Aptamers for Detection and Diagnostics (ADD) is a proposed mobile app acquiring optical data from conjugated quantum nanodots to identify molecules indicating presence of SARS-CoV-2 virus: Why public health and healthcare need smartphone sensors as a platform for early detection and prevention

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DRAFT

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ABSTRACT

Engineering a biomedical device as a low-cost, non-invasive, detection, and diagnostic platform for surveillance of infections in humans, and animals. The system embraces the IoT “*digital by design*” metaphor by incorporating elements of connectivity, data sharing and (secure) information arbitrage. Using an array of aptamers to bind viral targets may help in detection, diagnostics, and potentially prevention in case of SARS-CoV-2. The ADD tool may become part of a broader platform approach.

1. ADD for SARS-CoV-2

The scale of mortality and morbidity due to SARS-CoV-2 evokes us to explore unconventional approaches to mitigate the risks presented by pandemics. Scientists may be less aware of the discovery of aptamers thirty years ago but the “fit” of aptamers with respect to the molecular biology of the current problem makes it worthwhile to propose new tools. Innovation may arise from the combination of chemistry and molecular biology with sensor engineering and opportunity for data dissemination¹ to benefit public health² by integrating the principle³ of internet of things⁴ (IoT⁵ as a design metaphor).

	Emergence	Cases	Fatality Rate	Transmissibility
SARS	2003	8,098	11%	+
MERS	2011	2,519	34%	+
SARS-CoV-2	2019	> 50 million	0.5-1% Est	+++
SARS-CoV-3?	??	??	??	??
SARS-CoV-4?	??	??	??	??

Table 1: Is the eight⁶ year interval between SARS, MERS and COVID-19 just an unrelated coincidence?

2. Aptamers for Detection and Diagnostics (ADD)

Single stranded (ss) DNA aptamers (ssRNA⁷ are equally useful⁸ but susceptible to degradation by ribonuclease) bind with **specificity** to SARS-CoV-2⁹ proteins (Nucleocapsid, Spike, Nsp1). Aptamers are conjugated with carbon or cadmium quantum (QT) nano-dots. If there are viruses (1, 10, 100, 1000) in a sample (sputum, saliva) at a detectable level, then it triggers QT.DNA (QTD) conjugated complex to transmit optical property change (EIS or electrochemical impedance spectroscopy is another option for signal transduction). An optical signal transduction mechanism may offer low cost data acquisition, enabling billions of people to use ADD (detection tool) *at home or anywhere* (**AHA**). The end-user must have access to the "QTD" conjugate (distributed by health departments in hamlets, towns and cities). QTD (product) may be a slurry in a tube labeled as "CoV-2-DETECTION & DIAGNOSIS" (C2DD). It remains to be investigated if inclusion of endo-b-N-acetylglucosaminidases (ENGases¹⁰) in the slurry may be necessary to expose the binding sites by partially removing the N-glycan coat if the viral Spike protein is the target (Figure 20). Imagine **C2DD** as a tube of lip balm or similar form factor. For supply chain and logistics, it will reduce operational cost of distribution if C2DD may be shipped as a tamper-proof sterile vial without the need for cold supply chain or special storage to extend shelf-life.

First, the end-user uses her **smartphone holo-lens "QTD" app** (may not be limited to Microsoft, others who can/may develop are Apple, Google, Baidu, Tencent) to take an image of the C2DD vial/tube *without* sample (no virus). Priming (tuning) step is **critical** to establish a baseline for signal transduction and app-embedded data analytics engine to set the system to "without virus" ground state to obtain an optical "ground zero" (baseline will be different for EIS). Open question for instrumentation is the need for UV activation (for traditional nanodots) to record the shift (valence electron transfer). Can the app be configured to *perform the activation* and record the photoluminescence change? Using visible light to activate and coupling activation/quenching with the app needs innovative chemical/device engineering.

Second, the end-user spits (or adds a small volume saliva or sputum using a swab/spoon) in the test tube (vial). *There is room for controversy in this step but it is the easiest non-invasive procedure.*

Third, end-user uses her smartphone holo-lens "QTD" **app** to record optical change (as soon as possible after adding saliva/sputum). Perhaps similar to bar code or EPC or QR code scanning.

Fourth, end-user uses her smartphone holo-lens "QTD" **app** to record optical changes every 5 minutes for 30 min (from the time of adding the sample). There will be questions about ENGase activity, binding kinetics of the aptamer, signal to noise ratio ([filtering algorithms (Kalman¹¹ filter), error correction], activation/quenching issues, damping of signals due to interference from host proteins, salinity and pH of mucus-mucin/saliva/sputum sample (any or all could jeopardize binding and signal).

3. ADD Digital Data Design

Baseline versus change over time will appear as a plot in the app (analytics, Figure 1, uses basic machine learning (ML) tools, for example, SVM or support vector machine). Fool-proof visualization by generating a "traffic signal" visual [green oval (NO virus detected); red oval (virus detected); yellow oval (inconclusive/ambiguous)]. Data gathered by the smartphone app (if enabled by user) to be transmitted to national centers of epidemiology (eg CDC in USA, ECDC in EU) and local hospitals (the choice will be user-dependent). Allowing collection of anonymized data may be one alternative (without recording IPv6/IPv4 addresses) but pros/cons to be considered for the greater good, public safety and privacy¹².

This app is a "frontline" detection tool which may be used **everyday** or each week, At Home or Anywhere (AHA), by individual users. The "C2DD" vial has no therapeutic value. Positive results (red oval - virus detected) may have to be re-confirmed using lab tests (PCR, mAbs) in a clinic or hospital. **C2DD PRODUCT and associated SERVICE "QTD" app if combined**, are **data-informed tools**. It does not offer or guarantee further testing or treatment. Distribution and pricing of the hypothetical C2DD product and proposed pay-per-use (PAPPU¹³) service for QTD will be debated by corporations. Free distribution of C2DD and a **micro-payment** model (pay-per-use) for the "QTD" app is **advocated**.

Users may hide or selectively control data/information sharing as well as access to surveillance data (data from daily screening for infection by the infectious agent in question). Secure sharing of surveillance data by users (**citizen science**) is recommended to generate a robust and representative status of the community or infected demographics in the region in terms of **molecular epidemiology**.

In general, data from molecular epidemiology is critical for resource-constrained healthcare supply chains to optimize planning (humanitarian logistics), allocate human resources (medical professionals) and organize transportation of materials to the geographic areas where assistance is needed, the most.

Citizen science¹⁴ efforts are germane for the efficacy of healthcare systems in case of widespread infections (epidemics/pandemics). The tools which makes citizen science possible and effective may be viewed as global public goods. Similar systems for **animal surveillance** (farms, cattle, poultry, meat) are necessary to reduce infection in domestic animals (pets) and from crippling the food supply chain.

Components of the ADD system (QTD, C2DD) including mobile data collection, information arbitrage and public health applications are not limited to SARS-CoV-2 but is a **platform approach** which includes digital design elements illustrated¹⁵ in Figure 1. Citizen science supported public health may immensely benefit from detection of viruses, bacteria, fungi, prions or **any infections agent** as long as an aptamer (oligonucleotide based on the idea¹⁶ of an "anti-sense" approach¹⁷) may bind a small molecule or a macromolecule (peptides or proteins) with sufficient specificity, sensitivity and selectivity to generate credible data which may be *distributed* in real-time to inform and initiate subsequent steps.

Figure 1: ADD system also includes data acquisition, analytics and data distribution which includes elements of the concept referred to as internet of things (IoT) which is a “digital¹⁸ by design” metaphor. Cartoon shows the potential path of raw data from the hypothetical binding between a sensor and a target¹⁹ molecule. Raw data from signal transduction due to binding activity is transmitted and acquired at the “edge” by the smartphone. The raw data is “processed” using tools either at the edge (embedded operations in the smartphone) or data may be uploaded to the cloud. Post-cloud computing analytics is returned to the edge device for display within an ADD application portal on the smartphone. The choice between edge versus cloud computing is a function of infrastructure (availability of wireless bandwidth, at the edge). The user may observe a difference in the time that it takes to process the data and display information (delayed visualization due to latency, function of bandwidth and speed).

Data scoring and processing is recommended due to variability of systems. ADD proposes the use of aptamers but other alternative arrays (see section 6) which may use the general approach (above) may “weigh” the information based on probability of false positive / false negative outcomes from tests²⁰ (separate from false positives / false negatives in machine learning²¹ models). Assigning weighted risk to data and running other analytics can be performed on the mobile device (smartphone) or in the cloud, depending on access to and quality of telecommunications infrastructure. Cloud computing could add latency²² between upload and display of information or prediction, depending on availability, reliability and connectivity to the internet. Several regions of the world still lack sufficient access to the internet²³.

