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Real-time, systematic disease detection on cruise ships: feasibility assessment for outbreak prevention.

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Abstract

The heavy toll of COVID-19 on the cruise industry has highlighted the long-standing issue of disease and epidemic management on ships. Optimal prevention of outbreaks on cruise ships would be achieved if each individual on board could be accurately diagnosed at the onset of symptoms, with or without a visit to the ship's health center. This paper discusses whether the current state of the art in point-of-care diagnostics, biosensors, and wearable devices can meet this challenge.

Prevention of outbreaks on cruise ships begins in the ship's health center with accurate diagnosis of sick individuals. Diagnostic capabilities there should be expanded to include a broad range of commercially available point-of-care tests, in order to cover all common infectious diseases.

This should be complemented by real-time, accurate, individualized disease detection throughout the ship should be achieved. The most mature option for respiratory disease recognition is undoubtedly the monitoring of respiratory sounds in the cabin or via wearable devices. Correlating symptoms and vital signs correlation measured with specific models of smart wearable devices is feasible, but is not fully generalized and validated. More selective solutions based on biomarkers or direct pathogen detection would be particularly appropriate but are still at the research stage.

Until disease tracking becomes fully available, it is proposed to perform real-time, continuous symptom tracking. This can be achieved with current commercial technologies, either with smart wearable devices, with fixed cabin sensors and/or with sensors deployed throughout the ship. A positively screened individual would be offered an immediate visit to the health center. There, a point-of-care diagnosis

would be performed immediately to assess the risk that the symptoms are caused by an infectious disease.

Introduction

The heavy toll of COVID-19 on the cruise industry has been documented since 2020. Highly publicized outbreaks on cruise ships in the early days of the pandemic were followed by documented cases of the virus being widely spread in their home countries by passengers returning from cruise ships. Cruises were eventually banned in some countries, while on the other hand, increasing travel restrictions reduced the number of cruise passengers from 30 million in 2019 to 6 million in 2020. It is estimated that cruise lines lost \$77 billion between March and September 2020 alone (Muritala et al., 2022; Syriopoulos et al., 2022).

Since then, the cruise industry has recovered, but the pandemic has dramatically highlighted the long-standing issue of disease and epidemic management on ships (Minooee & Rickman, 1999). A general distinction can be made between respiratory and gastrointestinal diseases (Kak, 2007). As of May 2023, the American Centers for Disease Control and Prevention list influenza, COVID-19, and the common cold as main respiratory illnesses and Norovirus as the most common digestive illness. In addition, Legionnaires' disease remains a concern with frequent outbreaks.

To ensure health on board, members of the Cruise Lines International Association (CLIA) (95% of the world's ocean-going cruise capacity) claim to follow the guidelines proposed by the American College of Emergency Physicians (ACEP) for cruise ship medical facilities, established in 1995 and regularly revised since then¹. The World Health Organization also publishes an International Medical Guide for Ships, which includes the contents of the ship's medicine chest (World Health Organization., 2007). During the COVID-19 crisis, the European Medicines Agency published (and revised several times) recommendations for managing COVID on board cruise ships (European Medicines Agency, 2022), which were different from the available recommendations to manage Influenza-like illness².

To prevent outbreaks on board, the obvious question for the ship's physician is to accurately identify a disease carried by passengers or crew. Legionnaires' disease, influenza or COVID-19 may all present with similar respiratory symptoms, but the recommendations in the event of an outbreak are very different. Time is also a critical factor. Even in the case of a person with a readily identifiable illness, the latency between the onset of symptoms and the visit to the doctor will result in

¹ <https://www.acep.org/patient-care/policy-statements/health-care-guidelines-for-cruise-ship-medical-facilities> , last accessed May 15th, 2023

² <https://www.cdc.gov/quarantine/cruise/management/guidance-cruise-ships-influenza-updated.html>, last consulted May 15th, 2023

additional contaminations on the ship. A third aspect is exhaustivity of the detection of sick passengers: in the case of a person with mild symptoms, they may not even visit the doctor, though they may be contagious.

To address these three challenges, it is obvious that the whole extent of analytical equipment regularly used ashore for precision diagnostics is not available on board. While the appropriate biological samples can be sent to shore for accurate laboratory analysis, shipping and processing delays mean that the resulting information is most often used for post-crisis management (e.g., insurance claims). On the other hand, the ACEP health care guidelines for cruise ships recommend availability of a set of lab testing capabilities (including blood count, urinalysis, several cardiac enzymes). However, the only listed infectious diseases are Malaria, Legionella, Influenza A and B and HIV, and their lab testing procedures take days. The only rapid screening tests included in health care recommendations are presently the ones for COVID-19.

Overall, optimal prevention of outbreaks on cruise ships would be achieved if each individual on board could be accurately diagnosed at the onset of symptoms, with or without a visit to the ship's health center. This paper discusses whether the current state of the art of point-of-care diagnostics, biosensors, and wearable devices can meet this challenge. A first section discusses point of care diagnosis options at the ship's health center. A second section discusses whether diseases could be diagnosed in real time throughout the ship. Two approaches are considered: direct monitoring of individuals or monitoring of their cabins. Finally, the most promising options for disease detection on cruise ships are summarized.

