

REVIEW

COVID-19, nausea, and vomitingPaul L R Andrews,*  Weigang Cai,[†]  John A Rudd[‡] and Gareth J Sanger[†] 

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Abstract

Exclusion of nausea (N) and vomiting (V) from detailed consideration as symptoms of COVID-19 is surprising as N can be an early presenting symptom. We examined the incidence of NV during infection before defining potential mechanisms. We estimate that the overall incidence of nausea (median 10.5%), although variable, is comparable with diarrhea. Poor definition of N, confusion with appetite loss, and reporting of N and/or V as a single entity may contribute to reporting variability and likely underestimation. We propose that emetic mechanisms are activated by mediators released from the intestinal epithelium by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) modulate vagal afferents projecting to the brainstem and after entry into the blood, activate the area postrema (AP) also implicated in anorexia. The receptor for spike protein of SARS-CoV-2, angiotensin 2 converting enzyme (ACE2), and transmembrane protease serine (for viral entry) is expressed in upper gastrointestinal (GI) enterocytes, ACE2 is expressed on enteroendocrine cells (EECs), and SARS-CoV-2 infects enterocytes but not EECs (studies needed with native EECs). The resultant virus-induced release of epithelial mediators due to exocytosis, inflammation, and apoptosis provides the peripheral and central emetic drives. Additionally, data from SARS-CoV-2 show an increase in plasma angiotensin II (consequent on SARS-CoV-2/ACE2 interaction), a centrally (AP) acting emetic, providing a further potential mechanism in COVID-19. Viral invasion of the dorsal brainstem is also a possibility but more likely in delayed onset symptoms. Overall, greater attention must be given to nausea as an early symptom of COVID-19 and for the insights provided into the GI effects of SARS-CoV-2.

Introduction

In addition to the prominent respiratory and pyrexial symptoms of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2),¹ the symptom complex can include symptoms associated with the digestive tract including anorexia, nausea, vomiting and diarrhea. Of these, diarrhea has received the most attention in the original literature,^{2–6} commentaries,^{7–9} and reviews.^{10–12} Surprisingly, nausea and vomiting have not been discussed in detail. This is a serious omission as nausea and vomiting can be the presenting symptoms, as exemplified by the first cases of COVID-19 in the United States¹³ and China.² Initially, the occurrence of nausea and vomiting was reported to be “uncommon” with an incidence of < 4%,⁷ but more recently, their prevalence has been described as “common.”¹¹ Superficially at least, the incidence of nausea and vomiting seems comparable with that for diarrhea (~ 5–6% in some systematic studies^{14,15}); ~ 10% in others¹⁰; some studies report incidences for diarrhea of ≥ 30%.^{3,11}

It is important to understand the incidence of nausea and vomiting during COVID-19 and the mechanisms by which this can occur. Patients with digestive tract symptoms, including nausea, vomiting, and diarrhea, may have delayed hospital admission and a worse clinical outcome than those without.¹⁶ It has been

argued³ that the value of diarrhea as a clinical symptom in the diagnosis and spread of COVID-19 may be underestimated, particularly as digestive tract symptoms may precede respiratory ones.¹¹ However, nausea is an acute onset, early warning of a problem in the upper digestive tract (primarily stomach and small intestine), which can receive air when swallowing, and is a component of the body's epithelial defenses, triggered in the “natural” world by ingested toxins.¹⁷ This means that nausea may be the first indication of gastrointestinal (GI) infection by SARS-CoV-2; interestingly, “virus” is the Latin word for “poison.” Given the current paucity of knowledge, we first address key questions about COVID-19 in relation to the prevalence of nausea and vomiting and then discuss plausible mechanisms.

How good is the epidemiological data on the incidence of nausea and vomiting in COVID-19?

Nausea is a self-reported sensation, but unless it is clearly defined for the patient, particularly in epidemiological studies and drug trials, there is a potential for confusion. Firstly, reporting of the symptom needs to be specifically requested to avoid the practice of merging the terms nausea, retching, and vomiting into a single adverse event. Secondly, the patient will base their understanding of the

word on what they have been told nausea feels like (most likely originally by a parent or a clinician) or their previous experience of nausea (most likely in motion sickness); this may also be influenced by cultural and linguistic differences. Thirdly, symptoms that can occur with nausea or independently such as lack of desire to eat, dyspepsia, and epigastric discomfort short of overt pain may or may not be reported as nausea. These problems are compounded by the lack of a validated diagnostic biomarker for nausea although elevated plasma vasopressin and gastric dysrhythmia are associated with nausea.^{18,19}

It has been proposed to use pictograms to improve digestive tract symptom assessment,²⁰ helping to minimize linguistic and translation issues—particularly important when assessing comparability of symptom reporting from a global pandemic where cultural perceptions and understanding of nausea may complicate accurate reporting.

The literature contains multiple definitions of nausea (table 1.1,¹⁸ for 30 definitions from the literature), which may be associated with different body areas (e.g. head, chest, and epigastrium).¹⁹ Here, we define nausea as “a self-reported, unpleasant sensation associated with the desire to vomit or the feeling that vomiting is imminent”.¹⁸ Although vomiting is easier to define (the forceful oral expulsion of upper digestive tract contents), it may be identified incorrectly and used interchangeably with retching (unproductive, forceful, externally visible, rhythmic contractions of thoracic, and abdominal muscles usually preceding vomiting²¹) and can be confused with intense gastroesophageal reflux. Nausea and vomiting can be reported as a single entity (nausea or vomiting,¹ nausea and/or vomiting²²) although they are a sensation and motor act respectively.

However, in reviewing the publications where data on the incidence of both nausea and vomiting have been collected, it is clear that both can be an early “acute” symptom of COVID-19. Detailed data need to be collected on the incidence of N & V at all stages of SARS-CoV-2 infection. We highlight four important issues related to the epidemiology.

1. *Nausea and vomiting need to be reported separately.* In the studies where this has been performed, the incidences are either identical (e.g. 1% vs 1%; 5% vs 5%;²³ 3.7% vs 3.7%²⁴) or higher than for vomiting (e.g. 10.1% vs 3.6%; 17.3% vs 5.0%; 26.4% vs 15.4%^{25–27}). A similar equivalence in the incidence of nausea and vomiting is seen for SARS and MERS where the overall incidences of both are higher at ~20%.¹² Although the data on COVID-19 are limited, the incidence of nausea appears to be highly variable with a range of 1–30%^{23,26} (Figure 1). Our literature analysis of 41 studies of >12,000 COVID-19 patients (including children²⁸) in which nausea and/or vomiting data was reported, showed that the median incidence of nausea was 10.5% and that of diarrhea reported in the same studies was 11%; the latter comparable with the prevalence of 10.4% reported in a recent systematic review⁵⁸ but higher than in some other studies.^{14,15} These findings support the view that nausea and diarrhea should be given equal prominence as symptoms. Notably, the median incidence of vomiting was 7% (Fig. 1), an incidence comparable with the 6.9% reported for abdominal pain in a systematic review/meta-analysis.⁵⁸ It should be noted that as far as

we are aware, separate detailed data on the incidence of nausea and vomiting in male and female patients have not been published and apart from the studies in children, there is no detailed age-stratified symptom data.

2. *What is the co-occurrence of nausea and vomiting with other digestive tract symptoms in COVID-19?* Considering the likely effects of SARS-CoV-2 on the digestive tract (discussed further), a relationship between symptoms such as nausea/vomiting and diarrhea would not be unexpected but identifying the time of onset of each postinfection is essential to assessing their relative relevance for diagnosis. Without data on individual patients, it is not possible to draw firm conclusions, but some studies have begun to report the incidence of single and groups of symptoms. For example, nausea or vomiting with diarrhea has been reported with an incidence of 4.9%²⁹ and 4.3%.²² In the 41 clinical studies analyzed above, 27 reported the incidence of nausea/vomiting and diarrhea with our analysis showing a correlation (Spearman *R*, 0.8 and 0.7). Identification of the temporal expression of symptoms and their clustering will be essential for classification of the ways in which SARS-CoV-2 infection can present, and to quickly recognize evolving patterns of presentation, as this may be a reflection of viral load and its relative impact on the respiratory and digestive tracts, and subsequently the brain (see further for the discussion). One study noted that patients with nausea and vomiting, and diarrhea were more likely to have fever, than those with either digestive symptom alone.³⁰ Finally, it is recognized that type II diabetes is a risk factor for COVID-19.⁵⁹ The frequent occurrence of gastroparesis in diabetic patients⁶⁰ may make this group either more sensitive to the nausea and vomiting during SARS-CoV-2 infection or result in more intense symptoms.