Scoring, processing and assigning risk within the analytical engine may benefit from machine learning (ML) tools to create a set of models or rules, to be described by and agreed on by experts. The system may scan and screen the image or data from the holo lens app (optical signal) to compare with these models or rules. Assigning an “image risk score” (IRS) may influence the presentation of the raw data where the “traffic signal” “red” may be provided with a sub-text containing a confidence score or include a qualitative comment (**likely** presence of virus) associated with a Likert-type²⁴ indicator/scale.

In any procedure, enabling the IRS to influence the raw data must be stringently controlled. Models or rules must be agreed by global experts whose credibility may be above question. Hence, these models and rules must stay outside the realm of testing services or labs or groups that are involved with creating systems, for example, ADD. It is preferable if model scoring (assigning risk score to an upload) runs on a platform which is not influenced by the local operator or the mobile user. The smartphone uploading the data may use a “tool” that applies the IRS engine residing in a secure infrastructure in a public cloud (FDA, NIH, NSF, CDC, ECDC) using appreciable level of cybersecurity (eg. Microsoft Azure, Amazon AWS). The smartphone must have the permission and physical availability to wireless internet or mobile data network to remotely access analytical tools in the cloud, such as, the IRS engine.

One alternative is to install (and update) the data scoring models/rules (IRS engine) in the ODS (operational data store, see Figure 1). The ‘message broker’ receives uploads and sends them to the ODS, which serves “hot” data to the app. ODS database is tuned for rapid reads, and serves requests made by the mobile app (only recent uploads and metadata about those uploads, including “risk scores”).

Risk scores are generated from models which are trained from historical data relevant to the test in question (using aptamer or antibody or other molecules, for example, hACE2). There must be access to sufficient statistical data from each type of test to create a credible risk score. If the model is based on bad data (garbage in), the risk score and IRS engine will spew bad information (garbage out). The model’s responsibility to assign “risk score” impacts the “traffic signal” and could alter the outcome. Model training²⁵ requires vast quantities of historical data, curated and pooled across multiple users who used the test and **verified** their outcome. If the binding was positive it must be corroborated by PCR²⁶ or another test with even higher specificity to confirm the result from the binding test using ADD tool.

Model-building is an iterative exercise that requires lab data from testing to be evaluated by credible scientists before data scientists can use it (curate?) to train ML models, which are error prone²⁷. In model scoring, a model (in the IRS engine) is called to act on the uploaded (input) data. This analysis generates a prediction, displayed on the smartphone as information or recommendation for the user. The outcome the user views depends on the **design choices** made in ML model²⁸ training. It is absolutely central that model scoring requires **“features”** (characteristics germane to model/analysis). Creating features²⁹ is the task of a **team** of specialists (scientists collaborating with data experts). Harvesting

feature vectors and data relevant to the feature is the task of feature extractors. It may be provided by humans or we may use automated³⁰ feature³¹ selection/extraction³² to generate features from raw data.

4. Beyond ADD

Scientific and engineering challenges to design ADD must embrace trans-disciplinary activities. But, no new physics is necessary. ADD may be available to **billions**, as a low-cost mobile AHA (at-home) **product** linked to IoT-type **service** app. The user experience is related to the service, not the product. The convergence of hardware and software with science and engineering as well as analytics and machine learning to **meaningfully** ascend the DIKW pyramid (data, information, knowledge, wisdom) is key to creating any detection **platform** where other tools and devices may upload data using open data APIs and standards-compliant data interoperability (DDS³³) tools to aggregate or explore cumulative analytics, integrated with other systems, for example, geographic information systems³⁴ or GIS.

In the broader spectrum, ADD is an embryonic element of a potential **global health surveillance platform** (GSP) which may be pivotal as an early warning signal for humans and animal farms. Lessons from tsunami detection are sorely missing from public health policy discussions. Implementation of GSPs are neither a part of any local public health strategy nor on the agenda of precision population health management organizations (CDC, ECDC, WHO).

An important element of the **global health surveillance platform** (GSP) may include data from non-invasive profiling, referred to as “*pay-per-pee*” healthcare, which may be instrumental in molecular profiling for longitudinal studies on health and wellness³⁵. GSPs may try not to dwell on genomics³⁶ (DNA) and expression³⁷ (RNA³⁸) in imprecision³⁹ medicine but include proteomics because gene expression is insufficient unless the **functions** are **implemented** by proteins. Aptamers⁴⁰ in proteomic profiling (GWAS⁴¹, metabolomics) and other applications⁴² including ADD may benefit from synergistic integration to help predict status of health (collected papers⁴³ provide select applications of aptamer).

Genomics is a “snapshot” (static structure of the infrastructure) and transcriptomics (RNA, GTEx) is an indicator of expression, which is data, but data may not (always) contain information. Proteins bind⁴⁴ in a myriad of ways⁴⁵ and translates *data to usable information* to maintain standard dynamic operating procedures (physiology, homeostasis, metabolomics).

Proteomics is a “time series” but its analysis over time may be interrupted due to feasibility and logistics of implementing programs like *pay-per-pee* healthcare, not to mention the complexity involved in extracting sense, often cryptic, from thousands of protein profiles, *over time*. Static protein profiles using NMR and mass spec⁴⁶ tools only capture *snapshots*. Can proteomics make sense⁴⁷ of a cytokine storm as markers of counter-anti-inflammatory response⁴⁸ even before the infectious agent is detected? Perhaps it is utopian to expect proteomic profiling as a daily practice in healthcare and home-health.

<https://dspace.mit.edu/handle/1721.1/56251>

Weigh-scale, BMI, FOBT, urine analysis, sugar, ketone body analysis, blood pressure monitor, pulse oximeter, networked to phone via WiFi and/or Bluetooth with biometrics and face recognition for secure communication with physician and hospital or clinic, globally.

5. Prevention follows Detection and Diagnostics

If viewed⁵⁰ as non-classical antibodies⁵¹ then the role of aptamers vastly exceeds that of detection. It spills over into prevention, perhaps as an alt-vaccine, albeit non-immunogenic. Identifying aptamers that can detect viral proteins in saliva implies that the aptamers may also bind the same protein (albeit with altered kinetics⁵²) if administered topically (nasal spray, throat spray, soft-mist inhaler). Protecting the naso-pharyngeal area by saturating it with aptamers which binds (irreversibly?) to proteins from respiratory viruses (SARS) may be a preventative measure. Asymptomatic⁵³, pauci-symptomatic and COVID-19 patients clearly expressing symptoms associated with SARS-CoV-2 may continue application of the aptamer cocktail to reduce the spread of infection by disabling (?) nascent virions. Aptamers preventing the spike protein (S1 RBD) of SARS virion from *attaching* to the ACE-2⁵⁴ viral receptor protein of uninfected cells may slow down the infection and development of COVID-19.

It follows that aptamers can also bind to any or all viral proteins not only in the extracellular space but also *inside* the cell. Delivering a portfolio of functional aptamers inside the cytosol must face the challenges posed by bio-availability and toxicity due to the potential for perturbing functions of essential⁵⁵ cellular proteins. Creating aptamers as *alt-vaccines* for *any* infecting organism (virus, bacteria, fungi, prion) which uses a protein in its lifecycle may be an (~30 year) old idea. Will the use of aptamers gain greater prominence in global public health practices, as a low-cost *global public goods tool* to contain the current and future epidemics and/or pandemics, worldwide, in humans and animals?

Single stranded RNA or ssDNA aptamers are not linear “tapes” but 3-dimensional *shapes* as illustrated by the discovery of tRNA⁵⁶ by Paul Zamecnik, Mary Louise Stephenson and colleagues at MGH, HMS. Publication of the discovery of tRNA by Zamecnik in 1958 catalyzed an array of milestones including the discovery of mRNA by Brenner⁵⁷ and Gros⁵⁸ as well as the *lac operon* model of feedback inhibition by Jacob and Monod⁵⁹, all three published in 1961. The role of proteins in regulation⁶⁰ emerged as central to physiology and metabolism. In transcription, translation and replication⁶¹ the binding between proteins and nucleic acids acted as a “switch” (mechanism of action). The notion⁶² of aptamers⁶³ germinated⁶⁴ in 1990 but it drew on knowledge from binding between oligonucleotides and proteins. Aptamers may be 20-60⁶⁵ oligonucleotides or more. Binding specificity⁶⁶ of an enriched pool may be orders of magnitude different (K_d) between a nearest neighbor or an analog. Sequential steps⁶⁷ are necessary from a starting sample (for example, 9×10^{14} ssDNA oligonucleotides) to arrive at an enriched pool of aptamers (19 ssDNA aptamers). The process has evolved⁶⁸ in complexity⁶⁹ and unique structures may be involved⁷⁰ in conferring specificity. In many applications⁷¹ of aptamers⁷² the debate also involves issues pertaining to trust and doubts⁷³ due to the constant demand for increasing accuracy and precision with respect to sensitivity, selectivity and specificity, in detection and diagnostics.