Point of care diagnosis at the health center

The most natural place to identify illness on a cruise ship is the ship's health center. In fact, passengers or crew members who feel ill are expected to go directly to the ship's physician. In addition, crew members can identify passengers with worrisome symptoms and refer them to the doctor as well. The ability to accurately and rapidly diagnose illness in the ship's health center is therefore critical.

Citing (Mabey et al., 2004), point of care (POC) tests are “diagnostic tests performed in the clinic, with results available within a short time so that patients can be treated without a return visit”. While POC tests are of particular interest in the developing world to detect disease such as malaria and syphilis, they perfectly answer the needs of cruise ships: no need for lab equipment, reduced space, rapid results, low cost. The general principle is to allow a direct color identification of positive results. The relevant sample, such as saliva, urine or blood, is placed on the test (either dipstick or lateral-flow format) and the test changes color according to presence of the disease. Most tests rely on immunochromatography, eg. detection of antigens or antibodies. Figure 1 provides an illustration of a POC test in the lateral flow format.

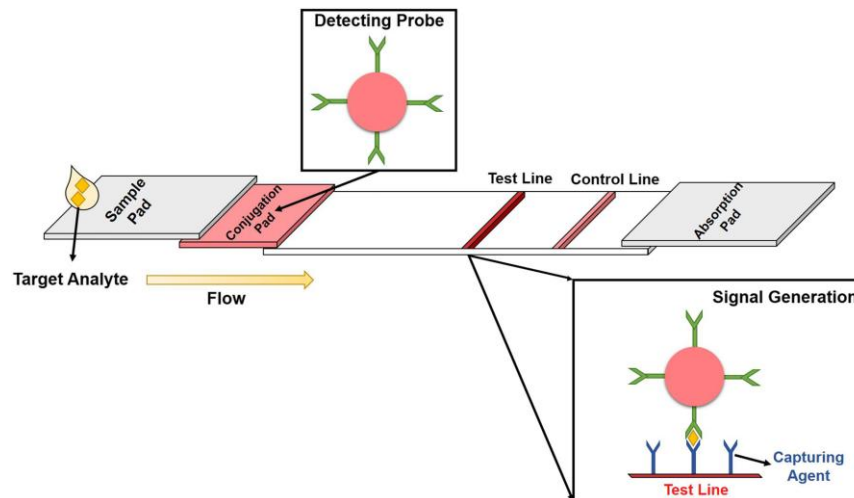


Fig 1: Schematic representation of lateral flow assay. The target analyte is labelled by the detecting probe, inside the conjugation pad (Naseri et al., 2022)

(Naseri et al., 2022) provides examples of POC tests for virus detection, with particular emphasis on solutions targeting COVID-19. Solutions to identify the different influenza viruses are also described. Regarding gastrointestinal diseases, one of the main concerns on board cruise ships is to detect norovirus. POC diagnostics are available for this as well, as detailed in (Chand & Neethirajan, 2017; Kim et al., 2018; Qian et al., 2022; Weng & Neethirajan, 2017).

There is also a clear need to rapidly track diseases caused by environmental factors: legionella in HVAC or water systems, e-coli, salmonella or listeriosis in food or water. In this case, the identification of the disease is needed to search for its root cause on the ship. (Chen et al., 2022; Roy et al., 2022; Sohrabi et al., 2022) review the available POC tests, while (Liu et al., 2022) focuses on POC diagnostic for food-borne pathogens.

In summarize, all the major diseases of interest to cruise ships can now be diagnosed in near real-time with POC tests. Following the COVID pandemic, it is now recommended that cruise ships carry COVID diagnosis tests in their medicine's chest. Giving the low cost of these tests (although they have a limited shelf life), it may be valuable to extend this practice to the major infectious diseases, and even to less prominent ones.

It is important to note that these references mostly report research results, that may or may not be translated into commercial products. Even for diseases for which commercial rapid screening products exists, accuracy may be limited. For example, (Mabey et al., 2004) reports that some types of POC tests have not undergone sufficient performance evaluations, while others have limited sensitivity (Pate et al., 1998; Widjaja et al., 1999; World Health Organization, 2023).

Overall, this suggests the question of equipping the health center with more types of POC tests should be approached on a case-by-case basis: for each relevant disease, the available commercial products could be reviewed and compared in terms of accuracy, response time, price, and shelf life. Based on this, an appropriate strategy could be developed: number of tests to have on board; how to pro-

ceed (from an epidemic mitigation point of view) in the case of both positive and negative tests.

Real-time, systematic and selective disease identification

The main limitation of point-of-care diagnosis at the health center is that it requires decisive action by the individual to go to the health center, which has financial and time implications. This action by the individual is usually triggered only in the case of severe symptoms, long after they have become contagious or long after the environmental cause has started. Thus, by its very nature, diagnosis at the health center cannot provide a complete or early identification of individuals with a specific disease.