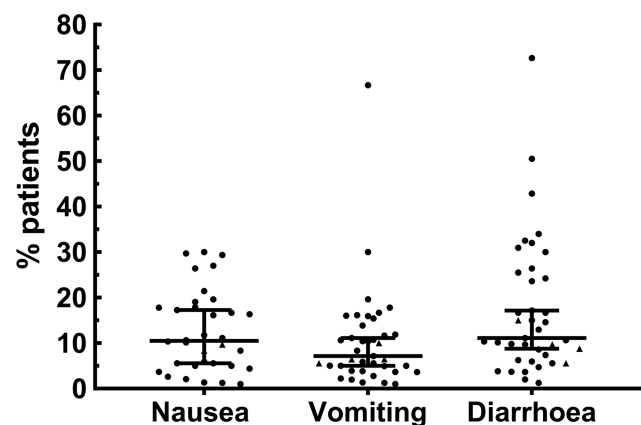


Figure 1 The incidence of nausea and/or vomiting and diarrhea from 41 clinical studies^{1,2,4,5,16,22–57}: nausea, *n* = 34; vomiting, *n* = 39; diarrhea, *n* = 39. Values for individual studies are shown together with the median and 95% confidence intervals. No distinction was made between nausea and vomiting in 10 studies, so the same incidence was used in both categories. The total number of patients in the studies was 12 239. Five studies (data indicated by triangles) reported only data on children (1.5 months to 17 years).^{28,34,37,38,51}

3. *What is the severity of the nausea?* To date, the published studies have only reported on the presence or not of nausea and vomiting, with no descriptions of their severity, comparable with those used routinely to assess these symptoms as side-effects of anticancer chemotherapy.⁶¹ A study of almost 2000 patients reported that GI symptoms (predominantly diarrhea, nausea, vomiting, and abdominal pain) were “judged to be mild” in 74% of patients,³¹ which could imply it was more severe in the remaining 26%. Additionally, there is a paucity of data on the temporal pattern of nausea and vomiting during the course of the disease. One publication commented that digestive symptoms (including vomiting but not nausea) became more pronounced as the severity of disease increased.¹⁶ In another, the prevalence of nausea or vomiting was twice as high in hospitalized patients (not intensive care unit) compared with the emergency department (10% [6.2–15.8] vs 22.6% [19.5–26.1]) but interestingly reduced to 10.2% (6.9–14.7%) in patients in intensive care.³² A recent commentary on the research priorities in the digestive manifestations of COVID-19⁶² called for “a more rigorous and systematic assessment of the prevalence, spectrum and severity of digestive manifestations”. We agree but strongly argue that nausea should be included as part of the symptom cluster. Similarly, the utility of mobile technology for collecting real-time data on symptoms of COVID-19 (see further) has been demonstrated,^{63,64} but the symptom check list included in the supporting information⁶³ included diarrhea, abdominal pain and skipping meals, not nausea or vomiting. Such mobile technology is ideally suited to obtain data on the presence and intensity of nausea with a high temporal resolution and to investigate changing patterns of symptom expression.
4. *The relationship between nausea and appetite.* A few studies report lack/loss of appetite or poor/low appetite, with an incidence apparently higher than that of nausea (23.2%, 49.5%, and 40%).^{16,22,30} Of these studies, some^{16,30} did not report nausea but others²² reported “nausea and/or vomiting” with an incidence of 12% but the percentage of patients with either nausea or vomiting or both was not reported. While reduced appetite is a common symptom of infection, it can also be secondary to nausea as indicated by a preclinical study of the cytokine growth differentiation factor 15⁶⁵ demonstrating anorexia by induction of nausea and/or engaging with emetic mechanisms; this is also the case in cancer chemotherapy.⁶¹ The incidence of anorexia in COVID-19 patients in intensive care units is reported to be ~2× that of patients who were not.³³ As described above, it is likely that some patients will report loss of appetite when in reality, they have nausea, emphasizing the need for clarity and consistency of definitions when collecting data on nausea (as proposed for diarrhoea³). The recent study of real-time tracking of self-reported symptoms⁶³ identified “skipped meals” as the symptom with the second highest odds ratio of SARS-CoV-2 infection after loss of smell; nausea as a potential underlying cause of skipping meals should be investigated further. Although children become infected with COVID-19, they appear to be relatively asymptomatic in relation to adults, but there are reports of vomiting.^{28,34} However, young children may not be capable

of verbalizing nausea and food refusal in children has been argued to be an indicator of nausea.⁶⁶

In summary, more attention should be given to recognizing nausea, which as we highlighted above must be clearly defined to avoid confusion, as a potential early symptom of COVID-19 particularly when collecting epidemiological data. It is plausible that infected subjects who do not have the classical symptoms (fever and persistent cough and loss of taste/smell) may have initially experienced mild, transient nausea, and dismissed it. Accordingly, asymptomatic but SARS-CoV-2 positive individuals, many of whom are likely to be in the younger age groups, need to be investigated to determine if they have recently had an episode of nausea, which was dismissed or ascribed to “food poisoning.” Thus, because nausea is an early alerting symptom of a challenge (toxic food and chemicals, bacterial toxin, and virus) to the upper digestive tract, this may be an overlooked initial symptom of SARS-CoV-2 infection. Such studies are also important because if nausea is an early symptom of COVID-19, the vomiting that may follow would lead to ejection of aerosolized, viral contaminated vomit, as occurs in patients infected with norovirus.⁶⁷

Finally, it is important to recognize that subjects with nausea (primarily studied in motion sickness) may have a reduction in cutaneous blood flow to the forehead manifest as “pallor”⁶⁸ associated with “cold sweating.”¹⁸ As the forehead is a common site at which temperature is taken, nausea induced by SARS-CoV-2 could be a factor confounding detection of raised core temperature by a single time point measurement of forehead temperature alone.

How could SARS-CoV-2 induce nausea and vomiting?

There are no formal studies at present so we have reviewed the effects of SARS-CoV-2 (and other coronaviruses) on the digestive tract in the light of knowledge of the established mechanisms of nausea and vomiting; this is the same approach that has been used to understand the pathogenesis of other symptoms (e.g. diarrhoea¹⁰).

SARS-CoV-2 can readily access the digestive tract by several routes (Fig. 2). We hypothesize that SARS-CoV-2 would induce acute (first few days postinfection) nausea and vomiting by causing the release of key hormones from the enteroendocrine cells (EECs) in the mucosa of the upper GI tract or after gaining direct entry into the blood, by acting directly within the brainstem.

1. Pathways of nausea and vomiting

Induction of nausea and vomiting from the digestive tract occurs via two main mechanisms^{18,69}:

- a) Activation of abdominal vagal afferents, either mechanoreceptors located in the muscle layers or afferents terminating in close apposition to the mucosa activated by neuroactive agents (e.g. 5-hydroxytryptamine [5-HT], substance P [SP], and cholecystokinin [CCK]) released locally from the EECs to act at receptors expressed by afferent nerve terminals. Among the EEC cells, the enterochromaffin (EC) cells in the duodenum and jejunum contain most of the 5-HT present in the body of humans and other mammals, which when released by chemical (e.g. cancer chemotherapy and oral emetics) and pathological (e.g. inflammation) stimuli, has a particularly prominent role in induction of emesis via activating abdominal vagal afferent nerve terminals⁷⁰ (Fig. 2)