Current and future⁷⁴ application⁷⁵ of aptamers include chemistry⁷⁶, chemotherapy⁷⁷, food⁷⁸ safety, diagnostics⁷⁹, antibodies⁸⁰, alt-vaccines⁸¹, imaging⁸² and different⁸³ types⁸⁴ of biosensors⁸⁵. ADD as a detection tool for SARS-CoV-2 proposes aptamer-based sensors (aptasensors) to detect SARS-CoV-2 proteins. When an aptamer binds with the target, the signal (data) will be transduced and captured by a mobile device. Analytical tools will process data and display information on smartphones (Fig 1). Data dissemination will follow according to user preferences, to inform public health authorities or hospitals.

Optimism for aptamers as detection tools⁸⁶ extend to SARS-CoV-2 due to the detection of SARS-CoV (etiologic agent of 2008 SARS epidemic) C-terminal of N (nucleocapsid) protein at a concentration as low as 2 picograms/mL using a RNA⁸⁷ aptamer in a nanoarray. Tests using saliva⁸⁸ may be unsuitable for RNA⁸⁹ aptamers due to presence of ribonuclease⁹⁰ (RNase). DNA aptamers previously shown to bind to the N protein of SARS-CoV (K_d 4.93±0.3nM⁹¹) also⁹² binds to the N protein of SARS-CoV-2. The N protein⁹³ of SARS-CoV-2 shares 91% sequence homology with the N protein⁹⁴ of SARS-CoV but is less similar (16% - 38%) with N protein from the other 5 known human coronaviruses. Thus, detection⁹⁵ of N protein in saliva using an aptamer-based ADD aptasensor is *possible*. Aptamer-based technologies⁹⁶ directed toward SARS-CoV-2 Spike protein are gaining⁹⁷ momentum⁹⁸. Blocking⁹⁹ the S protein from attaching to hACE-2 may perturb viral entry and prevent¹⁰⁰ the spread of infection. Aptamers created against the S1 RBD¹⁰¹ may block binding to hACE-2 (internally) or serve as a detection tool (external ADD aptasensor) to test saliva/sputum for SARS-CoV-2. Other¹⁰² SARS-CoV-2 targets¹⁰³ including Nsp1¹⁰⁴ may be less accessible in saliva because they are synthesized after viral entry. But, during the burst cycle, when new virions are released, viral proteins inside the host cell may be exposed. The targets are not limited to external viral proteins (spike, nucleocapsid, envelope proteins; Figure 4).

Signal transduction and data acquisition follows detection. In addition to EIS (electrochemical impedance spectroscopy¹⁰⁵) signals, optical signals are preferred because data acquisition using cameras and apps in smartphones are feasible in locations where resources may be limiting. Protein¹⁰⁶ detection¹⁰⁷ by conjugating aptamers with quantum dots¹⁰⁸ is a tried¹⁰⁹ and true¹¹⁰ process¹¹¹ which may be the optical signal (data) for this **system**. Changes in optical characteristics due to binding may be captured by cameras on mobile phones or HoloLens¹¹² app in smartphones may scan the saliva sample (think barcode or QR¹¹³ code scan). Cameras (sensors) associated with the holo-lens (Kinect¹¹⁴) can scan the “field” and collects data to create a digital geometry¹¹⁵ (digital model, 3D image). For ADD, HoloLens tools required for holographic functions¹¹⁶ may be unnecessary, for example, accelerometer (speed of movement), gyroscope (tilt, orientation) and magnetometer (compass). Optical data captured from saliva containing testing vials will be analyzed (machine learning tools; see Figure 1) followed by visualization of information on the mobile device and (secure) information arbitrage, if authorized.

6. Alternative Arrays

Figure 3: **Multiplexed¹¹⁷ Detection Tool for SARS-CoV-2.** Upper panel presents potential recognition and detection chemistries. The data (fusion, middle panel) will be analyzed and assay results displayed (bottom). The data and information will be displayed on a mobile device (see cartoon in Figure 1). Three distinct binding targets for SARS-CoV-2 spike protein RBD are presented in sections A, B (ADD) and C. In (A) RBD-antibody (SARS-CoV-2 strain specificity) is functionalized with EDC-NHS chemistry to metal (gold, Au) nanoparticles (or may be attached/adsorbed on laser inscribed graphene, LIG). In (B) single-stranded DNA aptamers with thiol linker is adsorbed to metallized LIG (ADD aptasensor). In (C) histidine-tagged human ACE2 is adsorbed to metallized LIG. (D) Binding elicits signal (EIS, impedance spectroscopy) which is transduced to a mobile device. Data acquisition is followed by “hot” data upload to embedded tiny database (tinyDB¹¹⁸) in the device (ODS in Figure 1). Analytics may be executed on the device (embedded logic, machine learning tools) or uploaded to cloud server. The data fusion (model scoring) step may be necessary to make sense of the data, *in combination*, to provide not only raw data (results from A, B and C) but information, extracted from data and processed according to a simple SNAPS¹¹⁹ paradigm to convey the *meaning of the outcome*, to inform the non-expert end-user.

Interpretation of data may be necessary due to the caveats of target binding and recognition. The specificity of the antibody used in the tool may not bind or bind with lower affinity (K_d) with viral target protein (Spike protein) due to mutations in the epitope which generated the immunoglobulin (IgG). Lack of binding or lower affinity of binding can interfere with signal generation and failure to log signal over noise. Thus, individuals carrying SARS-CoV-2 may fail to test positive (false negative) if the viral variant possesses mutations preventing the antibody (A) to bind with the mutated Spike protein. Other factors (temperature, pH, salinity) may also interfere with signal (see “model scoring” in Appendix).

In (B), binding with the aptamer is highly specific but it depends on precisely which oligonucleotide (sequence of the ssDNA from an enriched pool) binds to which part of the Spike protein. For ADD, one aptamer may bind to the RBD (receptor binding domain) of the SARS-CoV-2 Spike protein. The length of the RBD (primary sequence) used in screening and enriching for the aptamer(s) may influence the shape (structure) of the RBD during selection phase. The complementarity of the shape of the RBD and the secondary/tertiary structure of the ssDNA *complex* is key to the binding specificity and affinity. If the test sample contains the whole Spike protein (includes RBD) as well as fragments (peptides with different lengths of amino acid sequence) which may or may not contain the RBD then the binding to the aptamer may fluctuate (widely) because the primary sequence of the protein may influence the secondary and tertiary structural outcome. The latter may change the configuration of the RBD in a given fragment and prevent binding to the aptamer, generating a false negative. If a sample contains other proteins and peptides, it is possible that the 3D configuration of an arbitrary protein or protein fragment could mimic or compete, albeit partially, with the RBD, and elicit a signal by binding with the aptamer, even if the binding is ephemeral due to reduced affinity (false positive result).

Binding of the Spike protein RBD to the immobilized hACE2 protein target (C) is probably the weakest link in this tripartite approach. Presence of mutations, dynamic or modified configuration and the effect of the environment (temperature, pH, salinity) may perturb binding and corrupt the signal.

Error correction and data curation may be necessary to prevent data corruption (false negative, false positive, limit of detection) to improve the information and recommendation for end-users. If the confidence in the raw data from each element is high, then the data may be responsibly combined (*after data scoring, image risk score*) to display the information with an assigned degree of confidence which may be more than the sum of the parts (positive, negative, false positive, false negative). The strategy from data acquisition and display vs information and recommendation must reduce risk, optimize level of precision and accuracy to maximize the value of the information for the user and/or the community. Of greater concern is the *accumulation* of errors, which when aggregated (time series data from ADD used as a surveillance tool), may generate spurious results with respect to the status of the population.

7. Array of Targets

The ADD approach for detection of infectious agents is based on targets identified from the biology and/or lifecycle of the organism and its interaction with the host (humans, animals). The RBD (receptor binding domain) of the Spike protein from SARS-CoV-2 and the human ACE2 cellular receptor (in bats, rats, pangolins and related animals in the phylogenetic tree; reviewed in reference 9) are under intense scrutiny. But, exploring the biology of SARS-CoV-2 reveals other equally potent targets. Developing drugs, antibodies and aptamers may benefit from a brief review of the viral biology. For SARS-CoV-2 detection alone, there are at least two other external proteins which may serve as targets for binding to aptamers, the M protein and the E protein in addition to S protein (Figure 4).

Figure 4: ssRNA genome of SARS-CoV-2 is longer compared to other RNA viruses (HIV, Influenza, Zika, Ebola; see Figure 16). It is encased in a nucleocapsid core (N protein¹²⁰) and resides inside the virus. External surface of the virus is studded with S (spike), M (membrane) and E (envelope) proteins.

The receptor binding domain (RBD) of the Spike protein appears to make the first contact with the human cellular receptor ACE2 (angiotensin converting enzyme 2). Disrupting this event is the Holy Grail for preventing the virus from entering the cell. The mechanism by which Spike protein facilitates viral entry is not merely due to the recognition (between RBD and ACE2) but a cascade of events that begins after successful binding. The events that follow result in *fusion* of the viral envelope with the cell membrane, thereby allowing the viral genetic material (+ssRNA) to be delivered inside the cell in order to create progeny viruses. *Fusion* is mediated by the *fusion machinery* and *fusion peptide* sub-segments of Spike S2 protein which includes a step resembling a “jack-in-the-box” toy¹²¹. These segments of the Spike protein are *better conserved* and occupy a distinctly different part of the Spike protein (Figure 5).