For early and systematic disease detection, the ideal solution is to continuously monitor the presence/absence of one or more selected diseases at the individual passenger or crew level in real time. As a starting point, we note that (Bruno Almeida et al., n.d.), in another chapter of the same book, detail possible strategies for real time symptom detection throughout the ship. This is a valuable first step in epidemic management. The present section goes beyond symptom detection and discuss whether disease can be detected selectively and systematically throughout the ship. There are two ways to do this on board a cruise ship, either by monitoring individuals directly with a wearable health monitor, or by monitoring their cabin. This section discusses the feasibility of the same in the context of a cruise ship.

Smart wearable devices

The rapid development of smart wearable devices (SWDs) over the past 15 years has strongly attracted the attention of the healthcare community as a means to provide non-invasive, continuous health monitoring at low cost (Chan et al., 2012; Mukherjee et al., 2022). While SWDs encompass a wide range of very different solutions (from smart tattoos to smart helmets), their common denominator is the inclusion of one or more sensors that are packaged in a solution that can be worn on the body. Healthcare SWDs can be broadly divided into two groups, those that monitor symptoms and general physiological information such as heartbeat or temperature, and those that monitor one or more specific biomarkers of a disease. The first group generally includes solutions that are either commercially available or for which all the building blocks (sensors, electronics...) are on the market (i.e. they could theoretically be on the market in the near future). The second group tends to include solutions for which one or more of the key components is still a major research challenge.

As described in detail in (Chan et al., 2012; Mukherjee et al., 2022), a major area of application in healthcare has been chronic diseases. Until the pandemic, the use of SWDs to detect infectious disease was rare. COVID-19 brought to light a body of previous work on the topic, while motivating rapid new developments, as reviewed by (Mohammadzadeh et al., 2020): a watch-like device for COVID detection using body surface temperature and heart rate was reported (Chung et al., 2020), while a Fitbit wearable device was proposed for influenza detection (Radin et al., 2020); various wearable solutions were also reported for Ebola (3), Chikungunya (1), and Dengue (1); the review also includes SWD for general “infectious diseases”. Since this review in 2020, (Mukhtar et al., 2021) also described a prototype solution for COVID screening including heartbeat, O₂ saturation, temperature and cough sensors. (Al-Halhouli et al., 2021) extended the review, with a specific focus on SWDs based on printed electronics.

Overall, the studies suggest the feasibility of disease identification through symptom monitoring by SWD. One limitation is that the studies are rarely based on already commercial SWDs – which would be immediately deployable in a cruise ship context. As an exception, the study by (Radin et al., 2020) is particularly interesting because it relied on an already commercial SWD that is widely used in the USA and collected data from a significant number of users (47000+). The data from the SWDs (sleep duration and resting heart rate) showed a very good correlation across the USA with the “Influenza-like-Illness” evolution curves by state published by the CDC (Fig. 2). This suggests a quite mature solution. On the other hand, by focusing on aggregated “Influenza-like-Illness” data, the study does not claim selectivity between different types of influenza-like illness.

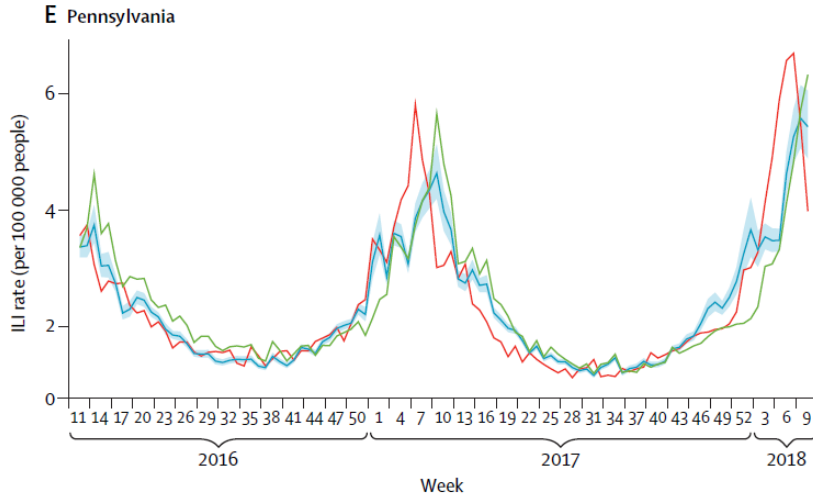


Fig 2 : Weekly CDC Influenza-like illness(ILI) rates (red), predicted ILI rates from the baseline model H0 model (green) and for an optimized model H1 (blue, with 95% confidence intervals in light blue), for Pennsylvania. Data are from March 16, 2016, to March 1, 2018. CDC=Centers for Disease Control and Prevention. ILI=influenza-like illness. Reproduced from (Radin et al., 2020)

Selectivity in disease detection based on symptoms and general physiological monitoring is a critical bottleneck in the literature on SWDs. As reviewed by (Al-Halhouli et al., 2021), the symptoms and vital signs monitored by physicians to diagnose a number of emerging viral diseases (COVID-19, Crimean-Congo Hemorrhagic Fever, Ebola Virus Disease, Marburg Virus Disease, Lassa Hemorrhagic Fever, Middle East Respiratory Syndrome, Severe Acute Respiratory Syndrome, Nipah Virus disease, and Rift Valley fever) differ between diseases. And most of these symptoms and vital signs can be monitored by existing commercial or pre-commercial SWDs. Thus, in theory, selectivity could be achieved. However, this has not yet been proved in the general case.