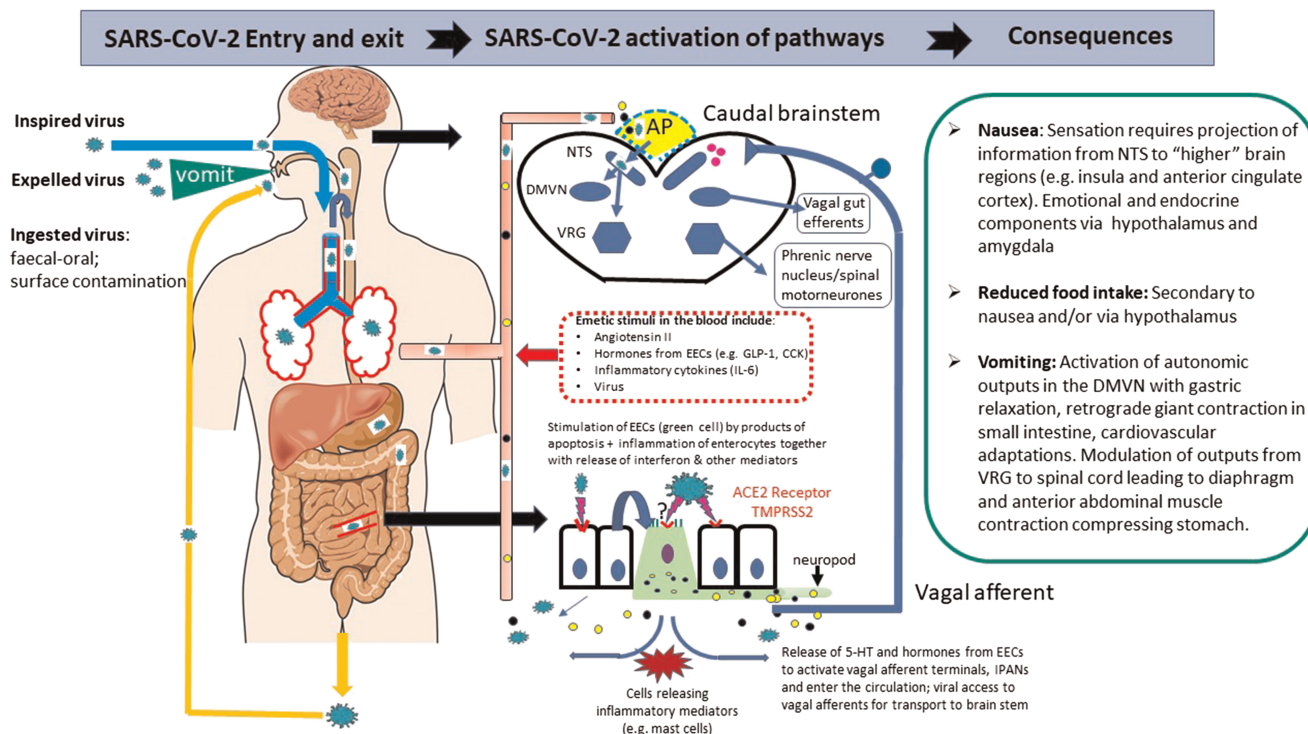


Figure 2 Diagram summarizing the potential mechanisms by which SARS-CoV-2 could induce nausea and vomiting. The left-hand panel shows the routes by which virus can enter the body to access the airways and digestive tract. Air can enter the digestive tract during swallowing. The presence of high levels of angiotensin converting enzyme 2 receptor in the airways and digestive tract is indicated by red lines. The middle panel shows the potential mechanisms (based on evidence discussed in the text) for the interaction of the virus with the digestive tract epithelium leading to release of neuroactive agents from enteroendocrine cells and inflammatory mediations which act either by stimulating/sensitizing abdominal vagal afferent terminals and/or act on the area postrema in the dorsal medulla where the blood brain and cerebrospinal fluid barriers are relatively permeable. In addition, angiotensin II levels may increase and have central actions together with virus, which may enter the circulation from damaged lungs and digestive tract epithelia. The right hand panel summarizes the consequences of vagal afferent and area postrema activation to induce nausea and vomiting by projection of information to higher brain regions (nausea and anorexia) and vomiting by motor pathways in the ventral brainstem and spinal cord. 5-HT, 5-hydroxytryptamine; ACE 2, angiotensin converting enzyme receptor 2; AP, area postrema; CCK, cholecystokinin; DMVN, dorsal motor vagal nucleus; EEC, enteroendocrine cells in the digestive tract; GLP-1, glucagon-like peptide-1; IL-6, interleukin-6; NTS, nucleus tractus solitarius; TMPRSS2, transmembrane protease serine 2; VRG, ventral respiratory group of neurones. [Color figure can be viewed at wileyonlinelibrary.com]

b) Release of neuroactive agents into the hepatic portal vein and subsequently the systemic circulation to act on the area postrema, a circumventricular organ located at the caudal extremity of the fourth ventricle where the blood–brain and cerebrospinal fluid–brain barriers are relatively permeable (Fig. 2). These agents may originate from the EECs (e.g. glucagon like-1 peptide and CCK) but also as cytokines from inflamed or damaged GI epithelia.

Both the vagal afferents and area postrema efferents activate the nucleus tractus solitarius (NTS), subjacent to the area postrema in the brainstem, which in turn activates the visceral and somatic motor pathways for vomiting elsewhere within the brain stem and also sends projections to higher brain regions generating the sensation of nausea^{18,19} (Fig. 2). The release of neuroactive agents from EECs is implicated in both acute, early onset nausea and vomiting when the release is by Ca⁺⁺-mediated exocytotic mechanisms and in more protracted responses when inflammatory-like responses and cell damage are implicated.⁶¹ The likelihood that nausea

requires less intense activation of the above pathways than does vomiting means that greater emphasis should be given to nausea rather than vomiting as an initial symptom of digestive tract infection by SARS-CoV-2.

2. ACE2 in the digestive tract, viral entry, nausea, and vomiting by peripheral actions of SARS-CoV-2

Release of neuroactive agents from the digestive tract acting locally (vagal afferents) and systemically (area postrema) has been implicated in nausea and vomiting induced by toxins ingested with food, therapeutic drugs, and bacteria.^{69,71–73} We know of only one study investigating a direct link between viral infection and the mechanisms of nausea and vomiting. The virus commonly responsible for infantile gastroenteritis (vomiting and diarrhea are symptoms), rotavirus, has been shown to infect and replicate in EC cells (from midgut carcinoid tumor and GOT1 cells), increasing intracellular [Ca⁺⁺] and secretion of 5-HT from the EC cells. Notably, 5-HT secretion increased by 6 h after infection.⁷⁴ Using supernatant from viral infected MA104 cells, secretion of 5-HT from

GOT1 and primary EC tumor cells occurred within 60 min demonstrating that it was most likely due to viral protein(s) from infected cells rather than due to cell replication. Cell $[Ca^{++}]$ was elevated and 5-HT secreted in response to the enterotoxigenic glycoprotein NSP4 previously shown to be secreted from human intestinal cells infected with rotavirus. In mice infected with rotavirus, there was colocalization between viral proteins and 5-HT-containing EC cells, and Fos immunohistochemistry showed intense activation of the NTS suggestive of vagal afferent activation (see above). The same laboratory also demonstrated an ability of adenovirus 41, a cause of acute gastroenteritis with diarrhea and vomiting, to increase 5-HT release from human EC cells.⁷⁵

Finally, it is worth noting that rotavirus infected infant mice displayed diarrhea, which was treated with the 5-HT₃ receptor antagonist ondansetron, which also improved weight gain and interestingly, attenuated viral shedding.⁷⁶ The latter may be of clinical value as ondansetron and other 5-HT₃ antagonists are widely available for treatment of acute cancer chemotherapy induced nausea and vomiting.⁶⁹

So, what of SARS-CoV-2? The angiotensin converting enzyme II (ACE2) protein is the receptor for the spike protein of SARS-CoV-2, providing a key component of the entry route for the virus into cells as is the case for SARS and MERS.^{77,78} Cellular serine protease transmembrane protease serine-2 (TMPRSS2) is required together with ACE2 for viral entry.^{79,80} Early human and rodent studies identified ACE2 in the digestive tract and particularly not only the ileum but also other regions of the small intestine.^{77,81,82} More recent studies have confirmed the presence of ACE2 in human small intestine, including the duodenum, and some have shown expression of TMPRSS2.^{3,83–85} In particular, the studies have identified ACE2 and TMPRSS2 in “absorptive enterocytes” and more generally “epithelial cells.”^{6,84} Expression of ACE2 mRNA has also been shown in the relatively sparse EECs within the enterocytes of human stomach and ileum,⁸⁶ although a transcriptomic and proteomic study of human and mouse intestinal EECs did not highlight ACE2 as among the most highly expressed receptors in either species.⁸⁷ These data find some concordance with a study of mouse small intestine appearing to indicate that although the ACE2 receptor was highly expressed in enterocytes, there was no expression in “endocrine” cells (although the viral receptor HCoV-229E (ANPEP) was present in this population).³ However, mice lack the ability to vomit and other differences between human and rodent digestive tract suggest caution should be exercised in translating from one species to another.^{88,89} A recent study using human small intestinal organoids cultured from adult stem cells in a variety of different media showed infection of enterocytes by SARS-CoV and SARS-CoV-2.⁸³ Notably, however, EECs stained with an antibody for Chromogranin A⁺ (CGA) were never infected; CGA is expressed in all EEC cells, particularly the monoamine containing subpopulation.⁹⁰ These data contrast with the expression of ACE2 by EECs within human stomach and ileum and with an ability of enteroviruses to infect EECs.^{86,91} They suggest that the SARS viruses are unlikely to enter EECs to cause GI disturbances by directly stimulating the release of hormones from these cells. However, key experiments remain. For example, might the EECs of the organoid differ in some way from the native EEC, preventing viral entry? Nevertheless, if confirmed, it seems that the induction of enterocyte apoptosis and the rapidly increasing inflammatory and immune cell *milieu* surrounding the

EECs (measured as increased mRNA for cytokines and interferon stimulated genes)⁸³ will secondarily induce the release of hormones from the embedded EECs (Worthington *et al.*⁹² for mechanisms).