Figure 5: Sequence conservation¹²² of sarbecovirus S glycoproteins plotted on the SARS-CoV-2 Spike protein structure [viewed from the side (A) and top (B)]. The receptor binding domain (RBD S1) is separate from the region of the Spike S2 protein necessary to initiate viral entry. The latter is better conserved (fusion machinery, fusion peptide) and perhaps better targets for ADD aptasensors.

The better conserved segment of the Spike protein may offer valuable epitopes¹²³ and potential binding sites for aptamers (unless glycan moieties interfere). In addition to the RBD (which appears to be more variable), the conserved portions of the S2 subunit responsible for fusion (fusion machinery, fusion peptide) are likely targets for aptamer binding. It remains to be seen if reagents (monoclonal antibodies, aptamers) aimed at the fusion specific domain of the S protein can disrupt viral entry and serve as tools for detection *as well as* prevention.

Interfering¹²⁴ with the human cellular proteins ACE2 and TMPRSS2 (which are viral targets) to prevent viral binding may not be prudent. Reagents directed against proteases, usually non-specific, may perturb physiological functions essential for homeostasis. The events which follow after the viral Spike protein docks with the human ACE2 protein are illustrated (Fig 6 copied from Scientific American¹²⁵).

Figure 6: Cascade of events¹²⁶ leading to viral entry into host lung cell identifies the “*jack-in-the-box*” mechanism as a pivotal tool used by the fusion machinery of the Spike protein to deliver the viral RNA inside the host cell. Selectively disabling the fusion machinery of the Spike protein is an attractive target for aptamers and other reagents. If available, the latter may not only detect and diagnose but prevent infection, even if virus particles may have already reached the human apical surface¹²⁷ area. Superior region of the lungs are more vulnerable to infection due to higher number of hACE2 receptors. The number of hACE2 decreases from superior to inferior. Lower part of the lungs have less ACE2 and TMPRSS2 proteins, corroborated by the observation that these genes are expressed at a higher level in upper nasal epithelial tissue compared with bronchial and small airway epithelial brushings¹²⁸.

The +ssRNA of SARS-CoV-2 (positive strand serves as mRNA) generates at least 27 or more viral proteins by creatively manipulating the host translational machinery. Theoretically, any or all viral proteins could serve as targets for anti-viral¹²⁹ strategies. Virus-encoded proteases¹³⁰ are distinct¹³¹ from cellular proteases and may serve as good¹³² targets. The viral protease¹³³ 3-chymotrypsin-like protease¹³⁴ or 3CLpro¹³⁵ aka M^{Pro} is encoded by Nsp5 and appears¹³⁶ to cleave (see “scissors” in Figure 7) essential viral proteins from “polyproteins” generated from translation of open reading frame (ORF) 1a and 1b (Fig 7). Papain-like protease¹³⁷ PLpro (ORF 1a, Nsp3¹³⁸), cleaves¹³⁹ proteinaceous post-translational (ref 131) modifications on host proteins to evade host anti-viral immune responses. Nsp1¹⁴⁰ suppresses host translation by cleaving cell mRNAs¹⁴¹ and competes¹⁴² with mRNAs for binding to human 40S ribosomal mRNA channel¹⁴³ (as well as 43S, 80S subunits). Type 1¹⁴⁴ interferon¹⁴⁵ (IFN-1) response¹⁴⁶ is modulated by Nsp1, Nsp 6 and Nsp13, which interferes indirectly with IFN-1 by suppressing the phosphorylation and/or nuclear translocation of other cellular molecules¹⁴⁷ involved in catalyzing the IFN-1 response.

Figure 7: (Top) SARS-CoV-2 genome¹⁴⁸ encodes nonstructural proteins (nsp), structural and accessory proteins. Nsps are encoded by ORF1a & ORF1b generating pp1a (nsps 1-11) or pp1ab (nsps 12-16). The structural and accessory proteins are synthesized by translation of their respective sub-genomic mRNAs. (Bottom) Translational repression (Kamitani *et al*) and binding to 40S ribosome (Thoms *et al*) by Nsp1.

Figure 8: The positive sense (+ss) RNA genome is translated by the host translation machinery to make polyproteins that are co-translationally cleaved by proteases (PLpro/Nsp3 and 3CLpro/Nsp5) encoded in the polyprotein to generate components of RdRp or RNA dependent RNA polymerase (Hartenian and Nandakumar *et al*). The RdRp complex uses the genome as a template to generate negative sense subgenome and genome length RNAs, which are in turn used as templates for synthesis of positive sense full length progeny genomes and subgenomic mRNAs. Each and/or any protein factor in this complex may be a target for anti-viral reagents, for example, aptamers, antibodies, small molecules and inhibitors.

The conundrum and complexity presented by an abundance of anti-viral targets, a variety of strategies and potentially many cell types susceptible to infection, adds to the pharmaceutical dilemma where the problems of bio-availability, cross-reactivity and toxicity may force a solution to extinction. Viral proteins are distinct but structural homologies and overlapping functional issues are non-trivial.

Figure 9: Identification of ACE2 receptors on many other cells (humans). The SARS-CoV-2 virus is not only a respiratory virus or results only in pneumonia. It is causing systemic diseases presenting a vast array of symptoms and acuity.

The medical chaos due to our lack of understanding of the biological minutiae of SARS-CoV-2 is not completely without a silver lining, albeit bleak. The ray of “hope” emanates from ExoN (Figure 8) the protein produced from Nsp14 segment of ORF1b (see Figure 7). It appears that SARS-CoV with inactivated ExoN is growth impaired and mutates at a much higher level (>20 -fold¹⁴⁹ higher, see right panel in Figure 10). SARS-CoV with one of the longest genomes (see Figure 16) among common RNA viruses (HIV, Influenza, Rhino, Ebola) abhors errors¹⁵⁰ in replication (not corrected in other common RNA viruses with low fidelity RNA replication). High fidelity replication has enabled SARS-CoV to maximize its genome size (see Figure 16) using RNA-dependent proof reading system, repair and error correction implemented by Nsp14-ExoN (there are Nsp14 homologs in other viruses). Lack of error correction in humans¹⁵¹ may result in disease, dysfunction and death, even due to point mutations.

Figure 10: Mutated or inactivated Nsp14-ExoN results in >20 -fold increase (Eckerle *et al* 2010) in genomic errors (B, right panel). ExoN in RdRp of SARS-CoV-2 enables error correction (left panel).

Error correction in SARS-CoV-2 may have implications for optimizing target selection for anti-viral strategies. The choice of the receptor binding domain in subunit 1 (S1 RBD) of the SARS-CoV-2 Spike protein, therefore, may be incomplete as a target (Figure 3). It appears that the fusion machinery and the fusion peptide (FP) region of the Spike protein (subunit 2) is better conserved and will *continue* to *remain* better conserved due to the error correction mechanism (see Figure 10). Hence, sub-segments within subunit S2 of S protein may be better targets. The obvious caveat in this discussion is whether the chosen sub-segments in S2 may be sufficiently exposed or available to bind with the anti-viral molecules.

A

SS AA

S1 S2

FP HR1 HR2 TM

Linker

HR1

HR2

HR1 ENQKQIANQFNKAISQIQESLTTTSTALGKLQDVVNQNAQALNTLVKQLS

Linker LVPRGSGGSGGSGGLEVLFGQP

HR2 DVDLGDISGINASVVNIQEEIDRLNEVAKNLNESLIDLQEL

B

HR1

a d a d a d a d a d a d a d a d a d a

SARS-CoV ENQKQIANQFNKAISQIQESLTTTS-----TALGKLQDVVNQNAQALNTLVKQLS

MHV_A59 ENQKMIASAFNNALGAIQDGFDAITN-----SALGKIQSVVNANAEALNNLLNQLS

HCoV-OC43 QNOKLIANAENNALGAIQEGFDATN-----SALVKIQAVVNANAEALNNLLQQLS

IBV KNQEKIAASFNKAIGHMQEGFRSTS-----LALQIQDVVNKQSSILTETMASLN

HCoV-229E ENQKILAASTFKAMTNIVDAFTGVNDAITQTSQALQTVATALNKIQDVVNQOQNSLNHLTSQLR

FIPV KNQKILASAFNQAINITQSFQKVNDAHQTSRGLATVAKALAKVQDVVNITQQAALSHLTVOQL

:*: *: *:*: : : : : ** :*: *** :. : *

HR2

a d a d a d a d a d a d a d a d

SARS-CoV PDVDLGDISGINASVVNIQEEIDRLN-----EVAKNLNESLIDLQELGKVEQ

MHV_A59 PDLSDDFEK-LNVTLLDLTYEMNRIQ-----DAIKKLNESYINLKEVGTVEM

HCoV-OC43 PDLSDLY--INVTFDLQVEMNRIQ-----EAIKVLNQSYINLKDITGVEY

IBV PDLDEFN--VTVPILDIGSEIDRIQ-----GVIQGLNDSLIDLLETLSILKT

HCoV-229E PDLVVEQ--YNQITILNLTSEISTLENKSAELNITVQKLQTLIDNINSLTVLDKMLNRRVET

FIPV PELTFDI--FNATYVLNLTGEIDDLFTRSEKLHNTTVELAILIDNINNTLVNLEMLNRRET

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8. Discussion

Could we detect SARS-CoV-2 in saliva, prevent¹⁵⁵ membrane fusion and block viral entry¹⁵⁶ with the same aptamer or another type of molecule based¹⁵⁷ on the better conserved S2 of the SARS-CoV-2 Spike protein? Could we detect SARS-CoV-2 in saliva of asymptomatic individuals without COVID-19? ADD may use better targets for its aptasensors beyond RBD S1 and hACE2. ADD *can* be accomplished, as suggested by the evidence from creation of DeMEA¹⁵⁸ (but it uses high cost microfluidics¹⁵⁹).