In the specific case of cough-inducing diseases (including COVID-19), this challenge of selectivity has been successfully addressed based on sound monitoring. Machine-learning-based processing of respiratory sounds (cough, breath, voice) allows differentiation between respiratory diseases (Ijaz et al., 2022). This approach has shown positive results in field trials with dozens of patients for infectious (bronchitis and COVID-19) and non-infectious (asthma) respiratory diseases (Andreu-Perez et al., 2022; Pal & Sankarasubbu, 2021). Considering sound sensors are available at low cost, this type of strategies has a great potential for generalization. At this time, proof of concepts have been already successful with smart phones and smart watches (Ijaz et al., 2022) (Fig. 3).

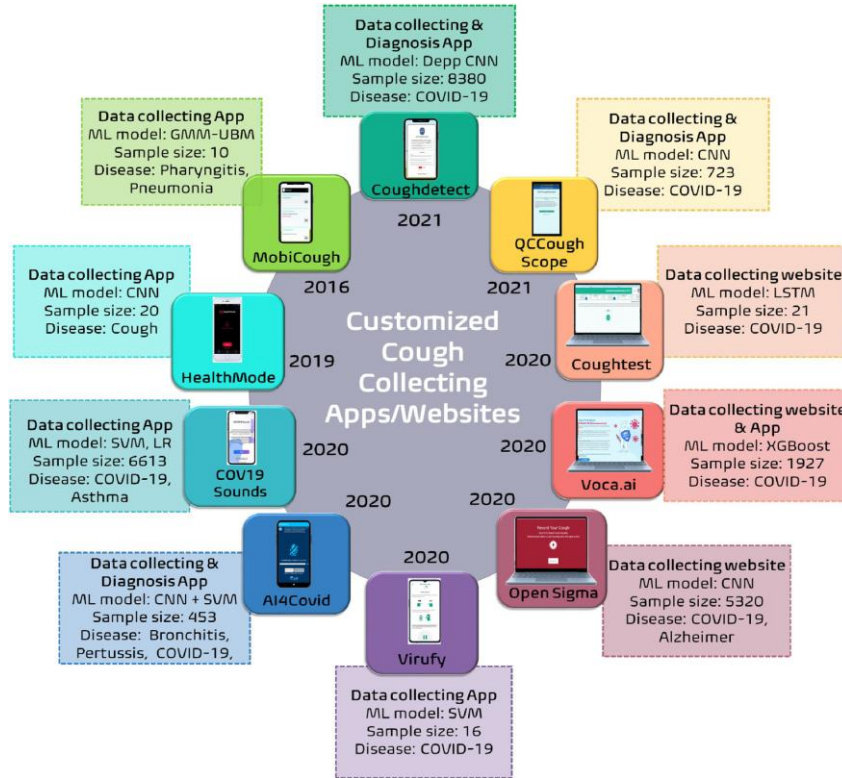


Fig . 3 : Customized cough detection and disease diagnosing applications. Reproduced from (Ijaz et al., 2022).

To ensure selectivity, the most common strategy is to incorporate sensors into the SWDs sensors that will monitor biomarkers of the disease. This requires sampling of bodily fluids, such as blood, saliva or sweat, or breath analysis. Monitoring either sweat or breath is the most promising strategy in the context of cruise ships, as it is minimally intrusive (compared to blood or saliva sampling).

For sweat monitoring (Tseng et al., 2021), the principle is to stick smart tape on the skin. Smart tattoos are also an option. Either type of devices collects sweat and analyzes it for specific biomarkers. To collect adequate amounts of sweat, additional chemicals can be used to increase sweat production. So far, the main application is the monitoring of chronic diseases (Marques-Deak et al., 2006): diabetes, cancer, cystic fibrosis, etc... Applications for infectious disease detection are very rare. Recently, (Jagannath et al., 2021, 2022) demonstrated the possibility of tracking inflammatory markers of disease in sweat using on-body sensing with a watch-like device, a solution relevant to COVID or influenza monitoring (Fig. 4). This study is a research paper, so significant translational research is needed before it can be used and validated under field conditions. However, it is important because it opens up the way to accurate (by design because of biomarker detection) and exhaustive (because smart tape could be very cheap) tracking of a specific virus in large numbers of people.