In addition, gut microbiota have been implicated in modulation of gut inflammation⁹³ but as yet, it is unclear how changes in gut microbiota during SARS-CoV-2 infection may contribute to the generation of symptoms. For example, a pilot study of the fecal microbiome in hospitalized patients showed an association between changes in the microbiota, fecal levels of SARS-CoV-2 and the severity of respiratory symptoms.⁹⁴ However, only one of the patients reported GI symptoms (diarrhea before admission) and none during admission. Microbiota were included in a model of SARS-CoV-2-induced diarrhoea.¹⁰ This is of particular relevance as ACE2 has been implicated in the regulation of the gut microbiome and susceptibility to colitis.⁹⁵

Finally, we should not overlook the impact of viral-induced digestive tract damage, loss of integrity, and release of an “inflammatory soup” on infection, resulting in sensitization of vagal afferents via receptors for diverse agents including cytokines, prostaglandins, amines, and purines. There is limited mechanistic data on cytokine-induced emesis. One study in the cat showed that intramuscular injections of IL-2-induced emesis after the area postrema was ablated, providing indirect evidence for a peripheral action,⁹⁶ but in rat area postrema cells IL-1 β increased Ca^{++} influx.⁹⁷ A more recent study of the cytokine growth differentiation factor 15 favors a central action.⁶⁵ Activation of prostanoid receptors on vagal nerve terminals represents an additional pathway shown to induce vomiting.⁹⁸

An observation of potential therapeutic relevance comes from a study with the NK₁ receptor antagonist aprepitant in patients with HIV.⁹⁹ NK₁ antagonists are used to treat cancer chemotherapy-induced emesis by both central and peripheral actions with interactions between the 5-HT₃ and the NK₁ receptor.^{61,69} In HIV patients, aprepitant administered over 2 weeks reduced plasma concentrations of cytokines (G-CSF, IL-6, IL-8, and TNF α) with *in vitro* and preclinical studies in nonhuman primates providing additional evidence for antiretroviral and anti-inflammatory effects. Overall, this combination of actions of aprepitant together with the anti-emetic activity⁶⁹ may make the drug worthy of investigation in COVID-19 patients particularly as aerosolized vomit is a viral vector.⁶⁷

Further studies are required to investigate the presence of ACE2 and TMPRSS2 in the various subpopulations of EEC cells (particularly EC cells).^{100,101} Additionally, it should be noted that many of the GI hormones capable of inducing nausea and vomiting can also reduce appetite and food intake (e.g. CCK and glucagon like-1 peptide) by acting on the area postrema and hypothalamic circumventricular organs, so may also relate to the appetite suppression reported on admission in a few studies, but at a relatively high incidence.^{16,30}

Finally, although attention has focused on the intestinal epithelium, the early human studies reported the presence of ACE2 in the smooth muscle cells of the muscularis mucosa and muscularis propria and the vascular smooth muscle and endothelium in the stomach, small intestine, and colon.⁷⁷ This does not necessarily mean that SARS-CoV-2 gains entry into the muscle cells as additional binding to a chemokine coreceptor may be needed. Nevertheless, further studies are needed to assess whether actions of

SARS-CoV-2 on GI smooth muscle could be involved in the pathophysiology of GI symptoms. The presence of ACE2 (and TMPRSS2) in these locations requires study using current molecular techniques and functional studies using *in vitro* pharmacological models¹⁰² to assess whether actions of SARS-CoV-2 on GI smooth muscle could be involved in symptom generation. For example, changes in GI motility may be involved in COVID-19 diarrhea, described more as an increase in stool frequency rather than liquidity¹⁶ so may not be (completely) of epithelial origin.

3. ACE2 in the gut-brain axis, viral entry, nausea, and vomiting by central actions of SARS-CoV-2

As the COVID-19 pandemic has progressed, there has been increasing awareness of the central nervous system as a target, with some authors including nausea, vomiting, and headache as “neurologic signs.”¹⁰³ There is preclinical data showing ACE2 expression in the brain notably in the NTS and the area postrema¹⁰⁴ and more limited evidence for the presence of ACE2 in the brain.^{105,106} The view that SARS-CoV-2 can access the brain via the blood (the circumventricular organs where the blood–brain barrier is relatively permeable being assumed to be particularly vulnerable) or by neuroinvasion via the vagal afferents (which supply both the lungs and the digestive tract) is growing in strength^{105,107,108}; SARS-CoV is neuroinvasive and has been detected in human brain.¹⁰⁹ While the vagal transport of SARS-CoV-2 is unlikely to account for acute onset of nausea and vomiting, access of the virus to the NTS and more directly via the area postrema is a potential mechanism by which later nausea and vomiting may be induced and a pathway by which regulation of breathing and blood pressure can be compromised. Vomiting is a key symptom of porcine hemagglutinating encephalomyelitis coronavirus, which can access the brain stem, but it must be noted that it has not been determined if this effect is due to a central (e.g. NTS) or peripheral effect.¹¹⁰

Viral damage to the dorsal brain stem, which has a major role in regulation of digestive tract function, could contribute to the development of postviral digestive tract symptoms (e.g. gastroparesis), which may emerge during recovery.

Are there lessons to be learnt for the digestive tract from the interactions between SARS-CoV and ACE2 in the respiratory system? The interactions between SARS-CoV, ACE2, and the respiratory epithelium in the pathogenesis of acute respiratory distress syndrome (ARDS)/acute lung injury, has a number of lessons for understanding the effects of SARS-CoV-2 on the digestive tract (for reviews see.^{111,112} The key observations in the airways, mostly from mice studies are (i) ACE2 is protective against acute lung injury by its conversion of angiotensin II (AII) to angiotensin (1–7) and angiotensin I to angiotensin (1–9), with severe ARDS in *Ace2* KOs being improved by administration of an angiotensin 1 receptor (AT₁) antagonist; (ii) Once initiated the severity of ARDS is influenced by ACE2 and other components of the renin-angiotensin system (RAS); and (iii) *Ace2* KOs are resistant to SARS-CoV; in wild-type mice, SARS-CoV downregulates ACE2 in the lungs with consequent elevation of AII levels, also reported in patients with ARDS.¹¹³ These studies give insights into viral effects on the lungs, but as

the studies were in mice which do not vomit,^{74,75} the effect of *ACE2* KO on vomiting is unknown.

The presence of ACE2 and SARS-CoV-2 in digestive tract epithelium and the superficial similarities between airways and the digestive tract, including the presence of EECs linked to the vagus,¹¹⁴ enables speculation on the effects of ACE2 and SARS-CoV-2 interactions in the digestive tract in relation to nausea and vomiting.

- a) SARS-CoV-2 infection in the digestive tract causes inflammatory damage, with consequences for induction of nausea and vomiting, discussed above. The inflammatory effects are local and systemic. In human ARDS plasma IL-6, increases and interestingly treatment with recombinant human ACE2 showed a trend to decrease IL-6,¹¹³ an effect if repeated in COVID-19 patients may be beneficial to the digestive tract as well as any effects of cytokines on nausea, vomiting, and food intake.
- b) Interaction between SARS-CoV-2 and ACE2 in both the respiratory and digestive tracts will elevate plasma AII concentrations; in patients, the average concentration of plasma AII is ~ 3× higher than in healthy subjects with an average concentration of ~ 300 pg/mL.³⁵ In preclinical studies, AII has been shown to induce emesis when given intravenously and into the cerebral ventricles^{115,116} and to increase neuronal activity in the area postrema^{117–119} with AT₁ receptors implicated. This provides a plausible mechanism by which elevated plasma AII in COVID-19 could induce nausea and vomiting, providing an additional trigger to those from the GI tract (Fig. 2). There is also preclinical evidence that systemic AII can have central effects to suppress respiration, which are not dependent upon the integrity of the AP.¹²⁰ Circulating AII can also affect gastric and intestinal motility and could contribute the genesis of nausea (and diarrhea). The EC₅₀ for contraction of the human small intestine *in vitro* was 1.5×10^{-8} M,¹²¹ a concentration less than the average of ~ 300 pg/mL reported in COVID-19 patients,³⁵ which equates to $\sim 3 \times 10^{-7}$ M, and an earlier study reported contraction of gastric muscle with a threshold concentration of AII of 10^{-9} M.¹²²
- c) Angiotensin 1 and 2 receptors are found throughout the digestive tract and modulate smooth muscle activity as well as epithelial secretion and absorption.¹²³ Actions of elevated AII could influence any of these functions with motility changes most likely to be implicated in nausea and abdominal pain (these could also involve local vasoconstriction) and both motility and epithelial transport in pathogenesis of diarrhea. Understanding the digestive tract effects of SARS-CoV-2 will require a detailed understanding of the RAS in the human digestive tract.

