner (SIGNA, GE Healthcare, Chicago, IL) in accordance with COVID-19 institutional hygienic and safety rules. During the COVID-19 outbreak, the PET-MR facility was isolated from the rest of the Nuclear Medicine Department and dedicated to research investigations on COVID-19. This avoided any interference with ongoing clinical activities of the department. Mortuary bags were not opened during the procedure.

MRI sequences consisted of whole-brain axial 3D T1-weighted imaging (T1WI; repetition time [TR]/echo time [TE]/flip angle [FA] 8 milliseconds/3 milliseconds/12°, inversion time [TI] 450 milliseconds, field of view [FOV] 24 × 24 cm, matrix 240 × 240, resolution 1 × 1 × 1 mm), axial T2-weighted imaging.
Brain MRI findings reflecting antemortem changes

MRI data were subsequently screened for signal abnormalities reflecting antemortem changes. These were divided into recent (i.e., potentially related to COVID-19) and longstanding (i.e., unlikely related to COVID-19) changes. Recent changes included hemorrhages, edema, and olfactory cleft and bulb abnormalities. Hemorrhages were considered recent if hyperintense on T1WI or in the absence of signal abnormality suggestive of cerebral amyloid angiopathy (CAA) or small vessel disease (SVD). Long-standing signal abnormalities included white matter changes with an imaging pattern suggestive of microvascular ischemic chronic disease, enlargement of perivascular spaces, cerebral atrophy, and late-stage lacunar ischemic or hemorrhagic changes. The severity of T2/FLAIR white matter hyperintensities of presumed vascular origin was coded according to the Fazekas scale from 0 to 3 on T2WI and T2WI FLAIR sequences. Basal ganglia and centrum semiovale enlargement of perivascular spaces was rated with a total score ranging from 0 to 8 on axial T2WI sequences. Cerebral atrophy was assessed both by using the simplified global cortical atrophy score, retaining the worst (highest) score across the brain, and by calculating the Evan index on 3D T1WI sequences. Supratentorial and infratentorial cortical sequelae and deep lacunes, pontine microischemic leukoencephalopathy, and presumed old microhemorrhages or macrohemorrhages were also noted.

Data availability

Deidentified postmortem brain MRI data can be shared on reasonable request for scientific purpose and after approval of the CUB Hôpital Erasme Ethics Committee and authorities.

Results

Table 1 summarizes included decedents’ characteristics. Clinical and biological data of included decedents are detailed in table e-1 available from Dryad, doi.org/10.5061/dryad.4qrf6q7p.

Among the 62 patients who died of COVID-19 infection during the inclusion period, 19 decedents fulfilled the inclusion criteria. The time interval between death and MRI acquisition varied between 2.07 and 23.75 hours (mean 13.67 hours). Forty-three decedents were excluded from this study because of an excessive delay (>24 hours) between death and first MRI scanning opportunity (n = 18), negative reverse transcriptase PCR on nasopharyngeal swab specimen (n = 7), negative chest CT scan findings (n = 6), history of focal brain lesion (n = 10), or MRI incompatibility (n = 2). The mean age of included decedents was 77 (range 49–94) years. All decedents had severe COVID-19 with 1 to 5 comorbid
conditions (i.e., hypertension, cardiac disorder, diabetes mellitus, chronic obstructive pulmonary disorder, chronic kidney disease, or body mass index >25 kg/m²). Anosmia was not reported in any decedent, but it was not systematically assessed. Decedents developed typical COVID-19 complications such as coagulopathy (6 of 19), acute kidney injury (14 of 19), or acute cardiac injury (18 of 19). D-dimer level was abnormal in all tested decedents (11 of 19). The assessment of arterial hypertension before death was limited for most patients admitted to COVID-19 wards due to their respiratory distress and end-of-life status. Among the patients who died in the intensive care unit (ICU; decedent [D] 2, D8, D9, D15, D19), none had mean arterial pressure >100 mm Hg, and most of them received vasopressors before death to achieve at least 65–mm Hg mean arterial pressure. Mechanical ventilation was used in the 5 decedents hospitalized in the ICU, and 2 of them (D2 and D9) were placed on veno-venous extracorporeal membrane oxygenation. None of the 14 decedents hospitalized in COVID-19 wards benefited from mechanical ventilation. Fifteen decedents died of respiratory failure, while 4 died of septic shock and multiorgan failure. All decedents were on anticoagulation (therapeutic 6 of 19, prophylactic 13 of 19).

### Brain MRI findings reflecting postmortem changes

Signal abnormalities consistent with early postmortem changes are detailed in table e-2 available from Dryad, doi.org/10.5061/dryad.4qrfj6q7p.