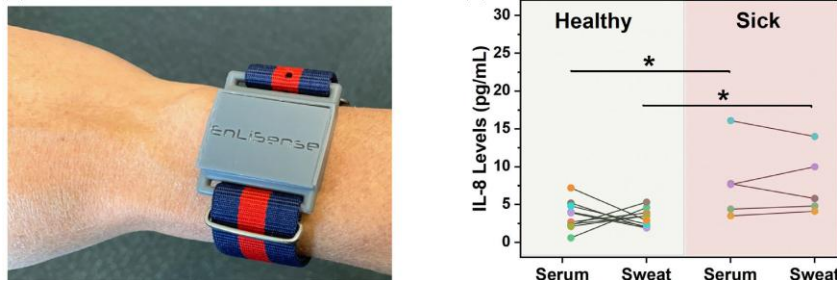
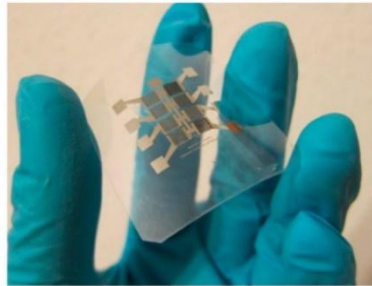


Fig . 4 : Sweat monitoring – reproduced from (Jagannath et al., 2021) : (a) SWEATSENSOR device worn on hand by a subject recruited for the study. (d) Comparison of IL-8 levels between healthy (n = 10) and sick cohort (n = 5). The levels between serum to sweat are also compared for each subject. Statistical significance $p < 0.05$ (horizontal black line marked with *) was achieved between healthy and sick cohort using ANOVA ($\alpha = 0.05$) in both serum and sweat

Another promising approach is breath monitoring. (Hu & Koo, 2022) reported on a face mask for COVID detection that changes color in response to COVID exposure (from one's own breath or from someone else's). While this is not directly a smart solution, it is a solution that could have value on a cruise ship.

Both sweat and breath carry odors that can be quantified by measuring their concentration in volatile organic compounds (VOCs). It has been demonstrated under clinical conditions and with laboratory analytical equipment that the VOC composition of breath and sweat carries selective information about some infectious diseases (Sethi et al., 2013; Ghosh et al., 2021). Based on this principle, (Malikhah et al., 2022) demonstrated the feasibility of detecting COVID by measuring the odor of axillary sweat samples using an electronic nose (e-nose) for volatile organic compounds. The main challenge of this approach is the technological maturity of e-noses for VOC monitoring, especially in the context of SWDs. It is still a major topic of research, as is reviewed by (Cheng et al., 2021). While studies by (Lorwongtragool et al., 2014; Seesaard et al., 2014) provide examples of e-nose applications for health monitoring, there does not yet appear to be any commercial or pre-commercial solution available that is suitable for disease tracking.

Flexible printed chemical sensor array



ZigBee module



Fig . 5 : Prototype of a wearable e-nose based on using the flexible inkjet-printed chemical sensor array integrated in ZigBee wireless network. Reproduced from (*Lorwongtragool et al., 2014*)

Cabin monitoring

Correlation of symptoms

Alternatively, instead of continuously monitoring a person with an SWD, one may choose to monitor their cabin. Each person on a cruise ship will spend time in their cabin on a regular basis, and providing sensor solutions for the cabin is less challenging (in terms of size and ruggedness requirements) than for a smart wearable device. Some of the monitoring options discussed with SWDs can be directly applied to the cabin as well, while the cabin context offers additional monitoring opportunities.

On the topic of cough monitoring, which is very promising for selective disease recognition with SWDs, the approach also works with in-situ, fixed sound sensors in the cabin (Ijaz et al., 2022). It may even have advantages over the use of SWDs: reduced ambient noise, larger size allowing higher quality of sensors, possibility to track additional symptoms through noise (e.g. increased frequency of toilet flushing).

On the other hand, odor monitoring for disease identification, which is not yet feasible with SWDs, is not yet mature in the cabin context either. In fact, highly sensitive, compact VOC sensors for indoor use are needed. While there are many ongoing studies, there are no market-ready solution yet (Khatib & Haick, 2022; Spinelle et al., 2015). The first pre-commercial solutions are likely to be more suitable for point-of-care testing (Beduk et al., 2021) than for continuous environmental monitoring of disease-related odors.

Direct disease detection

All of the methods described above, including all but two of the solutions with SWDs (the face mask that changes color in the presence of SARS-COV-2 (Hu & Koo, 2022); the sweat monitor of (Jagannath et al., 2021, 2022)), are based on the indirect detection of a disease by correlating symptoms and vital signs. In the present section, the feasibility of direct detection, in the cabin, of the pathogen itself or of selective biomarkers (RNA, DNA, antibodies...) will be discussed.

Let us first discuss the indoor localization of pathogens: for airborne and drop-let-borne pathogens they have been detected on surfaces or in the air; for pathogens with biomarkers or direct presence in saliva, sweat, urine and feces, they have been detected in bathroom effluents (grey water from sinks and showers; black water from toilets) (Pilevar et al., 2021). The ability to detect SARS-COV-2 in air sampled directly in a room (Rahmani et al., 2020) or in the room HVAC system (Sousan et al., 2022) was demonstrated (Fig. 6), while (J. Pan et al., 2022) identified the room surfaces where SARS-COV-2 is most present: air filters, sink floor, and countertop. The presence of SARS-COV-2 in wastewater has been well documented since the seminal work of (Randazzo et al., 2020).

