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Editorial

Sensors Around the World: Europe, Middle East, and Africa

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The third installment in our "Sensors Around the World" Virtual Issue series spotlights contributions to *ACS Sensors* from authors located in Europe, Africa, and the Middle East. While we continue to receive many excellent contributions from European researchers, an increasing number of articles published in the journal originate from institutions and people located in Africa and the Middle East. It has been a pleasure to select some of the most important and interesting contributions to the journal from these regions over the past three years. Despite the unprecedented and ongoing impact of the global COVID-19 pandemic, it is evident that the sensing community continues to generate novel and impactful research outputs. As an Associate Editor, it has been reassuring to see that high-quality submissions to the journal continue apace. But this is perhaps unsurprising, since the sensing community has played a significant role in the global response to the COVID-19 pandemic, and will continue to do so. As you will see, some of the highlighted papers directly address challenges set by the COVID-19 pandemic, but many more tackle generic issues, such as fundamental method development, device engineering, new molecular sensors, optical spectroscopy, and data processing methodologies.

It goes without saying that the emergence of the SARS-CoV-2 virus and the ensuing COVID-19 pandemic has underscored the need for rapid, accurate, and affordable diagnostic tests able to properly diagnose, manage, mitigate, and control disease spread. Unsurprisingly, over the past two years many of us in the sensor community have responded to this challenge by enhancing the diagnostic toolbox. An excellent review of this global activity has been provided by Soler et al., who assess the role of label-free nanophotonic biosensors as robust point-of-care diagnostic tools.[1] In this regard, Velotta and colleagues have presented a colorimetric biosensor based on gold nanoparticle interaction induced by SARS-CoV-2 for the detection of viral particles in nasal and throat swabs.[2] The sensor operates in a rapid and robust fashion and offers detection limits that rival real-time PCR. In related studies, Timur and co-workers realized a paper-based lateral flow immunoassay based on the production of COVID-19-specific antigens and antibodies in combination with dye-loaded polymersomes for visual detection.[3] The approach is smart and sensitive and is well-suited to use in low-income countries, where access to diagnostic technologies is likely to be limited.

More generally, the ultimate utility of any point-of-care-diagnostic system is dependent on its analytical performance, unit cost, the ease with which it can be deployed in a desired location, and the ability to make sufficient quantity to meet demand. To this end, the development of paper-based diagnostic systems continues apace. For example, Bakker and co-workers have developed a capillary-assisted paper device for the analysis of potassium ions in serum, with ion recognition being achieved via the selective replacement of analyte with an ionic dye and detection via distance-based readout.[4] In addition, Tabatabaee et al. reported the fabrication and successful use of a paper-based assay for the rapid diagnosis of neonatal jaundice.[5] Significantly, bilirubin concentrations in blood could be quantified via a fluorescence quenching/recovery mechanism that is both specific and sensitive, and requires only a smartphone for detection at the point-of-care. That said, and despite the fact that complex biomolecular assays can often be performed within paper-based formats, reagent storage is an issue often overlooked (or ignored), but one that ultimately defines real-world utility. With this in mind, de la Rica and colleagues recently demonstrated an efficient method for storing protein-decorated nanoparticles on paper and subsequently releasing them on demand within a paper-based immunosensor.[6] Importantly, such an approach is finger-actuated and allows for the sensitive detection of glycoprotein B in serum within 12 min. In a quite a different application, Hemmateenejad and co-workers have also developed paper-based optoelectronic noses incorporating silver and gold nanoparticle arrays for the ultrasensitive and selective detection of over 45 volatile organic compounds and with detection limits on the ppb level.[7]

In the fullness of time, the utility of any sensor is defined not only by its analytical performance, but also by the ability to produce it in a cost-effective and timely manner. Accordingly, much recent activity has centered on assessing manufacturing technologies that allow for the fabrication of highly integrated systems. To this end, Liedert and co-workers have developed a roll-to-roll process for the large-scale fabrication of highly integrated microfluidic sensors, at rates in excess of 60 devices per hour.[8] Significantly, the fabricated sensors could then be used for the rapid and sensitive detection of C-reactive protein in whole blood. At the other end of the scale, Gizeli and associates have developed a 3D-printed platform for nucleic acid analysis, integrating DNA amplification and acoustic detection at the point-of-care and using crude biological samples such as whole blood, saliva, or nasal swabs.[9] Due to its simplicity and smartphone control, the approach is ideally

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suited for use in resource limited settings, with sample-to-answer times below 30 min.