The increase in T1WI signal intensity, when present, did not involve homogeneously the basal ganglia and the thalami but was limited to the pallidi and posterolateral thalami (figure 1).

<table>
<thead>
<tr>
<th>Table 1 Decedents’ characteristics</th>
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<tr>
<td>Age (range), y</td>
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<td>Sex, F/M, n</td>
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<tr>
<td>Comorbid conditions, n (%)</td>
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<td>Hypertension</td>
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<td>Body mass index, mean (range), kg/m²</td>
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<td>Ex-smoker</td>
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<td>Cognitive impairment</td>
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<td>Symptoms on admission, n (%)</td>
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<td>Fever (&gt;38.5°C)</td>
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<td>CNS symptoms on admission, n (%)</td>
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<td>Headache</td>
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<td>Agitation, confusion, disorientation</td>
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<td>Seizure</td>
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<td>Complications during hospital/intensive care unit stay, n (%)</td>
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<td>Respiratory failure</td>
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<td>Acute cardiac injury</td>
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<td>Septic shock/multiple organ failure</td>
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Moreover, a similar increase in T1WI signal intensity was also present in the substantia nigra, red nuclei, and dentate nuclei in many decedents (figure 1). These gray matter structures were thus included in the analysis of postmortem T1WI signal intensity changes in addition to the pallidal nuclei and posterolateral thalami. The only decedent (D11) who did not show clearly increased T1WI signal intensity in any of the above-mentioned deep nuclei was scanned after a delay of 3.38 hours, while decedents who had increased signal intensity in all these structures (D2, D8, D9, D10, D12, D16–D19) had a scan delay ranging from 14.90 hours (D12) to 23.75 hours (D16).

Suppression of fat on T2 WI was observed in all decedents. It was classified as complete (2) in 13 of 19 (mean scan delay 17.74 hours, range 4.35–23.75 hours) and incomplete (1) in 6 of 19 (4.85 hours, 2.07–12.28 hours) decedents (figure 2). There was in all cases some degree of marked subcutaneous fat suppression but not systematically in the deep orbital fat (figure 2).

On DWI, a cortical and periventricular high-signal-intensity rim was present in all decedents. It was classified as complete (2) in 15 of 19 decedents (mean scan delay 16.38 hours, range 2.07–5.05 hours; figure 3). A clear correspondence with ADC map or other sequence data was not found.

All decedents presented a diffuse reduction of ADC across the brain parenchyma. ADC values ranged from $152 \times 10^{-6}$ mm$^2$/s (D10 and D17; scan delays of 18.75 and 21 hours, respectively) to $347 \times 10^{-6}$ mm$^2$/s (D15; scan delay of 4.35 hours) in the left centrum semiovale, $216 \times 10^{-6}$ mm$^2$/s (D10; 18.75 hours) to $503 \times 10^{-6}$ mm$^2$/s (D11; 3.38 hours) in the left basal ganglia/thalamus, and $152 \times 10^{-6}$ mm$^2$/s (D17; 21 hours) to $434 \times 10^{-6}$ mm$^2$/s (D15; 4.35 hours) in the left cerebellum.

All decedents exhibited vascular signal loss on SWIs, some of them with increased visibility of vessels. The increased visibility of vessels was categorized as absent (0), discrete (1), moderate (2), or marked (3) on axial minimum intensity projections (10-mm thickness; figure 4). Increased visibility of vessels on SWI was categorized as absent (0) in 3 of 19 (scan delay range 17.10–22.37 hours), discrete (1) in 9 of 19 (scan delay range 3.52–23.75 hours), moderate (2) in 5 of 19 (scan delay range 2.07–18.40 hours), or marked (3) in 1 of 19 decedents (scan delay 20.13 hours).
Spearman rank correlation computations revealed significant negative correlations between scan delay and adjusted FLAIR TI ($\rho = -0.67$, $p = 0.0032$) and sum of the 3 ADC values ($\rho = -0.57$, $p = 0.0128$). Significant positive correlations were found with the sum of increased T1WI signal intensity scores ($\rho = 0.68$, $p = 0.0015$), T2WI fat suppression scores ($\rho = 0.76$, $p = 0.0001$), and DWI rim-like increased signal intensity score ($\rho = 0.61$, $p = 0.0053$). The correlation with SWI vessel visibility score ($\rho = -0.42$, $p = 0.08$) was not significant. All significant correlations survived Bonferroni correction (number of tests 6) except for the sum of ADC values.