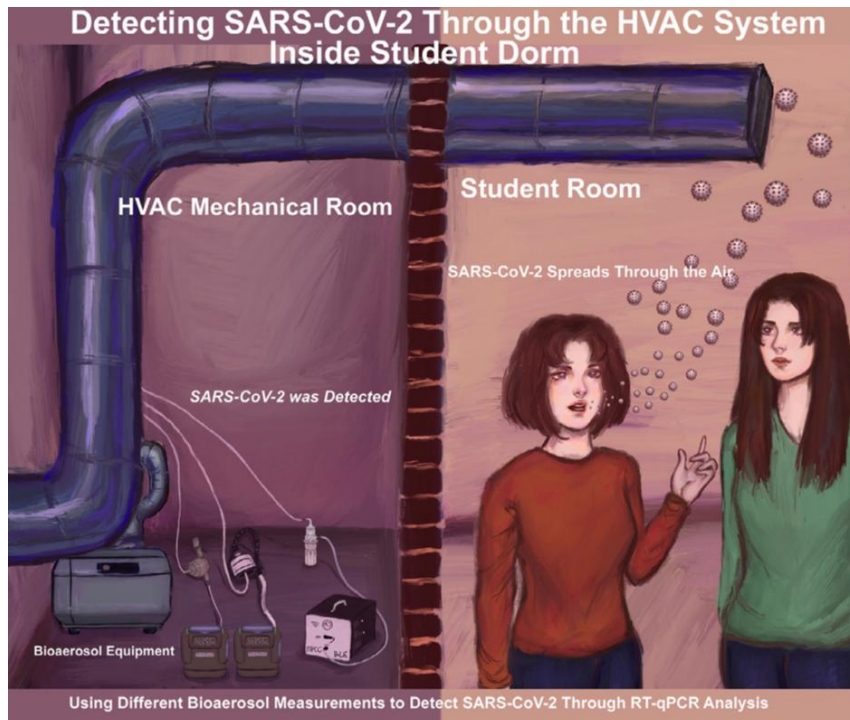


Fig . 6 : Illustration of HVAC-system based detection of SARS-COV-2 (*Sousan et al., 2022*)

Indoor pathogen detection is composed of three steps: sampling, sample preparation, and detection. The sample preparation stage – whenever required - include transfer of the sample in a medium appropriate for measurement and/or preconcentration.

Regarding sampling, automated air sampling has been available for some time; the numerous options are described in detail in (Krokhine et al., 2021; M. Pan et al., 2019) for example (Fig. 7). Air filters are also natural collectors of air-borne pathogens. Automated urine and stool sampling in the toilet has recently emerged and is now at prototype level (Grego et al., 2022; Mccord et al., 2019; Temirel et al., 2021) (Fig. 8). Let us remark here that, in the context of a cruise ship, these sampling solutions can be applied directly at cabin level, or by groups of cabins (e.g. connected to the same HVAC or blackwater system), or for the full ship.

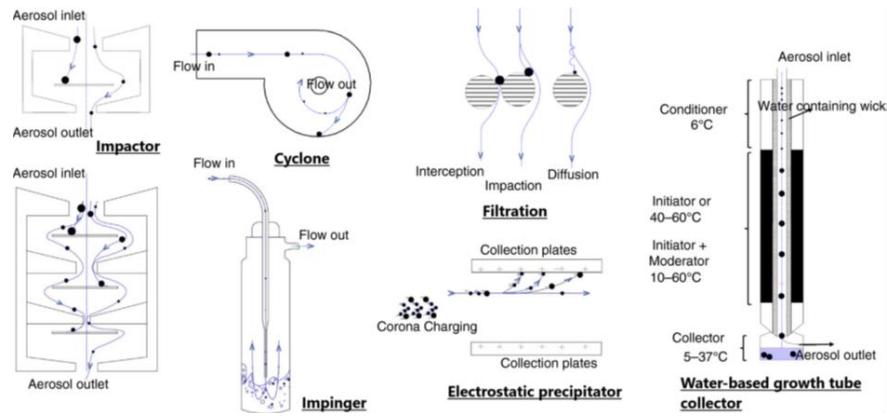


Fig. 7 : Solutions for collection of air samples. Reproduced from (M. Pan et al., 2019)