Possible role of medications and coexisting morbidities in nausea and vomiting in COVID-19 patients

The above sections have focused on the direct effects of SARS-CoV-2 on the digestive tract as the most likely cause of nausea and vomiting. However, two other potential causes need

to be recognized briefly for completeness. Firstly, prior to presentation at hospital, patients may be prescribed medications which may have nausea and vomiting as side effects. Of particular relevance are ACE inhibitors for treatment of hypertension (e.g. lisinopril) and antidiabetic drugs (e.g. metformin and liraglutide). Hospitalized patients being treated for COVID-19 may be treated with cytokine modulators, antibiotics, and antiviral agents, which may have nausea as a side-effect and should be considered when assessing the incidence of nausea. One publication reported that the incidence of nausea and vomiting did not differ whether patients did or did not receive either antibiotics or antiviral treatments.⁴ Secondly, nausea and vomiting may be secondary to damage outside the upper digestive tract. Although the lungs and airways might seem an obvious site given particularly considering their vagal afferent innervation, there is no evidence that nausea or vomiting can be induced from the airways. However, there is preclinical evidence that activation of respiratory system vagal afferents can block induction of vomiting.¹²⁴ Renal failure is also a symptom of severe COVID-19 and in other settings nausea and vomiting can be symptoms with the mechanism not defined, although it is unlikely to be due to renal afferents.¹²⁵ The liver is also damaged in severe COVID-19, and although it has a vagal afferent supply projecting to the brainstem,¹²⁶ there is no evidence implicating the afferents directly in nausea and vomiting.¹²⁷ It is likely that nausea and vomiting associated with hepatic failure is due to loss of the detoxifying function of the liver. Cardiac failure also occurs in severe cases of COVID-19. Ventricular cardiac afferents in the cat have been shown to be capable of inducing vomiting and are thought to be responsible for the nausea and vomiting associated with a myocardial infarct¹²⁸ so could provide a pathway for their induction in cardiac failure.

Therapeutic opportunities

Optimal anti-emetic treatment relies on an understanding of the pharmacology of the pathways involved. On the basis of our hypothesized mechanisms described above, we would expect the combination of a 5-hydroxytryptamine₃ (e.g. ondansetron and palonosetron) and a neurokinin₁ receptor antagonist (e.g. aprepitant) to be effective as they would block at the peripheral site of activation/sensitization of vagal afferents and central sites in the dorsal brain stem (NTS/area postrema).⁶⁹ It is interesting to note that the synthetic corticosteroid dexamethasone is being used to treat the inflammatory actions effects of SARS-CoV-2, but the use of dexamethasone as an anti-emetic may not be widely known outside the oncology community. In the treatment of the intense nausea and vomiting associated with some anti-cancer chemotherapy regimens, dexamethasone has been used for 40 years¹²⁹ in conjunction with more classical anti-emetics (e.g. metoclopramide, ondansetron, and aprepitant)^{61,69} where it enhances their efficacy with a particular improvement in nausea (see other studies^{61,69,130} for references). The anti-emetic effect of dexamethasone has been ascribed to its anti-inflammatory effect on the intestinal epithelium as its efficacy is greater in the delayed phase of chemotherapy-induced emesis where inflammatory damage releasing systemic mediators acting on the area postrema has been implicated.⁶⁹ However, there has been little formal research on the mechanism(s) underlying the

anti-emetic effects of dexamethasone, but such studies may provide additional insights into its effects on the digestive tract in COVID-19.

The provision of anti-emetics to patients presenting with nausea will help alleviate this unpleasant symptom, reduce the probability that the patient will vomit, but if vomiting is present they will reduce it and the associated potential viral spread by aerosolization in vomit.

Concluding comments

This review has highlighted nausea and vomiting as acute symptoms of COVID-19 with a focus on incidence of occurrence (Fig. 1) and on mechanisms (Fig. 2). The literature we reviewed shows the incidence of nausea ranges from 1% to 30% but with a median incidence of 10.5%, similar to that of diarrhea but less than that of vomiting (7%). A systematic review and meta-analysis of the incidence of nausea and vomiting as separate symptoms in COVID-19 is needed. However, many studies do not report nausea, and although more studies report vomiting, it is not clear if this represents difference in data collection methodology. We argue that there should be a greater focus on collecting data on nausea as it may be a more sensitive early marker of digestive tract infection (i.e. prior to fever and cough and probably preceding diarrhea) in addition to representing a neglected symptom with a particular potential to be overlooked in children. The absence of diagnostic biomarkers for nausea is an additional challenge.¹³⁰ A possible mechanism is discussed whereby nausea and vomiting can be initiated by SARS-CoV-2 within the blood acting directly on brainstem structures. We also propose that the EECs may be a target for SARS-CoV-2 responsible (in part) for the pathogenesis of nausea and vomiting; these proposals require further testing using available techniques and may give insights into supportive treatments (e.g. 5-HT₃ and NK₁ receptor antagonists). Further studies of mechanisms are needed and in addition to *in vitro* studies of EEC cell lines these may include studies in the ferret, which is sensitive to SARS-CoV-2¹³¹ and which is an established animal model for the study of emetic mechanisms and anti-emetic pharmacology.¹³² The incidence of nausea/vomiting and diarrhea in COVID-19 is lower than in SARS, but the SARS-CoV-2 protein spike is 10–20× more potent at binding ACE2 compared with SARS,¹³³ so a comparison of the effects on different cell populations in the GI epithelium may provide an insight into the reasons. The brain stem as a site at which mediators from the digestive tract induce nausea and vomiting and loss of appetite is discussed. Finally, as the majority of patients who develop COVID-19 recover, the potential development of postinfection functional bowel disorders¹³⁴ needs to be monitored, where nausea and vomiting may also be symptoms. Thus, the recognition of nausea and vomiting as key symptoms should lead to greater understanding of how SARS-CoV-2 attacks the GI tract and brainstem so preventative measures can treat the symptoms and limit the spread of the virus by vomiting.