**Brain MRI findings reflecting antemortem changes**

Recent and long-standing MRI signal changes are summarized in table e-3 available from Dryad, doi.org/10.5061/dryad.4qrj6q7p. Figure 5 illustrates recent structural cerebral abnormalities in COVID-19 non-survivors. Parenchymal brain MRI abnormalities were found in 4 decedents.

D2 presented subcortical macrohemorrhages and microhemorrhages with posterior predominance, both supratentorially and infratentorially, which were best documented on SWI. The associated increased T1WI signal intensity in the larger lesions and overlying cortical edema suggested subacute hemorrhages (figures 5 and 6). A previous brain MRI, obtained in November 2016, did not show any hemorrhage. This decedent died in the ICU.

D4 exhibited 2 small arciform subcortical hemorrhages, 1 right temporal and 1 right occipital on SWI, corresponding to a discrete linear signal loss on T1WI and T2WI (figures 5 and 6). There was no surrounding vasogenic edema, microbleeds, or superficial hemosiderosis. White matter changes evocative of microvascular disease were limited, consisting of smooth periventricular hypointensities, including caps around the ventricular horns and periventricular halos (Fazekas grade 1, figure 6). No antemortem MRI was available for this patient. D4 died 24 hours after admission and had systolic/diastolic blood pressure of 115/86 mm Hg at admission.

D7 showed superior precentral and parietal cortico-subcortical swelling associated with marked supratentorial white matter changes. The decedent’s blood pressure measured 1 to 3 times a day in a COVID-19 ward oscillated between 90/55 and 140/80 mm Hg during the 5 days before death.

D9 had extensive T2WI hazy hyperintensity in bilateral centrum semiovale and was hospitalized in the ICU.

Four decedents had asymmetric olfactory bulbs with ipsilateral (D8) or without (D5, D11, D12) olfactory cleft obliteration. No other abnormality was found along the olfactory tract.

No signal abnormality was found in the brainstem except in D10, who had a midline pontine signal abnormality evocative of capillary telangiectasia (figure e-1 available from Dryad, doi.org/10.5061/dryad.4qrj6q7p).

**Discussion**

In this case series of COVID-19 non-survivors, we performed a systematic and comprehensive assessment of the abnormalities encountered on their early post-mortem brain MRI. Changes related to postmortem signal changes were analyzed first.21–24 Then, antemortem changes were distinguished between presumed recent or chronic brain pathology with the use of common radiologic markers and scales.26–29

The present population of COVID-19 non-survivors was typical of those previously reported in the literature,31–33 in particular regarding age, comorbid conditions, and complications leading to poor clinical outcome.

Five brain MRI findings were attributed to postmortem changes. The significant correlation between quantitative evaluation of these changes and the scan delay reinforced this hypothesis. These findings were (1) the necessary adaptation of the FLAIR TI to obtain adequate water suppression, (2) increased T1WI signal intensity of the deep nuclei, (3) T2WI fat suppression, (4) DWI rim-like increased signal intensity, and (5) decreased parenchymal ADC values. Overall, we attribute...
Parenchymal brain MRI abnormalities were observed in 4 of 19 decedents (21%), while asymmetric olfactory bulbs were found in 4 others (21%).

D2 had diffuse subcortical microbleeds and macrobleeds with posterior predominance. Considering his clinico-biological context, these abnormalities were evocative of multifocal hemorrhagic lesions triggered by DIC.37,38 DIC is indeed frequently observed in patients with severe COVID-19.37 Nevertheless, intracerebral hemorrhage is also a possible and rather frequent (5%–10% of patients) complication of extracorporeal membrane oxygenation, although diffuse microbleeds are seen only sporadically and do not display a posterior predominance.39 A combination of different causes underlying intracranial hemorrhages in D2 therefore has to be considered, with blood-brain barrier breakdown possibly favored by SARS-CoV-2–related endothelial dysfunction as a hypothetical synergic pathophysiologic mechanism.

In D4, we observed 2 posterior macro-subcortical bleeds, which shared some similarities with those observed in D2. Their origin is arguably more difficult to interpret in the absence of a previous brain MRI. Still, we suspect that pathophysiologic mechanisms other than the classic SVD and CAA took place. SVD is associated with microbleeds and lacunes (posterior fossa, basal ganglia, supratentorial white matter), white matter hyperintensities, and cortical infarcts.40,41 Hemorrhages due to CAA are associated with large lobar macrohemorrhage, lobar microbleeds,25 cortical superficial siderosis,42 white matter hyperintensities, and enlargement of perivascular spaces in the centrum semiovale.33 D4 instead presented an isolated left thalamic lacune and very mild white matter hyperintensities (Fazekas grade 1) for his age (79 years), no enlargement of perivascular spaces, and no other hemorrhage. Although according to the modified Boston criteria25 the diagnosis of CAA is deemed probable in the presence of 2 lobar bleeds, it is so in the absence of other causes of hemorrhage. Other possible causes could be head trauma (not reported and unlikely given the imaging appearance of the bleeds), hypertension (normal blood pressure at admission with death after 24 hours, intracranial hemorrhage more often located in deep brain structures and associated with radiologic signs of SVD44), anticoagulant therapy (prophylactic anticoagulation in this decedent), or blood clots (D-dimer level not available). Considering the COVID-19 status of the decedent, it might be hypothesized that these 2 subcortical hemorrhages were triggered by blood-brain barrier breakdown phenomena similar to those in D2.