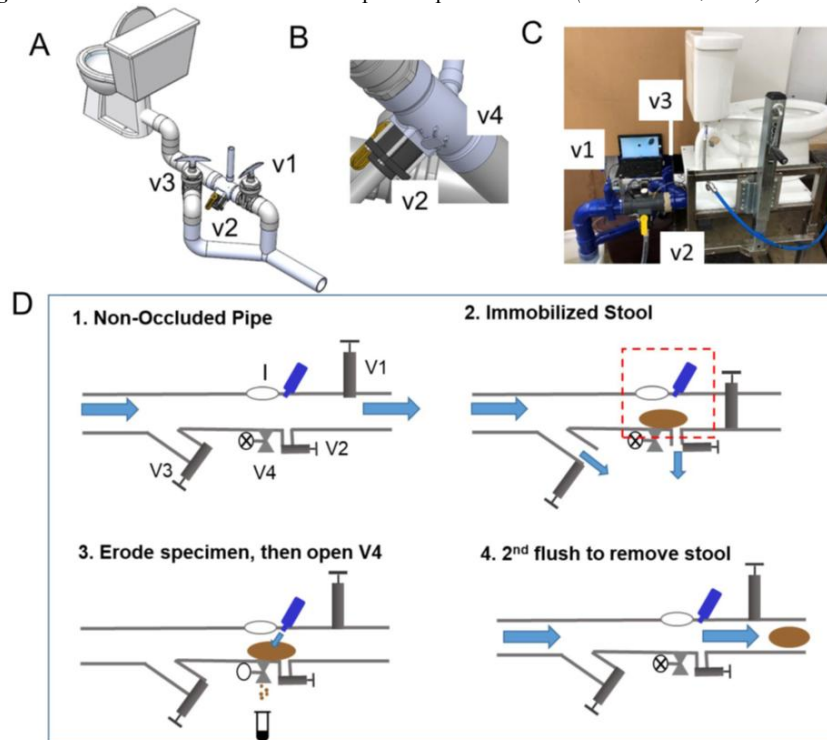


Fig. 8 : Schematics (A, B), prototype image (C) and principles of operation (D) of an automated, toilet-integrated stool sample collection system. Reproduced from (Grego et al., 2022)

On the detection side, a very large number of reviews cover the range of biosensors for identification of infectious diseases, such as (Pilevar et al., 2021) for water-borne pathogens, (Bhardwaj et al., 2021; Fronczek & Yoon, 2015; Pilevar et al., 2021) for airborne diseases. Limits of detection are now extremely low, e.g. single-virus-detection of SARS-COV-2 is possible with a portable solution based on carbon nanotube sensors (Liang et al., 2023).

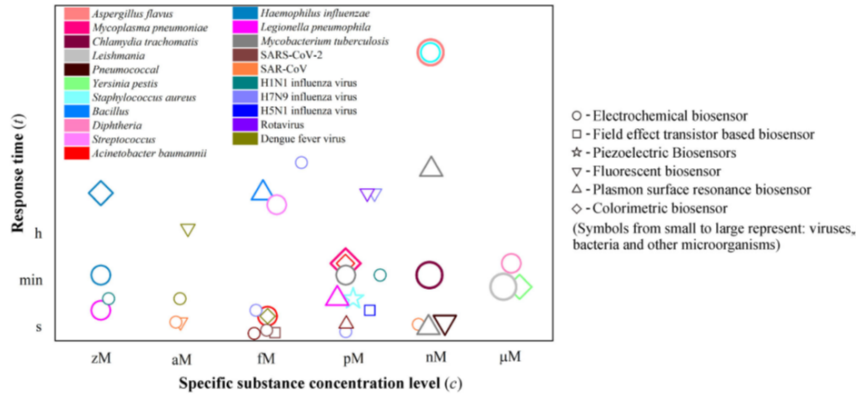


Fig. 9 : Classification of biosensors for infectious disease detection, by transduction type, limit of detection and response time. Reproduced from (Pilevar et al., 2021)

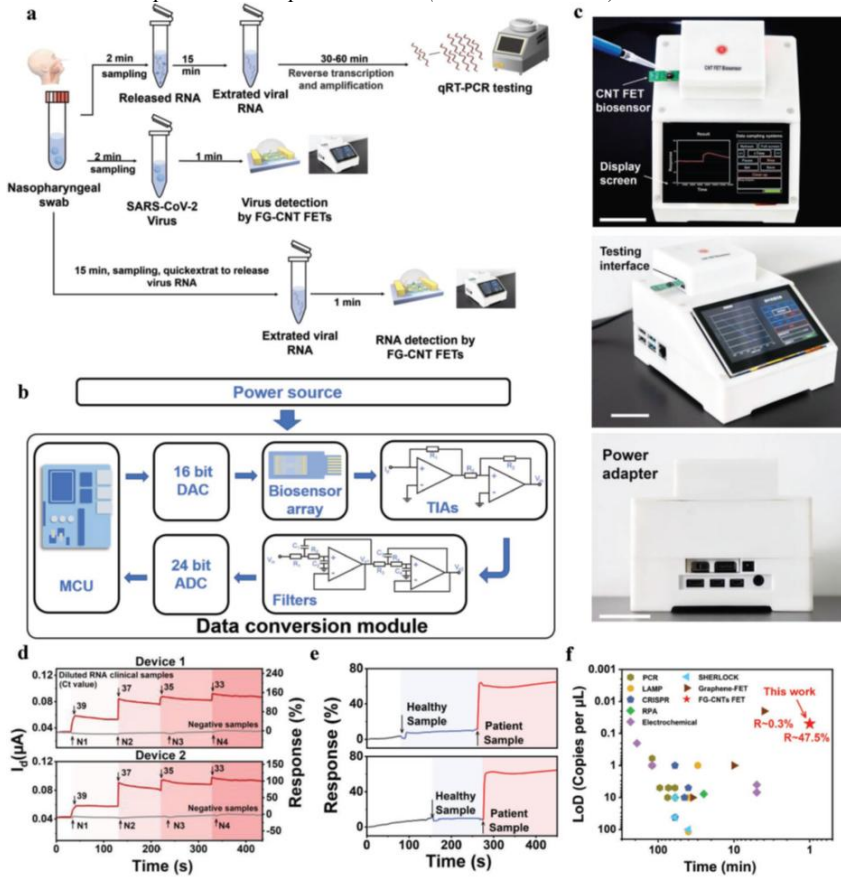


Fig. 10: Real-time detection of SARS-CoV-2 antigen and nucleic acid. a) Comparison of the workflow for detecting COVID-19 by qRT-PCR and multi-functionalized floating gate carbon nanotube field effect transistor (FG-CNT FET) FG-CNT FETs. b) Data conversion module of the