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References

- 1 Guan WJ, Ni ZY, Hu Y *et al.* Clinical characteristics of coronavirus disease 2019 in China. *N. Engl. J. Med.* 2020; **382**: 1708–20.
- 2 Jin X, Lian JS, Hu JH *et al.* Epidemiological, clinical and virological characteristics of 74 cases of coronavirus-infected disease 2019 (COVID-19) with gastrointestinal symptoms. *Gut* 2020; **69**: 1002–9.
- 3 Liang W, Feng Z, Rao S *et al.* Diarrhoea may be underestimated: a missing link in 2019 novel coronavirus. *Gut* 2020; **69**: 1141–3.
- 4 Lin L, Jiang X, Zhang Z *et al.* Gastrointestinal symptoms of 95 cases with SARS-CoV-2 infection. *Gut* 2020; **69**: 997–1001.
- 5 Song F, Shi N, Shan F *et al.* Emerging 2019 novel coronavirus (2019-nCoV) pneumonia. *Radiology* 2020; **295**: 210–7.
- 6 Xiao F, Tang M, Zheng X, Liu Y, Li X, Shan H. Evidence for gastrointestinal infection of SARS-CoV-2. *Gastroenterology* 2020; **158**: 1831–3 e3.
- 7 Gao QY, Chen YX, Fang JY. 2019 Novel coronavirus infection and gastrointestinal tract. *J. Dig. Dis.* 2020; **21**: 125–6.
- 8 Gu J, Han B, Wang J. COVID-19: gastrointestinal manifestations and potential fecal-oral transmission. *Gastroenterology* 2020; **158**: 1518–9.
- 9 Ng SC, Tilg H. COVID-19 and the gastrointestinal tract: more than meets the eye. *Gut* 2020; **69**: 973–4.
- 10 D'Amico F, Baumgart DC, Danese S, Peyrin-Biroulet L. Diarrhea during COVID-19 infection: pathogenesis, epidemiology, prevention and management. *Clin. Gastroenterol. Hepatol.* 2020; **18**: 1663–72.
- 11 Hajifathalian K, Mahadev S, Schwartz RE *et al.* SARS-COV-2 infection (coronavirus disease 2019) for the gastrointestinal consultant. *World J. Gastroenterol.* 2020; **26**: 1546–53.
- 12 Wong SH, Lui RN, Sung JJ. Covid-19 and the digestive system. *J. Gastroenterol. Hepatol.* 2020; **35**: 744–8.
- 13 Holshue ML, DeBolt C, Lindquist S *et al.* First case of 2019 novel coronavirus in the United States. *N. Engl. J. Med.* 2020; **382**: 929–36.
- 14 Rodriguez-Morales AJ, Cardona-Ospina JA, Gutierrez-Ocampo E *et al.* Clinical, laboratory and imaging features of COVID-19: a systematic review and meta-analysis. *Travel Med. Infect. Dis.* 2020; **34**: 101623.
- 15 Li LQ, Huang T, Wang YQ *et al.* COVID-19 patients' clinical characteristics, discharge rate, and fatality rate of meta-analysis. *J. Med. Virol.* 2020. <https://doi.org/10.1002/jmv25757>
- 16 Pan L, Mu M, Yang P *et al.* Clinical characteristics of COVID-19 patients with digestive symptoms in Hubei, China: a descriptive, cross-sectional, multicenter study. *Am. J. Gastroenterol.* 2020; **115**: 766–73.
- 17 Davis C, Harding R, Leslie R, Andrews P. The organisation of vomiting as a protective reflex. In: *Nausea and Vomiting: Mechanisms and Treatment*. Springer, 1986; 65–75.
- 18 Stern RM, Koch KL, Andrews P. *Nausea: Mechanisms and Management*. New York: Oxford University Press, 2011.
- 19 Koch KL, Hasler WL. *Nausea and Vomiting: Diagnosis and Treatment*. Springer, 2016.
- 20 Tack J, Carbone F, Holvoet L, Vanheel H, Vanuysel T, Vandenberghe A. The use of pictograms improves symptom evaluation by patients with functional dyspepsia. *Aliment. Pharmacol. Ther.* 2014; **40**: 523–30.
- 21 Andrews P, Bhandari P, Garland S *et al.* Does retching have a function. An experimental study in the ferret. *Pharmacodyn. Therap.* 1990; **9**: 135–52.
- 22 Cholankeril G, Podboy A, Aivaliotis VI *et al.* High prevalence of concurrent gastrointestinal manifestations in patients with SARS-CoV-2: early experience from California. *Gastroenterology* 2020; **159**: 775–7.
- 23 Chen N, Zhou M, Dong X *et al.* Epidemiological and clinical characteristics of 99 cases of 2019 novel coronavirus pneumonia in Wuhan, China: a descriptive study. *Lancet* 2020; **395**: 507–13.
- 24 Zhou F, Yu T, Du R *et al.* Clinical course and risk factors for mortality of adult inpatients with COVID-19 in Wuhan, China: a retrospective cohort study. *Lancet* 2020; **395**: 1054–62.
- 25 Wang D, Hu B, Hu C *et al.* Clinical characteristics of 138 hospitalized patients with 2019 novel coronavirus-infected pneumonia in Wuhan, China. *JAMA* 2020; **323**: 1061–9.
- 26 Zhang JJ, Dong X, Cao YY *et al.* Clinical characteristics of 140 patients infected with SARS-CoV-2 in Wuhan, China. *Allergy* 2020; **75**: 1730–41.
- 27 Reddm WD, Zhou JC, Hathorn KE *et al.* Prevalence and characteristics of gastrointestinal symptoms in patients with severe acute respiratory syndrome coronavirus 2 infection in the United States: a multicenter cohort study. *Gastroenterology* 2020 in press.
- 28 Lu X, Zhang L, Du H *et al.* SARS-CoV-2 infection in children. *N. Engl. J. Med.* 2020; **382**: 1663–5.
- 29 Cholankeril G, Podboy A, Aivaliotis V *et al.* Association of digestive symptoms and hospitalization in patients with SARS-CoV-2 infection. *medRxiv* 2020.
- 30 Han C, Duan C, Zhang S *et al.* Digestive symptoms in COVID-19 patients with mild disease severity: clinical presentation, stool viral RNA testing, and outcomes. *Am. J. Gastroenterol.* 2020; **115**: 916–23.
- 31 Elmunzer BJ, Spitzer RL, Foster LD *et al.* Digestive manifestations in patients hospitalized with COVID-19. *medRxiv* 2020.
- 32 Argenziano MG, Bruce SL, Slater CL *et al.* Characterization and clinical course of 1000 patients with coronavirus disease 2019 in New York: retrospective case series. *BMJ* 2020; **369**: m1996.
- 33 Wang F, Yang Y, Dong K *et al.* Clinical characteristics of 28 patients with diabetes and covid-19 in Wuhan, China. *Endocr. Pract.* 2020; **26**: 668–74.
- 34 Xia W, Shao J, Guo Y, Peng X, Li Z, Hu D. Clinical and CT features in pediatric patients with COVID-19 infection: different points from adults. *Pediatr. Pulmonol.* 2020; **55**: 1169–74.
- 35 Liu Y, Yang Y, Zhang C *et al.* Clinical and biochemical indexes from 2019-nCoV infected patients linked to viral loads and lung injury. *Sci. China Life Sci.* 2020; **63**: 364–74.
- 36 Zhang L, Bai T, Jin Y *et al.* Digestive involvement of the coronavirus disease 2019: need attention on the 'gut-type' in the novel coronaviral infection. *Lancet Gastroenterol. Hepatol.* 2020 April 6.
- 37 Qiu H, Wu J, Hong L, Luo Y, Song Q, Chen D. Clinical and epidemiological features of 36 children with coronavirus disease 2019 (COVID-19) in Zhejiang, China: an observational cohort study. *Lancet Infect. Dis.* 2020; **20**: 689–96.
- 38 Wang D, Ju XL, Xie F *et al.* Clinical analysis of 31 cases of 2019 novel coronavirus infection in children from six provinces (autonomous region) of northern China. *Zhonghua Er Ke Za Zhi* 2020; **58**: 269–74.
- 39 Shi H, Han X, Jiang N *et al.* Radiological findings from 81 patients with COVID-19 pneumonia in Wuhan, China: a descriptive study. *Lancet Infect. Dis.* 2020; **20**: 425–34.
- 40 Fang D, Ma J, Guan J, Wang M, Song Y, Tian D. Manifestations of digestive system in hospitalized patients with novel coronavirus pneumonia in Wuhan, China: a single-center, descriptive study. *Chin. J. Dig.* 2020; **40**.
- 41 Yang X, Yu Y, Xu J *et al.* Clinical course and outcomes of critically ill patients with SARS-CoV-2 pneumonia in Wuhan, China: a single-centered, retrospective, observational study. *Lancet Respir. Med.* 2020; **8**: 475–81.
- 42 Chu M, Xu J, Zhong F *et al.* Digestive symptoms of COVID-19 and high expression of ACE2 in digestive tract organs. *Available at SSRN 3572849*. 2020.
- 43 Luo S, Zhang X, Xu H. Don't overlook digestive symptoms in patients with 2019 novel coronavirus disease (COVID-19). *Clin. Gastroenterol. Hepatol.* 2020; **18**: 1636–7.