D7 showed superior precentral and parietal cortico-subcortical swelling associated with marked supratentorial white matter changes. These findings are evocative of posterior reversible encephalopathy syndrome (PRES). PRES refers to reversible vasogenic brain edema predominating in posterior brain regions, which occurs in association with a variety of systemic disorders.45,46 PRES is typically caused by endothelial injury related to abrupt blood pressure changes or direct effects of cytokines on the endothelium.45,46 In D7, the blood pressure monitored during her stay in a COVID-19 ward did not support

those observations, at least partly, to the low temperature of decedent’s body (algor mortis) compared to that in vivo, greatly influencing T1, and, to a lesser extent, T2 relaxation times.34,35 These temperature changes were the common hypothesis formulated in existing postmortem literature,21–24 which we reproduced in the above-mentioned brain findings.

One observation, the increased SWI vessel visibility, was not investigated in previous postmortem brain MRI reports and did not significantly correlate with scan delay. While it could still represent a postmortem change, the lack of correlation could be explained by a multiplicity of factors that may lead to such a phenomenon, for example, decrease in intravascular oxy/deoxyhemoglobin ratio, blood stagnation, decrease in brain temperature, and possible premortem intravascular clotting associated with the putative endothelial injury caused by SARS-CoV-2.36 However, it was not present in the decedents with the most marked recent hemorrhagic (D2) or white matter (D9) changes and was only discretely present in the decedent with cortical edema (D7, grade 1). It therefore warrants further investigation.

The main limitation of the present postmortem MRI virtopsy lies in the severe SARS-CoV-2 pathology characterizing all decedents, which may limit the generalization of observed postmortem brain MRI findings to other clinical settings.
the hypothesis that hypertension was at the origin of PRES in her case. PRES has been reported in patients with normal blood pressure or hypotension. In those patients, endothelial dysfunction from, for example, the cytotoxic effects of infection (e.g., cytokine storm) is one of the considered pathophysiologic mechanisms. PRES has been reported in a young adult with COVID-19 who developed acute confusional state and transient cortical blindness. PRES should therefore be considered a potential complication of COVID-19.

D9 had extensive hazy T2WI hyperintensity of the centrum semiovale of uncertain significance. This could be the manifestation of early edematous changes due to blood-brain barrier breakdown associated with hypoxia or deep watershed infarction. Still, unspecific chronic changes related to the decedent’s metabolic disorders (hyperthyroidism and hyperaldosteronism) cannot be excluded. Such hazy white matter T2WI hyperintensity has been reported in 37% of patients with COVID-19 with neurologic symptoms admitted to the ICU, for whom a definite diagnosis was difficult to determine.

In those 4 decedents with parenchymal brain MRI abnormalities, blood-brain barrier breakdown might be the common denominator among DIC-related lesions, PRES, and centrum semiovale changes. It might be caused by endothelial dysfunction related to severe COVID-19 (i.e., severe hypoxia, DIC, cytokine storm) with or without direct SARS-CoV-2 infection of endothelial cells. Given the widespread endothelial expression of ACE2, such hypothetical endothelial infection might lead to secondary intracerebral endothelial inflammation and activation. Both cytokine storm and SARS-CoV-2 infection of endothelial cells occur in severe COVID-19, leading to a widespread endotheliitis. Of note, we did not find in our series larger ischemic or hemorrhagic strokes, which have previously been reported in COVID-19. This absence of large ischemic stroke may result from the widespread use of prophylactic or therapeutic anticoagulation in all decedents. This study therefore enlarges the clinical spectrum of possible vascular changes that can be found in patients with severe COVID-19.

Asymmetric olfactory bulbs with or without olfactory cleft obliteration were observed in 4 of 19 decedents. This may represent an MRI correlate of anosmia frequently observed in patients with SARS-CoV-2 and may support the neural retrograde hypothesis for SARS-CoV-2 CNS dissemination. Still, anosmia was not reported in any of the decedents, but it was not systematically assessed, and this study did not find any MRI signal abnormality downstream from the olfactory tract. Normal olfactory bulb and tract with no sign of nasal congestion have been reported in 1 SARS-CoV-2–infected patient with acute anosmia. Further studies are warranted to better understand the pathophysiologic mechanisms of anosmia in COVID-19.