Optical and spectroscopic innovations continue to advance core sensing technologies. Excellent examples of recent activities in this area include the demonstration of multi-frequency impedance cytometry for the high-speed single cell characterization at rates up to 400 cells per second[10] and the use of hyperspectral imaging and signal deconvolution to facilitate multi-indicator-based chemical imaging.[11] With a view to system miniaturization, Katiyi and Karabchevsky have described the fabrication and testing of a silicon nanostrip waveguide for on-chip overtone spectroscopy in the near-infrared.[12] Such a system is able to discriminate a number of common organic liquids and has obvious application in the on-site monitoring of chemical species. From a molecular perspective, the development of new molecular probes and reporters remains a vibrant area. A beautiful example in this regard was recently reported by Burgstaller et al., who engineered a novel genetically encoded pH probe by fusing a pH-stable cyan fluorescent protein with a pH-sensitive yellow fluorescent protein to generate a ratiometric biosensor for live imaging within cellular compartments.[13] Additionally, Novakova and co-workers have developed a novel class of fluorescence sensors based on tetrapyrazinoporphyrazines that appears to be well-suited to potassium ion recognition and the selective quantitation of thiocyanate levels in human saliva.[14] Most recently, George Shubeita and colleagues from New York University Abu Dhabi designed a FRET-based probe that reports on DNA intercalation, with a view to accelerating the discovery of novel intercalating drugs, via the rapid screening of chemical libraries. Notably, the probe was successfully used to identify known DNA intercalators from approved drug libraries and also discover previously unreported intercalators.[15]

As you will be aware, sensor device engineering is widely featured in *ACS Sensors*, and it comes as no surprise that European, African, and Middle Eastern researchers have contributed strongly in this area. For example, Junrui Zhang and colleagues from EPFL have reported an ISFET-based wearable for multianalyte (pH, Na^+, K^+, and Ca^{2+}) sensing.[16] Despite exceptionally low power consumption, such sensors provide for simultaneous and sensitive time-dependent recording of multiple analytes, while also integrating a readout interface and NFC communication. In addition, Kumar et al. have reported a label-free optical device for monitoring the biochemical activity of NAGase within bovine milk.[17] Notably, the developed sensor operates robustly in untreated milk and across the entire inflammatory spectrum. In related studies, Al-Ghobashy and co-workers have also developed a label-free potentiometric immunosensor to quantify recombinant human myelin basic protein in the milk of transgenic cows, enhancing its utility as a biotherapeutic agent.[18] Moreover, Torsi and associates have used smart bioelectronic organic transistors for selective, single-molecule sensing of genomic biomarkers for multiple sclerosis.[19] Here, it is worth noting that given the generality of the biofunctionalization protocol used, such a sensing platform could be used to detect a variety of protein markers at the single molecule level.

Sensors for cellular assays continue to advance, especially in regard to their *in vivo* application. For example, Tanumihardja and co-workers recently described a chip-based RuOx electrode sensor able to monitor cell metabolism via both pH and O_2 sensing.[20] In a related study, Macpherson and colleagues developed a membrane-less electrochemical sensor for pH and dissolved oxygen measurements. Importantly, the sensor allows for online analysis, detecting both species via a single voltametric measurement.[21] Additionally, Mousavi et al. have presented an electrochemical sensor able to directly detect the neurotransmitter acetylcholine (at nanomolar concentrations and with a temporal resolution of less than one second) in cerebrospinal fluid and rat brain homogenate.[22] Moreover, microtubule- and actin-based electrical measurements were used by Abdolahad and co-workers to monitor changes in the electrical properties of breast cancer cells upon administration of Mebendazole and Paclitaxel.[23] Finally, Murade and Shubeita recently introduced an oligonucleotide-based molecular sensor able to report on macromolecular crowding within cellular compartments. Interestingly, such a sensor is well suited to the study of both protein crowding and chromosome organization.[24]

Over the past decade, plasmonic sensors have become increasingly valuable in a diverse range of applications. For example, in two related papers, Sterl and co-workers describe how plasmonic hydrogen sensors can be realized using a layer of palladium nanostructures suspended above a metallic mirror.[25,26] Such sensors offer wide detection ranges, fast response times, extended lifetime operation, and detection limits down to 50 ppm of hydrogen. In related work, Pastoriza-Santos and colleagues report a hybrid plasmonic platform combining molecularly imprinted polymer films and Au nanoparticle assemblies for SERS-based recognition of polycyclic aromatic hydrocarbons (PAHs).[27] Pandey and Nanda also developed a chemiresistive sensor based on a guar gum nanocomposite and gold nanoparticles for the rapid detection of ammonia at the parts-per-quadrillion level. Importantly, the sensor is well-suited to both environmental and biomedical applications, with the authors demonstrating use in renal function assessments.[28] In another exciting biomedical development, Dev and colleagues at Uppsala University presented an affinity-based electrokinetic sensor for the detection and protein expression profiling of small extracellular vesicles from non-small-cell lung cancer cells, with the sensor revealing subtle changes in surface marker expression on short time scales.[29] Finally, McKendry and colleagues have used nanomechanical cantilever sensors as a tool to detect phenotypic antibiotic resistance.[30] In an elegant study, single bacterial cells from clinical samples are detected as they pass through a laser focus, yielding a simple readout of antibiotic resistance an order of magnitude faster than conventional methods.

To conclude, I hope that you will agree that sensor research in the EMEA region continues to thrive and evolve, and indeed, my only regret is that I could not include more papers in this Virtual Issue. Regardless, I do hope that you will make time to delve into the collection and appreciate the outstanding science and technology.

Andrew deMello, Associate Editor orcid.org/0000-0003-1943-1356

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AUTHOR INFORMATION

Complete contact information is available at:
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Notes

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