- 44 Yang W, Cao Q, Qin L *et al.* Clinical characteristics and imaging manifestations of the 2019 novel coronavirus disease (COVID-19): a multi-center study in Wenzhou city, Zhejiang, China. *J. Infect.* 2020; **80**: 388–93.
- 45 Buscarini E, Manfredi G, Brambilla G *et al.* Gastrointestinal symptoms as Covid-19 onset in hospitalized Italian patients. *medRxiv* 2020.
- 46 Wu J, Liu J, Zhao X *et al.* Clinical characteristics of imported cases of COVID-19 in Jiangsu Province: a multicenter descriptive study. *Clin. Infect. Dis.* 2020; **71**: 706–12.
- 47 Wang L, Gao YH, Lou LL, Zhang GJ. The clinical dynamics of 18 cases of COVID-19 outside of Wuhan, China. *Eur. Respir. J.* 2020; **55**: 2000398.
- 48 Wu WS, Li YG, Wei ZF *et al.* Investigation and analysis on characteristics of a cluster of COVID-19 associated with exposure in a department store in Tianjin. *Zhonghua Liu Xing Bing Xue Za Zhi* 2020; **41**: 489–93.
- 49 Li Y, Wang W, Lei Y *et al.* Comparison of the clinical characteristics between RNA positive and negative patients clinically diagnosed with 2019 novel coronavirus pneumonia. *Zhonghua jie he hu xi za zhi= Zhonghua jiehe he huxi zazhi= Chin. J. Tuberculosis Respiratory Dis.* 2020; **43**: E023-E.
- 50 Liu M, He P, Liu HG *et al.* Clinical characteristics of 30 medical workers infected with new coronavirus pneumonia. *Zhonghua Jie He Hu Xi Za Zhi* 2020; **43**: 209–14.
- 51 Liu W, Zhang Q, Chen J *et al.* Detection of Covid-19 in children in early January 2020 in Wuhan, China. *N. Engl. J. Med.* 2020; **382**: 1370–1.
- 52 Xu X, Yu C, Qu J *et al.* Imaging and clinical features of patients with 2019 novel coronavirus SARS-CoV-2. *Eur. J. Nucl. Med. Mol. Imaging* 2020; **47**: 1275–80.
- 53 An P, Chen H, Jiang X *et al.* Clinical features of 2019 novel coronavirus pneumonia presented gastrointestinal symptoms but without fever onset. *Lancet Gastroenterol. Hepatol.* 2020 February 6.
- 54 Wei X-S, Wang X, Niu Y-R *et al.* Diarrhea is associated with prolonged symptoms and viral carriage in COVID-19. *Clin. Gastroenterol. Hepatol.* 2020; **18**: 1753–9.
- 55 Zhong ZF, Huang J, Yang X *et al.* Epidemiological and clinical characteristics of COVID-19 patients in Hengyang, Hunan Province, China. *World J. Clin. Cases* 2020; **8**: 2554–65.
- 56 Chen A, Agarwal A, Ravindran N, To C, Zhang T, Thuluvath PJ. Are gastrointestinal symptoms specific for COVID-19 infection? A prospective case-control study from the United States. *Gastroenterology* 2020; S0016–5085(20)30664–8.
- 57 Team CC-R. Characteristics of health care personnel with COVID-19 - United States, February 12–April 9, 2020. *MMWR Morb. Mortal. Wkly Rep.* 2020; **69**: 477–81.
- 58 Rokkas T. Gastrointestinal involvement in COVID-19: a systematic review and meta-analysis. *Ann. Gastroenterol.* 2020; **33**: 355–65.
- 59 Rao S, Lau A. COVID-19 has become a major public health problem. There is good evidence that ACE2 is a receptor for SARS-CoV-2, and high expression of ACE2 may increase susceptibility to infection. We aimed to explore risk factors affecting susceptibility to infection and prioritize drug repositioning candidates, based on Mendelian randomization (MR) studies on ACE2 lung expression. *Diabetes Care* 2020; **43**.
- 60 Parkman HP, Wilson LA, Farrugia G *et al.* Delayed gastric emptying associates with diabetic complications in diabetic patients with symptoms of gastroparesis. *Am. J. Gastroenterol.* 2019; **114**: 1778–94.
- 61 Andrews PL, Rudd JA. *The Physiology and Pharmacology of Nausea and Vomiting Induced by Anticancer Chemotherapy in Humans. Management of Chemotherapy-Induced Nausea and Vomiting.* Springer, 2016; 5–44.
- 62 Aroniadis OC, DiMaio CJ, Dixon RE *et al.* Current knowledge and research priorities in the digestive manifestations of COVID-19. *Clin. Gastroenterol. Hepatol.* 2020; **18**: 1682–4.
- 63 Menni C, Valdes AM, Freidin MB *et al.* Real-time tracking of self-reported symptoms to predict potential COVID-19. *Nat. Med.* 2020; **26**: 1037–40.
- 64 Drew DA, Nguyen LH, Steves CJ *et al.* Rapid implementation of mobile technology for real-time epidemiology of COVID-19. *Science* 2020; **368**: 1362–7.
- 65 Borner T, Shaulson ED, Ghidewon MY *et al.* GDF15 induces anorexia through nausea and emesis. *Cell Metab.* 2020; **31**: 351–62.
- 66 Richards CA, Andrews PL. Food refusal: a sign of nausea? *J. Pediatr. Gastroenterol. Nutr.* 2004; **38**: 227–8.
- 67 Tung-Thompson G, Libera DA, Koch KL, de Los Reyes FL, Jaykus LA 3rd. Aerosolization of a human norovirus surrogate, bacteriophage MS2, during simulated vomiting. *PLoS ONE* 2015; **10**: e0134277.
- 68 Holmes SR, King S, Stott J, Cledes S. Facial skin pallor increases during motion sickness. *J. Psychophysiol.* 2002; **16**: 150–7.
- 69 Sanger GJ, Andrews PLR. A history of drug discovery for treatment of nausea and vomiting and the implications for future research. *Front. Pharmacol.* 2018; **9**: 913.
- 70 Andrews PL, Rapeport WG, Sanger GJ. Neuropharmacology of emesis induced by anti-cancer therapy. *Trends Pharmacol. Sci.* 1988; **9**: 334–41.
- 71 Wu W, Zhou HR, Bursian SJ *et al.* Comparison of anorectic and emetic potencies of deoxyvalenol (vomitoxin) to the plant metabolite deoxyvalenol-3-glucoside and synthetic deoxyvalenol derivatives EN139528 and EN139544. *Toxicol. Sci.* 2014; **142**: 167–81.
- 72 Zhou HR, Pestka JJ. Deoxyvalenol (vomitoxin)-induced cholecystokinin and glucagon-like peptide-1 release in the STC-1 enteroendocrine cell model is mediated by calcium-sensing receptor and transient receptor potential ankyrin-1 channel. *Toxicol. Sci.* 2015; **145**: 407–17.
- 73 Hu DL, Zhu G, Mori F *et al.* Staphylococcal enterotoxin induces emesis through increasing serotonin release in intestine and it is downregulated by cannabinoid receptor 1. *Cell. Microbiol.* 2007; **9**: 2267–77.
- 74 Hagbom M, Istrate C, Engblom D *et al.* Rotavirus stimulates release of serotonin (5-HT) from human enterochromaffin cells and activates brain structures involved in nausea and vomiting. *PLoS Pathog.* 2011; **7**: e1002115.
- 75 Westerberg S, Hagbom M, Rajan A *et al.* Interaction of human enterochromaffin cells with human enteric adenovirus 41 leads to serotonin release and subsequent activation of enteric glia cells. *J. Virol.* 2018; **92**: e00026–18.
- 76 Bialowas S, Hagbom M, Nordgren J *et al.* Rotavirus and serotonin cross-talk in diarrhoea. *PLoS ONE* 2016; **11**: e0159660.
- 77 Hamming I, Timens W, Bulthuis ML, Lely AT, Navis G, van Goor H. Tissue distribution of ACE2 protein, the functional receptor for SARS coronavirus. A first step in understanding SARS pathogenesis. *J. Pathol.* 2004; **203**: 631–7.
- 78 Lu R, Zhao X, Li J *et al.* Genomic characterisation and epidemiology of 2019 novel coronavirus: implications for virus origins and receptor binding. *Lancet* 2020; **395**: 565–74.
- 79 Hoffmann M, Kleine-Weber H, Schroeder S *et al.* SARS-CoV-2 cell entry depends on ACE2 and TMPRSS2 and is blocked by a clinically proven protease inhibitor. *Cell* 2020; **181**: 271–80.
- 80 Zhang H, Penninger JM, Li Y, Zhong N, Slutsky AS. Angiotensin-converting enzyme 2 (ACE2) as a SARS-CoV-2 receptor: molecular mechanisms and potential therapeutic target. *Intensive Care Med.* 2020; **46**: 586–90.
- 81 Harmer D, Gilbert M, Borman R, Clark KL. Quantitative mRNA expression profiling of ACE 2, a novel homologue of angiotensin converting enzyme. *FEBS Lett.* 2002; **532**: 107–10.