Even if ADD is successfully engineered to be a low-cost biomedical device for non-invasive detection, *dissemination* of ADD and other systemic surveillance tools will still depend on community-specific economics of technology¹⁶⁰ to facilitate diffusion and adoption. Bringing data and information together to make sense and extract foresight (uncertain of the value of hindsight¹⁶¹) will be a challenge which new initiatives¹⁶² must address. Diffusion of the tool to vulnerable communities will be restricted unless the end-to-end system is cost-effective at a level where it is sustainable for repeated use, preferably daily, as a surveillance tool for humans, pets and farm animals.

Data when transformed into *usable* information may deliver value for the greater good, for the greatest number. ADD is one small surveillance tool but it isn't enough. Healthcare cannot be a knee-jerk reaction to epidemics and pandemics. Continuous monitoring (even for high risk individuals) may remain a mirage in view of the disproportionate socio-economic imbalance. While we must ADD up to address the crisis¹⁶³ at hand, we must also utilize this disaster as an opportunity to deploy profiling as a healthcare staple. Other tools, for example, wastewater¹⁶⁴ analysis¹⁶⁵ may offer transparency¹⁶⁶ and guide public health strategies regarding elements the community must address, in advance, to prevent melt-down of health services. When an emergency presents itself we must not disintegrate into quagmire.

Precision medicine and precision public health may benefit if we probe the broader question of physiological status as expressed by proteins but further complicated by our microbiomes¹⁶⁷. Isolated snapshots of data may be rate-limiting for communities under economic constraints. But, convergence of data from ADD along with multiple levels of profiling¹⁶⁸ (DNA, RNA, protein, RDW¹⁶⁹) as well as environmental¹⁷⁰ and wastewater¹⁷¹ data¹⁷², if included¹⁷³, may augment the value of information, which could be catalytic for medicine¹⁷⁴, in general, if aggregated and shared between open¹⁷⁵ platforms.

Analytical skills necessary to deconstruct the data and reconstruct its meaning, relevant to the individual and/or the community, may pose a rather insurmountable barrier in terms of tools and/or human resources. The ill-informed inclination is to hastily pursue a “quick and dirty” version (perhaps shoddy, yet masquerading as good enough) without a long term view or a vision that embraces a sense of service, science for the good of society and access to global public goods for all. It goes without saying that one shoe does not fit all. It is obvious that ADD is not enough to better prepare for the future¹⁷⁶.

Figure 12: Serum from a significant percentage of patients (one third) recovering from COVID-19 have low viral neutralizing activity. Depending on the acuity of the infection, patients may or may not follow *standard* immune profile (top¹⁷⁷). Low variation (Fig 10) in SARS-CoV-2 Spike protein is good news but mutations, D614G (middle panel and bottom) may still complicate¹⁷⁸ the immune response and expected anamnestic response to reinfection or use of classical¹⁷⁹ approaches¹⁸⁰ to vaccination.

If immunity from traditional vaccines are uncertain¹⁸¹, can we supplement with *alt-vaccines* (which are non-immunogenic, for example, aptamers), to better prepare for low-cost and rapid¹⁸² response to public health during future epidemics / pandemics?

9. Complexity of the biomedical scenario, socio-economic catastrophe and the public health crisis

Since 1980's the HIV epidemic has infected ~76 million people¹⁸³ (~1% of the global population) and almost half are dead (~33 million AIDS related deaths, disease caused by HIV) and currently the other half is still living or struggling with the disease. Yet, the thrust for HIV vaccine pales compared to the warp speed vaccine development collaboration¹⁸⁴ against SARS-CoV-2, which erupted in 2020 as the COVID-19 pandemic. Is it because SARS-CoV-2 is irreverent and indiscriminate in infecting humans?

Figure 13: The timeline of SARS-CoV-2 Vaccine Development¹⁸⁴ (mRNA-1273 vaccine¹⁸⁵) to control COVID-19 (codeveloped by NIAID, NIH and Moderna, Cambridge, MA). The mRNA encodes the SARS-CoV-2 full-length spike glycoprotein trimer, S-2P (stabilized¹⁸⁶ with two Proline¹⁸⁷ substitutions at the top of the central helix in S2 subunit). mRNA is encapsulated in lipid nanoparticles (0.5 mg per mL) and diluted with normal saline to achieve the final target vaccine concentrations¹⁸⁸.

Figure 14: 7-day rolling average of new COVID-19 cases¹⁸⁹ from January through September 21, 2020.

Coronaviruses have long co-existed with humans and animals. Error correction (Figure 10) has made the genome of the coronavirus one of the largest among viruses (Figure 16). What does it mean? Compared to diseases¹⁹⁰ due to relatively unknown viruses¹⁹¹, and despite the flu pandemic ~100 years ago, the coronavirus, in less than six months, has changed, perhaps permanently, global thinking, trends and technology. Tobacco Mosaic Virus (TMV) was discovered around 1890-1892¹⁹² but after more than 100 years¹⁹³ of virus discovery, we have *just now* acknowledged the threat to global health from viruses. Understanding the molecular basis of virulence is the single most important questions in basic biology which must be investigated by the best and brightest, if we ever expect to mitigate the risk from viruses.

Figure 15: Coronavirus phylogenetic tree. Human coronaviruses (courtesy of S. M. Gygli, NIAID)¹⁹⁴

Figure 16: Coronavirus pandemic wasn't really expected¹⁹⁵ according to at least one global expert¹⁹⁶. The coronavirus has the largest RNA genome. Is it just a coincidence or is there any bio-medical correlation?

While we still remain clueless about what constitutes virulence, the genome size does not offer any solace or solution. New evidence about Neuropilin-1 as a host factor¹⁹⁷ which facilitates cell entry¹⁹⁸ further thickens the plot. The deep quagmire¹⁹⁹ about R_0 and k ²⁰⁰ for COVID-19 defies epidemiological models²⁰¹ but prefers apocryphal Pareto²⁰² principles which suggests that 80% of new infections may be caused by only 20% (or less - 10% - see Figure 17 and reference 216) of the infected individuals. Are these individuals a high risk group due to inborn errors of immunity caused by mutations of genes involved in regulation of type I and type III interferons²⁰³ (IFN)? How many more genetic factors may underlie the differentiation between super-spreaders²⁰⁴ vs sub-spreaders for SARS-CoV-2? If the latter is true then how valuable is *generalizing* infection dynamics²⁰⁵ from communities as a prediction tool for *overall* public health, advance planning and use as early warning²⁰⁶ for cautionary preparation?

In future, genomic analysis may enlighten us if there are polymorphisms²⁰⁷ which may partially account for this differentiation. It may be worth digressing to note that some individuals may be more susceptible to leprosy, caused by *Mycobacterium leprae*. Genes²⁰⁸ associated with leprosy include HLA (human leukocyte antigen) proteins. Analysis of eleven HLA genes in 1155 Vietnamese individuals revealed 4 leprosy-associated independent amino acid variants [HLA-DR β 1 positions 57 (D) and 13 (F), HLA-B position 63 (E) and HLA-A position 19 (K)] which comprised 2 pairs of linked genes, with one set conferring susceptibility [HLA-DR β 1 and HLA-A] and one being protective²⁰⁹.

The demographics of infection by SARS-CoV-2 may be due to genetic²¹⁰ determinants²¹¹ and individual outcomes²¹² may be determined by our genes²¹³ as well as epigenetic factors which may be mapped to biomarkers²¹⁴. At this point it is unclear whether the etiologic agent of this 2019 coronavirus pandemic should be referred to as SARS-CoV-2 where SARS imply severe acute respiratory syndrome.

Figure 17: What is COVID-19? Respiratory illness? Blood clotting disorder²¹⁵? Cardiovascular disease? Autoimmune disease? Opportunistic “killer” for (~10%) patients with severe COVID-19 pneumonia and high titers of autoantibodies²¹⁶ against different types (type I IFN- α 2 and IFN- ω) of interferons?