This study failed to find specific brainstem abnormalities, bringing no support to a brain-related contribution to respiratory distress in COVID-19. Still, this does not exclude the possibility of SARS-CoV-2-related dysregulation of brainstem respiratory nuclei not observable on brain MRI.
Our study has some limitations. First, due to our strict inclusion criteria, 70% of patients with COVID-19 who died during the inclusion period at our institution were not included in the present study. Due to this high-level of exclusion, the study may not provide a complete picture of COVID-19–related brain MRI abnormalities. In particular, we included only decedents with positive detection of SARS-CoV-2 on nasopharyngeal swab specimen and a chest CT scan typical of COVID-19 to reinforce the possible associations between postmortem brain MRI findings and COVID-19 or its complications. Due to this stringent inclusion criterion, the study does not investigate the possible occurrence of brain lesions in SARS-CoV-2–infected decedents without pulmonary involvement (see, e.g., the work by Inciardi et al.30). We limited the delay between death and postmortem MRI data acquisition to <24 hours to reduce the effects of postmortem brain changes that could complicate the interpretation of brain MRI data.21,22 The strong correlations found between the delay and the evolution of brain MRI signal support this approach. We decided to exclude decedents with known focal brain lesions because they could complicate the interpretation of postmortem brain MRI data. Previously lesioned brain tissue may indeed represent an easier way for the virus to enter the brain due to, for example, blood-brain barrier breakdown. This might complicate the interpretation of the recent vs long-lasting origin of antemortem brain MRI abnormalities.

Second, several limitations are intrinsic to the virtopsy approach used in this study. Interpretations of brain MRI findings are indeed complicated by (1) postmortem brain changes (see above), (2) the global reduction of ADC that limits the use of this information for DWI data interpretation, and (3) the lack of circulation, preventing the use of both exogenous (gadolinium) and endogenous (e.g., blood oxygen level–dependent signal, arterial spin labeling, time-of-flight angiography) tracers.21,22 These intrinsic limitations forced us to adopt a systematic and descriptive approach to report the brain MRI findings and to provide prudent interpretation of those attributed to COVID-19, after reaching a multidisciplinary consensus.
Third, the design of this study was prospective in the sense that consecutive decedents fulfilling inclusion criteria during the inclusion period were all included in a prospective manner. The inclusion process therefore started at the time of death. This implied that, during the hospitalization, patients’ clinical status was not systematically investigated in light of the objectives of the study. We relied on the medical records for information about decedents’ neurologic status. With the high pressure of the COVID-19 outbreak on medical facilities and staff, stress was put on patients’ respiratory and systemic status. Thus, the neurologic status was not reported with full detail in the critically ill or end-of-life patients such as the included decedents.

Finally, because this study focused on COVID-19 non-survivors, it did not evaluate patients with COVID-19 and acute neurologic symptoms (e.g., stroke, seizures, etc.) who survived. This study therefore provides an incomplete picture of COVID-19–related brain disorders such as those previously reported and not found in this case series.\(^{11,12,14}\) Still, this study provides insights into the possible types of brain lesions that can be observed in COVID-19.

**Acknowledgment**

The authors express their most sincere gratitude to all the personnel of the morgue and of the PET-MR Unit of the CUB Hôpital Erasme. Their fantastic work and efforts made this study possible.

**Study funding**

This work was supported by a special call “COVID-19” funded by the Université libre de Bruxelles, the Fonds Erasme (Brussels, Belgium), and the Fondation ULB (Brussels, Belgium). The PET-MR project at the CUB Hôpital Erasme and Université libre de Bruxelles is financially supported by the Association Vincotte Nuclear (Brussels, Belgium). T.C. is clinical master specialist applicant to a PhD at the Fonds de la Recherche Scientifique (FRS-FNRS; Brussels, Belgium). G.N. and X.D.T. are postdoctorate clinical master specialists at the FRS-FNRS (Brussels, Belgium).

**Disclosure**

The authors report no disclosures relevant to the manuscript. Go to Neurology.org/N for full disclosures.
Publication history
A preprint of this article (without the supplementary material) has been uploaded to the MedRxiv server (https://medrxiv.org/cgi/content/short/2020.05.04.20090316v1). Received by Neurology May 8, 2020. Accepted in final form June 9, 2020.

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Appendix (continued)

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References