- 82 Gembardt F, Sterner-Kock A, Imboden H *et al.* Organ-specific distribution of ACE2 mRNA and correlating peptidase activity in rodents. *Peptides* 2005; **26**: 1270–7.
- 83 Lamers MM, Beumer J, van der Vaart J *et al.* SARS-CoV-2 productively infects human gut enterocytes. *Science* 2020; **369**: 50–4.
- 84 Zhang H, Kang Z, Gong H *et al.* Digestive system is a potential route of COVID-19: an analysis of single-cell coexpression pattern of key proteins in viral entry process. *Gut* 2020; **69**: 1010–8.
- 85 Zou X, Chen K, Zou J, Han P, Hao J, Han Z. Single-cell RNA-seq data analysis on the receptor ACE2 expression reveals the potential risk of different human organs vulnerable to 2019-nCoV infection. *Front. Med.* 2020.
- 86 Qi F, Qian S, Zhang S, Zhang Z. Single cell RNA sequencing of 13 human tissues identify cell types and receptors of human coronaviruses. *Biochem. Biophys. Res. Commun.* 2020; **526**: 135–40.
- 87 Roberts GP, Larraufie P, Richards P *et al.* Comparison of human and murine enteroendocrine cells by transcriptomic and peptidomic profiling. *Diabetes* 2019; **68**: 1062–72.
- 88 Horn CC, Kimball BA, Wang H *et al.* Why can't rodents vomit? A comparative behavioral, anatomical, and physiological study. *PLoS ONE* 2013; **8**: e60537.
- 89 Sanger GJ, Holbrook JD, Andrews PL. The translational value of rodent gastrointestinal functions: a cautionary tale. *Trends Pharmacol. Sci.* 2011; **32**: 402–9.
- 90 Engelstoft MS, Lund ML, Grunddal KV *et al.* Research resource: a chromogranin A reporter for serotonin and histamine secreting enteroendocrine cells. *Mol. Endocrinol.* 2015; **29**: 1658–71.
- 91 Drummond CG, Bolock AM, Ma C, Luke CJ, Good M, Coyne CB. Enteroviruses infect human enteroids and induce antiviral signaling in a cell lineage-specific manner. *Proc. Natl. Acad. Sci. U. S. A.* 2017; **114**: 1672–7.
- 92 Worthington JJ, Reimann F, Gribble FM. Enteroendocrine cells-sensory sentinels of the intestinal environment and orchestrators of mucosal immunity. *Mucosal Immunol.* 2018; **11**: 3–20.
- 93 Valdes AM, Walter J, Segal E, Spector TD. Role of the gut microbiota in nutrition and health. *BMJ* 2018; **361**: k2179.
- 94 Zuo T, Zhang F, Lui GCY *et al.* Alterations in gut microbiota of patients with COVID-19 during time of hospitalization. *Gastroenterology* 2020: S0016-5085(20)34701-6.
- 95 Hashimoto T, Perlot T, Rehman A *et al.* ACE2 links amino acid malnutrition to microbial ecology and intestinal inflammation. *Nature* 2012; **487**: 477–81.
- 96 Gonsalves SF, Landgraf BE, Ciardelli TL, Borison HL. Early toxicity of recombinant interleukin-2 in cats. *Arch. Int. Pharmacodyn. Ther.* 1991; **310**: 175–85.
- 97 Wuchert F, Ott D, Rafalzik S, Roth J, Gerstberger R. Tumor necrosis factor- α , interleukin-1 β and nitric oxide induce calcium transients in distinct populations of cells cultured from the rat area postrema. *J. Neuroimmunol.* 2009; **206**: 44–51.
- 98 Kan KKW, Wai MK, Jones RL, Rudd JA. Role of prostanoid EP3/1 receptors in mechanisms of emesis and defaecation in ferrets. *Eur. J. Pharmacol.* 2017; **803**: 112–7.
- 99 Barrett JS, Spitsin S, Moorthy G *et al.* Pharmacologic rationale for the NK1R antagonist, aprepitant as adjunctive therapy in HIV. *J. Transl. Med.* 2016; **14**: 148.
- 100 Diwakarla S, Fothergill LJ, Fakhry J, Callaghan B, Furness JB. Heterogeneity of enterochromaffin cells within the gastrointestinal tract. *Neurogastroenterol. Motil.* 2017; **29**: e13101.
- 101 Goldspink DA, Reimann F, Gribble FM. Models and tools for studying enteroendocrine cells. *Endocrinology* 2018; **159**: 3874–84.
- 102 Broad J, Góralczyk A, Mannur K, Dukes G, Sanger G. Drugs acting at 5-HT₄, D₂, motilin, and ghrelin receptors differ markedly in how they affect neuromuscular functions in human isolated stomach. *Neurogastroenterol. Motil.* 2014; **26**: 851–61.
- 103 Li YC, Bai WZ, Hashikawa T. The neuroinvasive potential of SARS-CoV2 may play a role in the respiratory failure of COVID-19 patients. *J. Med. Virol.* 2020; **92**: 552–5.
- 104 Doobay MF, Talman LS, Obr TD, Tian X, Davison RL, Lazartigues E. Differential expression of neuronal ACE2 in transgenic mice with overexpression of the brain renin-angiotensin system. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 2007; **292**: R373–81.
- 105 Baig AM, Khaleeq A, Ali U, Syeda H. Evidence of the COVID-19 virus targeting the CNS: tissue distribution, host-virus interaction, and proposed neurotropic mechanisms. *ACS Chem. Neurosci.* 2020; **11**: 995–8.
- 106 Li Z, Liu T, Yang N *et al.* Neurological manifestations of patients with COVID-19: potential routes of SARS-CoV-2 neuroinvasion from the periphery to the brain. *Front. Med.* 2020: 1–9.
- 107 Baig AM. Neurological manifestations in COVID-19 caused by SARS-CoV-2. *CNS Neurosci. Ther.* 2020; **26**: 499–501.
- 108 Zhou L, Zhang M, Wang J, Gao J. Sars-Cov-2: underestimated damage to nervous system. *Travel Med. Infect. Dis.* 2020: 101642.
- 109 Xu J, Zhong S, Liu J *et al.* Detection of severe acute respiratory syndrome coronavirus in the brain: potential role of the chemokine mig in pathogenesis. *Clin. Infect. Dis.* 2005; **41**: 1089–96.
- 110 Mora-Diaz JC, Pineyro PE, Houston E, Zimmerman J, Gimenez-Lirola LG. Porcine hemagglutinating encephalomyelitis virus: a review. *Front Vet. Sci.* 2019; **6**: 53.
- 111 Imai Y, Kuba K, Ohto-Nakanishi T, Penninger JM. Angiotensin-converting enzyme 2 (ACE2) in disease pathogenesis. *Circ. J.* 2010; **74**: 405–10.
- 112 Gaddam RR, Chambers S, Bhatia M. ACE and ACE2 in inflammation: a tale of two enzymes. *Inflamm. Allergy Drug Targets* 2014; **13**: 224–34.
- 113 Khan A, Benthin C, Zeno B *et al.* A pilot clinical trial of recombinant human angiotensin-converting enzyme 2 in acute respiratory distress syndrome. *Crit. Care* 2017; **21**: 234.
- 114 Mazzone SB, Udem BJ. Vagal afferent innervation of the airways in health and disease. *Physiol. Rev.* 2016; **96**: 975–1024.
- 115 Carpenter DO, Briggs DB, Strominger N. Peptide-induced emesis in dogs. *Behav. Brain Res.* 1984; **11**: 277–81.
- 116 Wu M, Harding RK, Hugenholtz H, Kucharczyk J. Emetic effects of centrally administered angiotensin II, arginine vasopressin and neurotensin in the dog. *Peptides* 1985; **6**: 173–5.
- 117 Carpenter DO, Briggs DB, Strominger N. Responses of neurons of canine area postrema to neurotransmitters and peptides. *Cell. Mol. Neurobiol.* 1983; **3**: 113–26.
- 118 Brooks MJ, Hubbard JI, Sirett NE. Extracellular recording in rat area postrema in vitro and the effects of cholinergic drugs, serotonin and angiotensin II. *Brain Res.* 1983; **261**: 85–90.
- 119 Hay M, Edwards GL, Lindsley K *et al.* Increases in cytosolic Ca²⁺ in rat area postrema/mNTS neurons produced by angiotensin II and arginine-vasopressin. *Neurosci. Lett.* 1993; **151**: 121–5.
- 120 Borison HL, Hubbard JI, McCarthy LE. Central respiratory inhibition by angiotensin II in anesthetized cats. *J. Pharmacol. Exp. Ther.* 1988; **247**: 781–90.
- 121 Ewert S, Spak E, Olbers T, Johnsson E, Edebo A, Fandriks L. Angiotensin II induced contraction of rat and human small intestinal wall musculature in vitro. *Acta Physiol (Oxf.)* 2006; **188**: 33–40.
- 122 Ludtke FE, Golenhofen K, Schubert F. Angiotensin II stimulates human gastric smooth muscle in vitro. *J. Auton. Pharmacol.* 1989; **9**: 139–47.
- 123 Fandriks L. The angiotensin II type 2 receptor and the gastrointestinal tract. *J. Renin Angiotensin Aldosterone Syst.* 2010; **11**: 43–8.
- 124 Zabara J, Chaffee RB Jr, Tansy MF. Neuroinhibition in the regulation of emesis. *Space Life Sci.* 1972; **3**: 282–92.
- 125 Borison HL, Hebertson LM. Role of medullary emetic chemoreceptor trigger zone (CT zone) in postnephrectomy vomiting in dogs. *Am. J. Physiol.* 1959; **197**: 850–2.

- 126 Jensen KJ, Alpini G, Glaser S. Hepatic nervous system and neurobiology of the liver. *Compr. Physiol.* 2013; **3**: 655–65.
- 127 Horn CC, Richardson EJ, Andrews PL, Friedman MI. Differential effects on gastrointestinal and hepatic vagal afferent fibers in the rat by the anti-cancer agent cisplatin. *Auton. Neurosci.* 2004; **115**: 74–81.
- 128 Abrahamsson H, Thoren P. Vomiting and reflex vagal relaxation of the stomach elicited from heart receptors in the cat. *Acta Physiol. Scand.* 1973; **88**: 433–9.
- 129 Baker J, Lokey J, Price N, Winokur S, Bowen J, Taylor A. Nabilone as an antiemetic. *New Eng. J. Med.* 1979; **301**: 728.
- 130 Andrews PL, Sanger GJ. Nausea and the quest for the perfect antiemetic. *Eur. J. Pharmacol.* 2014; **722**: 108–21.
- 131 Shi J, Wen Z, Zhong G *et al.* Susceptibility of ferrets, cats, dogs, and other domesticated animals to SARS-coronavirus 2. *Science* 2020; **368**: 1016–20.
- 132 Percie du Sert N, Andrews PLR. The ferret in nausea and vomiting research: lessons in translation of basic science to the clinic. Chapter 31. In: Fox JG, Marini RP, eds. *Biology and Diseases of the Ferret*. Iowa, USA: Wiley Blackwell, 2014; 735–78.
- 133 Wrapp D, Wang N, Corbett KS *et al.* Cryo-EM structure of the 2019-nCoV spike in the prefusion conformation. *Science* 2020; **367**: 1260–3.
- 134 Spiller R. Diarrhea-predominant bowel disorders following inflammation and infection. In: Spiller R, Grundy D, eds. *Pathophysiology of the Enteric Nervous System: A Basis for Understanding Functional Diseases*. Oxford, UK: Blackwell Publishing, 2004; 188–200.