Figure 18: Hypothetical²¹⁷ 5²¹⁸ cent²¹⁹ *déjà vu* graphene sensor (RIGHT) detects SARS-CoV-2 antigens. Can smartphone detection²²⁰ adapt²²¹ to other²²² sensors²²³ (LEFT) to detect²²⁴ SARS-CoV-2 in exhaled²²⁵ breath²²⁶ by mouth? Smartphone²²⁷ *breathalyzer* for malaria²²⁸ and marijuana (tetrahydrocannabinol)²²⁹ is close at hand. Can it serve²³⁰ as a global surveillance tool to bridge the chasm of inequity?

Figure 19: Detection of one copy RNA per μL (microL) from SARS-CoV-2²³¹ with mobile phone camera. Cas13a (C2c2) is complexed with a CRISPR RNA (crRNA) containing a programmable spacer sequence (red tube) to form a nuclease-inactive ribonucleoprotein complex (RNP). When the RNP binds to a complementary *target* RNA, it activates HEPN (higher eukaryotes and prokaryotes nucleotide-binding domain) motifs of Cas13a that then indiscriminately cleaves surrounding ssRNAs. Target RNA binding and subsequent Cas13 cleavage activity can therefore be detected with a fluorophore-quencher pair linked by an ssRNA, which will fluoresce after cleavage by active Cas13. Ott *et al* used the SARS-CoV-2 nucleocapsid (N) gene as the template (detection *target*) to create an array of crRNA spacer (red tube).

The socio-economic fall-out from the stochastic spread of infection and non-deterministic trends affecting certain countries, select groups (race, ethnicity) and underserved clusters, may be an example of “*writing on the wall*” we are slow to acknowledge. The cost of testing 100,000 individuals in the US approximate \$6 million. If 30 million tests are performed weekly it would require an additional \$75 billion and adding the cost of contact tracing might bring the total to approach \$100 billion²³².

The “*writing*” says that the NIAID-Moderna mRNA-1273 vaccine or any other safe and effective vaccine against SARS-CoV-2, when it may become available in 2021 or later, may still be out of reach for *billions* of people. CRISPR²³³-based tests may be promising²³⁴ in the future (see Figure 19). BinaxNOW \$5 test²³⁵ is at hand but may not be feasible for daily use in communities under economic constraints. The case of Hepatitis-C²³⁶ is an example how even after nearly 50 years, anti-viral drugs are not within the buying power of billions of people.

Death, destruction and the decay of civilization²³⁷ may continue and may *continue to amplify* in certain regions of the world, long after the pandemic. *If* the current pandemic is substantially contained by the end of 2021, then the aggregated loss from mortality, morbidity, mental health conditions, and direct economic losses in the US alone is conservatively estimated at \$16 trillion²³⁸. The US economy is about a quarter of the global economy²³⁹, hence, extrapolation suggests that losses due to this pandemic may be an estimated \$64 trillion, globally (about 80% of the global GDP²⁴⁰).

This mundane proposal is an elusive quest for an alternative path, albeit temporary and vastly incomplete, perhaps through the use of aptamers (or other variations based on oligonucleotides²⁴¹) to partially bridge the chasm of inequity²⁴² and cushion the blow from the mortality and morbidity, yet to be witnessed. Healthcare is a pillar (FEWSHE - food, energy, water, sanitation, healthcare, education) of life and living but it is prudent to avoid indulging in any illusion or delusion because neither aptamers nor vaccines or CRISPR tools, irrespective of their respective efficacies, are a panacea for the restoration of civilization, even if this pandemic subsides in a few years. The quintessential ingredients for public health and global rejuvenation are scientific credibility, color-blind magnanimity and ethical leadership.

Figure 20: Similar to HIV, SARS-CoV-2 Spike protein uses a N-glycan shield²⁴³ to thwart the host immune response (coating of N-glycans in cobalt blue, right). Mutations²⁴⁴, inborn errors of the immune system and other factors may make SARS-CoV-2 endemic²⁴⁵. Thus, it behooves us to explore other risk mitigation strategies. Anti-sense oligonucleotides, mini protein inhibitors²⁴⁶ and aptamers (this proposal) are alternatives.

10. Post-Pandemic Public Health and Healthcare: Broad Spectrum use of Sensors with Smartphones

Transaction cost²⁴⁷ of *humans-in-the-loop* detection or surveillance²⁴⁸ is often astronomical²⁴⁹ and the burden of cost²⁵⁰ for public health and healthcare systems is prohibitive even for affluent nations. For resource constrained communities, the mortality and morbidity due to lack of access to primary care must be reduced. Can we effectively combine the ecosystem of sensors, smartphones and data informed decision analytics to deliver usable information at the point of care or point of need, in near real-time?

In general, part of the solution may be found in remote sensing and imaging tools (oil and gas pipelines²⁵¹, leaves²⁵², tree²⁵³ canopy^{254,255}, radiation²⁵⁶). SEE or “sense everything everywhere” (paint-based computation²⁵⁷, sensors in fabrics²⁵⁸) was a ‘touchy-feely’ mantra at the turn of the millenium buoyed by the principle of ubiquitous²⁵⁹ computing²⁶⁰ but stumbled in practice due to the cost²⁶¹ of computation²⁶². Vinton Cerf’s “I P on Everything”²⁶³ (I *pee* on everything) was the witty clarion call for embedding the IPv6²⁶⁴ standard²⁶⁵ in all things²⁶⁶ to enable “bit dribbling” between “digital” objects. These ideas were preceded by “tangible bits”²⁶⁷ from Hiroshi Ishi²⁶⁸ and the “atoms to bits” paradigm²⁶⁹ of “*Internet 0*” from Raffi Krikorian²⁷⁰ and Neil Gershenfeld²⁷¹ followed by the origins²⁷² of internet of things²⁷³ by Sanjay Sarma^{274, 275} and others²⁷⁶. The borborygmi of radio frequency identification (RFID) and standardization of the electronic product code (EPC²⁷⁷) shifted the thinking from stationary goods and products with static bar codes to dynamic digital objects which can be uniquely identified in any process or supply chain and tracked and traced digitally between any number of transactions, globally.

Project Oxygen²⁷⁸ offered extraordinary insight into the art of the possible²⁷⁹ and represented a consilience and confluence²⁸⁰ of ideas but it was cost-prohibitive for real world applications, circa 2000. With decreasing cost of computation²⁸¹, memory²⁸², data storage²⁸³ and transmission²⁸⁴, these streams, which were occasionally bubbling since Isaac Asimov’s²⁸⁵ *Sally*²⁸⁶ in 1953, turned into a raging river bursting its banks. The convergence of these tools with initial thoughts about the networked physical world²⁸⁷ were far more than the sum of the parts. It exploded to become the inescapable tsunami of IoT²⁸⁸ which has infected every domain. The anastomosis²⁸⁹ of IoT with cyberphysical systems²⁹⁰ (CPS²⁹¹) has penetrated almost every field from asteroids to zeolites and engulfed them within the new²⁹² laissez-faire world of DIKW²⁹³ hierarchy. The mobile smartphone represents the grand conduit for the aggregated dissemination of distributed facets emanating from the DIKW pyramid. The mobile platform appears to be the global choice to access and implement all and any service which is possible, via the smartphone, in some form or the other, where the ubiquitous device serves as the platform for information²⁹⁴ arbitrage.

ADD is a recognition element and a tiny part of this landscape. ADD enables the sensor, data is captured, analyzed, communicated and visualized on a smartphone. It may detect infectious molecules relevant to SARS-CoV-2 in saliva and nasal swabs for early detection to prevent the spread of the virus. This principle is applicable to *any* infectious agent as well as any physiological molecule of interest (see Figure 21). The potential of developing a “breathalyzer” (identifying molecules in breath, see Figure 18) may make it easier to detect any molecule or molecules which are either volatile or lighter than air.

Based on the idea of swappable, modular, flash drives, sensors-on-a-chip in the form factor of flashdrives are not hypothetical but frontrunners as potential tools for dealing with infectious²⁹⁵ diseases. Cameras, accelerometers (speed, movement), gyroscopes (tilt, orientation), magnetometers (compass), lidars (range, depth sensing from reflected laser signal), GPS and other “sensing” tools are increasingly “standard” with smartphones. These “detectors” makes it possible to use multiple mediums and phases for detection of signals from molecules, changes in dipole moments (electro-magnetic field) and perhaps even perturbation *ambient* electromagnetic waves (transmission and capture of reflected radio waves).

Figure 21: Billions of users in underserved geographies may access limited health services by using²⁹⁶ ubiquitous tools that does not require installation of new infrastructure and re-uses “mobile lifestyle” devices to partially bridge the scarcity of resources. Smartphones may be catalytic for delivery of service, remote monitoring²⁹⁷ and health surveillance, not restricted to infectious diseases but as physiological probes for health and homeostasis or detecting onset of disequilibrium (BNP, Brain Natriuretic Peptide).