COVID-19 testing system. c) Prototype demonstration of the COVID-19 testing system, including test modules and power adapter sections (the scale bar: up: 4cm, middle: 3.5 cm; bottom: 5cm). d) Drain current versus time curve of diluted positive samples with concentrations from 0.05 copies/ μ L (Ct value is 39 to 100%) positive samples. e) Dynamic response signal detection in healthy and patient samples in UTM. f) Comparison of FG-CNT FETs (this work) with other SARS-CoV-2 RNA detection (LAMP: loop-mediated isothermal amplification; CRISPR: clustered regularly interspaced short palindromic repeats; RPA: recombinase polymerase amplification; SHERLOCK: specific high-sensitivity enzymatic reporter unlocking. R: response). Reproduced from (Liang *et al.*, 2023)

So, in principle, there is no scientific barrier to achieving automated sampling and then pathogen detection. However, in practice, solutions that combine an automated sampling system with a biosensor solution are extremely rare. The automated urine analysis solution developed by the Yellosis³ company (part of the Samsung startup ecosystem) was the only example found as of May 2023 (and it does not even target infectious diseases). Most likely, various companies are developing their own solutions in the wake of the COVID-19 pandemic, but so far they are either unsuccessful or have not widely advertised their results.

This lack of technological solutions points to a major complexity in translational research on biosensors for continuous disease monitoring: while solution exists at the research level, there are challenges in bringing biosensor solutions to a level of maturity compatible with continuous monitoring. For example, most biosensors couple a very sensitive transducer solution to a specific biological material; the interaction between this biological material and the target biomarker or pathogen is often not reversible, making the sensors disposable; if the interaction is reversible, the next hurdle is the (lack of) stability of the biological materials, which are relatively fragile to heat and common chemicals (such as chlorine); the durability of the sampling systems, especially for wastewater, is also a long-standing issue.

Summary of individualized disease monitoring solutions

Overall, the most technologically mature solution for disease identification at the individual level today is sound monitoring. This solution is applicable only in the case of respiratory diseases. It can be implemented using either smart wearable devices or fixed cabin sensors.

Vital signs monitoring via commercially available smart wearable devices is the second most mature option, but there are uncertainties regarding the accuracy of disease identification. While detecting whether an individual has a disease is straightforward, the capability to distinguish between diseases remains unclear and requires further investigation.

At prototype level, selective detection of an infectious disease by monitoring selected biomarkers in sweat has proven feasible, although the time-to-market of such a solution remains to be evaluated.

³ <https://cym702.com/app.php>, last accessed May 15th, 2023

On the other hand, despite strong need, automated, continuous direct monitoring of pathogens in air, on surfaces and in wastewater is not available today. The sampling solutions exist, as do the biosensors, but there are translational research challenges in coupling the two.

Conclusion and prospects

Optimal prevention of outbreaks on cruise ships begins in the ship's health center with accurate diagnosis of sick individuals. Diagnostic capabilities there are only available for a very small number of infectious diseases. In contrast, all the major diseases of interest to cruise ships can now be diagnosed in near real-time with point-of-care tests. Given the low cost of these tests, it appears feasible to equip the cruise ships with a wide range of these tests to adequately cover the most prevalent and impactful diseases.

Detection in the ship's health center should be complemented by real-time, accurate, individualized disease tracking throughout the ship. The most mature option is undoubtedly the monitoring of respiratory sounds in the cabin or via wearable devices (including via smart phones and smart watches), but this option is limited to respiratory diseases. Symptoms and vital signs correlation using specific (top shelf) models of smart wearable devices is a feasible option, but there are still doubts about the accuracy (with respect to different diseases) of the approach. More selective solutions based on biomarkers or direct pathogen detection are still at research level and are unlikely to be applicable in the near future.

Overall, it appears that the generalization of solutions for real-time, accurate, individualized disease tracking on ships is still questionable. Until these techniques reach technology maturity, symptom-based, continuous, real-time screening of diseased individuals would be a feasible strategy. As is described in (Bruno Almeida et al., n.d.), this can be achieved with current commercial technologies, either with smart wearable devices, with fixed cabin sensors and/or with sensors deployed throughout the ship. A positively screened individual would be offered an immediate visit to the health center. There, point-of-care diagnosis would be performed straightaway to assess the risk of the symptoms being caused by an infectious disease. This solution is not perfect, as it requires action on the part of the screened individual; however, proper configuration of the symptom-based screening algorithms would ensure early detection of sick passengers throughout the whole ship, which in turn would allow for early activation of epidemic mitigation measures.

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