Using information arbitrage to better contain the pandemic is the thrust of ADD. Expanding this principle as a routine for public health and healthcare, in general, is not a leap of imagination but natural progression. It bears reiteration that data informed decision analytics (DIDAS) must embrace sensor data plus smartphone (SDS) applications not as “pilot” projects but science in the service of society to catalyze the **SENSIBLE** system (**SENS**ors and **I**nformation arbitrage via **moBiLE** system). The marriage of DIDAS with SDS in the affluent world is a matter of social acceptance of SENSIBLE but the penchant for profit-first and lack of leadership are holding us back. In the rest of the world the barrier to diffusion of life-saving tools are, albeit with exceptions, greed, pursuit of unethical profitability, cost or paucity of infrastructure (engineering, energy, telecommunications) and rampant inequity in social cohesion.

One milestone for smartphone-based health surveillance may be the non-invasive²⁹⁸ glucose²⁹⁹ monitoring³⁰⁰ system which the healthcare system failed to aggressively adopt³⁰¹ despite significant³⁰² advances³⁰³. The chest-thumping about diabetes pandemic³⁰⁴ continues in parallel with avoidance of available³⁰⁵ solutions³⁰⁶. Cholesterol³⁰⁷ monitoring³⁰⁸ using smartphones³⁰⁹ may be a preventative measure for adults at increased risk for a slew cardiovascular diseases, a few of which may not show symptoms.

Decades after the discovery of atrial natriuretic peptide³¹⁰ (ANP, 1981), brain or B-type natriuretic peptide³¹¹ (BNP, 1987) and C-type natriuretic peptide³¹² (CNP, 1990), we *still* do not have SENSIBLE monitoring for BNP even though BNP sensors³¹³ including an aptamer-based³¹⁴ sensor for BNP-32 and cardiac Troponin I are available. These and other³¹⁵ biomarkers (CRP5/CRP6, TNF α) are indicators of cardiovascular dysfunction including congestive heart failure (CHF) and state of the patient after myocardial infarction, in addition to other conditions. BNP and other markers are key to risk stratification, diagnosis, prognosis, disease monitoring, titration of therapy, and identification of therapeutic targets for cardiovascular disease. Brain Natriuretic Peptide concentrations >400 pg/mL and N-terminal (NT) pro-BNP >400-900 pg/mL (age related) are prognosticators of congestive heart failure. Analysis of 48,629 patients³¹⁶ of acute decompensated heart failure found linear correlation between BNP levels and in-hospital mortality. Failure of BNP to decline during hospitalization predicts death or rapid re-hospitalization. However, BNP levels of 250 picograms per mL (pg/mL) or less during discharge predicts potential for survival. Accelerating availability of sensors³¹⁷ and transforming innovations³¹⁸ to SENSIBLE systems for prevention of cardiovascular disease should neither suffer from paralysis due to analysis nor asphyxiated by the rancour over margin of profitability.

Figure 22: Tip of the Ischemic Iceberg³¹⁹ hides >63% of the individuals who lack symptoms but are increasingly at risk for CVD, ischemia, myocardial infarction, congestive heart failure. BNP and other bio-markers may reduce the risk using the SENSIBLE system. We know these facts³²⁰ for ~40 years. Yet, the proponents of prevention *policies* wear that perpetual unctuous grin assimilating both the promises of a television evangelist and the sympathies of a funeral home director of marketing.

Figure 23: Smartphone cameras, LEDs, LiDARs and a FEAST³²¹ of signal transduction tools (optical, Raman spectroscopy, electrochemical impedance spectroscopy, surface plasmon resonance) are now available as data carriers. Cartoon (top) shows smartphone-based blood pressure³²² and non-invasive blood glucose³²³ monitoring³²⁴. The SENSIBLE system may be used to estimate blood cholesterol level, hemoglobin^{325, 326, 327} and uric³²⁸ acid³²⁹ as indicators of health, albeit imperfect. Data from smartphone based optic disc³³⁰ exam, photoplethysmography³³¹, electrocardiograph for arrhythmias³³² (see bottom panels), general ECG³³³, heart³³⁴ rate, respiratory³³⁵ rate (*reflection* of radio waves), pulse oximetry³³⁶ and other vitals, collectively, may create precision physiology portfolios (open data source interoperability).

It is likely that *hundreds* of papers are published *weekly* on sensors, many of which may be adapted/adopted as a part of the SENSIBLE family. Biosensing using mobile devices at the point of use is a staple, for example, in the food industry (spoilage, contamination, security), soil, water, agriculture, manufacturing, chemical industry, transportation, energy, etc. But, lack of open data and restrictions on data interoperability makes the transformation of data to information quite difficult. Scientists are eager to drill deeper to develop yet another sophisticated sensor but the real-world user is in quest of *answers* at the point of use, and does not have the luxury to deal with numbers, compilers and programmers.

This discussion about the cacophony of available sensors is an embarrassment of riches from decades of research and development scattered as parts, in silos or locked by patents. The form and functional orchestration and integration necessary for sensors to contribute to precision physiology requires cross-pollination of ideas. Multi-disciplinary teams are necessary to create end-to-end working SENSIBLE systems which can be synchronized, if authorized, as a part of the public health information system. If that data is shared in real time, it may reduce mortality, morbidity, cost to society, decrease the burden on emergency medical professionals, and actually aid in preventing dysfunction. If this data is anonymized to serve molecular epidemiology, it may help precision public health and channel benefits to the community by revealing the environmental conditions or instances which need additional attention.

A plethora of brilliant experts with deep knowledge can fill any university hall but few have the breadth of ideas which, if synthesized, synergized and integrated, may help to address or even solve a real problem in the public domain where non-experts are the end users. Solutions based approach must combine depth with breadth to deliver the fruits of science to society as global public goods. The latter may be missing in the academic context where chronic search for scholastic erudition is the norm. The concept of essential products and services as global public goods may not be appetizing in the corporate context due to their perpetual penchant to promote profit and profiteering, first. The cleavage between purpose and profit needs a new bridge and a new breed of thinkers and leaders with altruistic traits.

The laser-focus of biomedical professionals on saving the lives of those affected by COVID-19 and the public health community on preventing the spread of infection by SARS-CoV-2 is the only path, at present, to lift us out of the quagmire of the raging pandemic. Yet it may be crucial to use this disaster as a global opportunity to strengthen public private partnerships (academic-industry-government) for the ubiquitous deployment of global tools for early detection and prevention, not only for pandemics, but for public health and healthcare, in general. It is an enormous task and requires global leadership.

Ubiquity of smartphones is the available SENSIBLE platform to create at least one bridge over the chasm separating the *haves* from *have nots*. Inextricably linked economies of the under-developed, developing and developed nations makes it imperative that the leadership for global public health must be agnostic of prejudice. Trans-disciplinary cooperation and collaboration between corporations must rise above conventional economics³³⁷, narcissism, egocentricity and personal wealth creation. We need an overwhelming force for good, for a greater purpose, for the greatest number³³⁸ (of people).

11. Concluding Comments

The complexity of the physiological dysfunctions associated with the SARS-CoV-2 pandemic calls for multiple routes for detection, prevention and therapy. ADD is a tool for detection and perhaps an alternative approach to treatment that does not depend on the immune system due to reported heterogeneity of response, partially based on individual genetic constitution or inborn genetic errors.

From a public health perspective, the global diffusion of smartphones as ubiquitous devices is an opportunity to use smartphones for detection of the spread of any infectious agent. ADD is one tiny sub-component of the proposed SENSIBLE system. Realization of the SENSIBLE system is a difficult task. The deployment of the SENSIBLE system, with ADD and other sensor components, is an essential task, unless the veneer of health equity³³⁹ is only that, that is talk, or in other words *lippenbekenntnis*³⁴⁰.

The caveat in this line of thinking is the over-emphasis on the sensor and the SENSIBLE system as if the value proposition is undeniable. The latter is true for the affluent economies of the world but detection without follow-up is an exercise in futility. The latter is common in communities under economic constraints where tools to detect (SENSIBLE system) are impotent because there are very few resources to attend to the public health or healthcare need identified by the SENSIBLE system. Just because the user can detect the presence of mercury in drinking water does not mean that the user has another alternative source of drinking water in under-served or dystopian communities. Is it more or less psychologically debilitating to drink water or consume food if the user is cognizant that the water is contaminated with mercury³⁴¹ or the food is laced with bacteria³⁴² beyond the level of food safety?

Incongruity between the *pursuit* of science, *implementation* of the fruits of science and science as a *measurable service* to society is a conundrum beyond the horizon of tools and technology, for example, the SENSIBLE system. Entrepreneurial innovation can create SENSIBLE but implementing SENSIBLE requires leadership imbued with a sense of the future, especially for low-income countries with ultra-low per capita *disposable* income. In the absence of charity, SENSIBLE for public health and healthcare must carry with it a pay-per-use price tag which may be a micro-payment or even a nano-payment but still it *must* be a non-zero payment for the system to be sustainable and survive long enough to deliver value.

Ephemeral gimmicks demonstrating SENSIBLE in geographies with GDP which may be less than an average household income in Europe is a deliberate act to deceive, dressed up in a marketing³⁴³ garb by the glib, the smug and the smarmy. Enabling a SENSIBLE future and making it sustainable for most segments of the community, in greatest numbers, is a mission for a visionary leader who radiates the aura that kindness is a strength, not a weakness, humility is a virtue, not a lack of knowledge, that agreeing to disagree is a mark of civility³⁴⁴ and dignity, not a character flaw, that fear is not a tool for maiming diversity, speech or peace, that progress of civilization is development of the freedom³⁴⁵ to act on remediable injustices³⁴⁶ and lift many boats, not a few yachts. The best man for *that* job is a *woman*.

APPENDIX

APPENDIX - Brief Description of the Components³⁴⁷ for SARS-CoV-2 ADD Decision System (Fig 1)

Message Broker

When users upload images (the data after scanning with the HoloLens app or equivalent mobile tool), the mobile application (on their phones) writes messages with the image content and other metadata to a message-broker, which may be cloud-based message queuing (MQ³⁴⁸) protocol (open source software). The message broker allows devices to quickly offload data and confirm “sent” to a user (if cloud based), thereby decoupling the user experience from the data store (even if it uses a temporary tinyDB on the device, if the network is unavailable to access the cloud in real-time at the point of use). Messages can be queued in topics and the system may enable autoscaling (as usage of the application increases, more users can be provisioned, process user uploads and get them stored). The uploads (data) are also sent by the message broker to the feature extractor and long-term storage database (may use the batch upload option when device is proximal to a high bandwidth gateway which can offer access to cloud services).

Operational Data Store

The message broker transfers uploads to ODS (Operational Data Store³⁴⁹), which may be a cloud-based managed service or part of the tinyDB on the device, if cloud is inaccessible at the point of use. ODS must be able to store image data (supports binary blob column type) alongside time-index numerical and character data. It is intended to only serve “hot” (nascent) data to the application. Older data may be evicted (batch uploaded to cloud managed facilities) to optimize on-device service and prevent data amplification. ODS is tuned for fast random reads and serves requests made by mobile app when users view recent uploads and additional metadata about those uploads, including “risk scores”. ODS is optimized for fast writes and high efficiency time-series queries.

Feature Extractor

Extracts additional metadata from images/data uploaded from the mobile app (uploads it to the long-term system of record³⁵⁰ which includes raw data uploaded from the application, similar to “master data” in ERP³⁵¹). Feature Extractor may convert the uploaded image into a numeric matrix³⁵² or create hash table or representation of a region³⁵³ and correct for differences in resolution (for example, variation due to pixel density of cameras on different smartphones). Feature³⁵⁴ vectors³⁵⁵ may be maintained in the long-term system of record. It may be written to the operational data store to enable extraction/selection³⁵⁶ of incoming data (uploads from message broker) relevant to these feature vectors.

Long-term System of Record

Mobile applications may never access data directly from this data store³⁵⁷. Interactive-speed queries to this data store may not be supported. When necessary, objects stored in this “record” may be extracted and the data is loaded into an analytical data store. For object stores, this operation may be accomplished using query-over-files engines³⁵⁸. The thorniest problem that ferments within long-term data record is the inaccuracy of “accurate” data and the diabolical mayhem from “big data” if it is sourced and stored.

Analytical Data Store

Scientists and data experts will need historical data (from uploaded samples) to train task-specific³⁵⁹ machine learning (ML) models to assign risk scores to samples. Analytical data store (ADS database³⁶⁰) may be populated with data from the long-term system of record using scheduled batch data uploads.

Model Training

In model training³⁶¹, a statistical model is built from historical data. Models should be serializable³⁶² representations of the program generated by ML training. Serialization is essential for interoperability on different platforms. It is key to create composable models where models from different groups can be deconstructed to sub-elements which can be reconstructed to compose a new model (which may be greater than the sum of parts). Serialization enables the process of translating a data structure or object state into a format that can be stored or transmitted and reconstructed. Proprietary software vendors obfuscate or encrypt serialized data to prevent access. Standard architectures such as CORBA³⁶³ define the serialization formats in detail to enable open access.

Model Scoring

In model scoring, a model is called on input data, the model processes the input data and generates a prediction. The structure of this code depends on the *design choices* made during model training. For reliability of deployment, model scoring may run in a container³⁶⁴ (an unit of software) which contains code (and all its dependencies) that uses a model to produce predictions on new input data. If model scoring runs in a container then the model can be arbitrary code in the developer’s language³⁶⁵ of choice. Model scoring requires features created previously by the feature extractor (feature selection is critical).

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- ³⁴⁸ Message Queueing using an open lightweight broker, such as, Message Queueing Telemetry Transport, MQTT (<https://mqtt.org/>) or RabbitMQ (<https://www.rabbitmq.com/>) or heavy-duty Apache Kafka (<https://kafka.apache.org/>). Self-managed or run behind a managed IoT service from cloud providers: AWS IoT Core (<https://aws.amazon.com/iot-core/>) or Azure IoT Hub (<https://azure.microsoft.com/en-us/services/iot-hub/>) or related services provided by other vendors (<https://www.zdnet.com/article/the-top-cloud-providers-of-2020-aws-microsoft-azure-google-cloud-hybrid-saas/>).
- ³⁴⁹ Operational Data Store choices include InfluxDB (<https://www.influxdata.com/>), Apache Cassandra (<https://cassandra.apache.org/>) or Prometheus (<https://prometheus.io/>). Managed cloud database from Amazon <https://docs.aws.amazon.com/amazondynamodb/latest/developerguide/Introduction.html>.
- ³⁵⁰ Amazon S3 Glacier <https://aws.amazon.com/glacier/>
- ³⁵¹ Enterprise Resource Planning (ERP) – Master Data Management: Architecture and Technology <https://www.element61.be/en/resource/master-data-management-mdm-architecture-technology>
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³⁵⁷ Object stores: Amazon <https://aws.amazon.com/s3/>; Google Cloud <https://cloud.google.com/storage>; Microsoft Azure Blob <https://azure.microsoft.com/en-us/services/storage/blobs/>; Apache Cassandra <https://medium.com/walmartglobaltech/building-object-store-storing-images-in-cassandra-walmart-scale-a6b9c02af593>

³⁵⁸ Query-Over-Files Engines: Presto (<https://prestodb.io/>), Apache Drill (<https://drill.apache.org/>) or Apache Spark SparkSQL (<https://spark.apache.org/sql/>). If using application-specific custom code that directly reads files, orchestrated with batch-scheduling engine: Apache Airflow (<https://airflow.apache.org/>) or Prefect (<https://www.prefect.io/>)

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³⁶⁰ Analytical Data Store: Traditional relational database PostgreSQL (<https://www.postgresql.org/>) or hosted relational database products provided by cloud providers (<https://aws.amazon.com/rds/>). If intelligent caching of repeated queries is needed, data warehouse technologies (managed cloud service) include: Snowflake (<https://www.snowflake.com/>), Amazon Redshift (<https://aws.amazon.com/redshift>) or Google BigQuery (<https://cloud.google.com/bigquery>). For on-premises option: Teradata (<https://www.teradata.com/>).

³⁶¹ Machine Learning (see the cartoon on the last page of this article) model training tools: Apache Spark (<https://spark.apache.org/>), Dask (<https://dask.org/>) or Ray (<https://rise.cs.berkeley.edu/projects/ray/>). If application specificity does not require high degree of customization - use “autoML” tools - DataRobot (<https://www.datarobot.com/>), h2o (<https://docs.h2o.ai/h2o/latest-stable/h2o-docs/automl.html>), Amazon SageMaker Autopilot (<https://aws.amazon.com/blogs/aws/amazon-sagemaker-autopilot-fully-managed-automatic-machine-learning/>) or Google Cloud AutoML (<https://cloud.google.com/automl>).

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³⁶³ Common Object Request Broker Architecture (CORBA) <https://www.corba.org/>

³⁶⁴ Container: Docker <https://www.docker.com/resources/what-container>

³⁶⁵ Developer’s language of choice may include (but the “menu” is not limited to):

Java jar ([https://en.wikipedia.org/wiki/JAR_\(file_format\)](https://en.wikipedia.org/wiki/JAR_(file_format))),

Python pickle file (<https://docs.python.org/3/library/pickle.html>),

R rds file (<https://stat.ethz.ch/R-manual/R-devel/library/base/html/readRDS.html>) or a precompiled executable which can read in input data from “stdin” (standard input is a stream from which a program reads its input data) or from a file, created with C/C++ or language-agnostic description of a model:

Predictive Model ML (https://en.wikipedia.org/wiki/Predictive_Model_Markup_Language) or

Portable Format for Analytics (<http://dmg.org/pfa/>)

Cartoon for Reference # 361: Machine Learning Algorithms – ML makes better sense without the nonsense of AI

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