Nanosensors:
Transitioning Nanosensors from the laboratory to the marketplace: Challenges and Lessons learned

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A vast amount of nanosensors have been developed, tried and tested:
- biosensors
- electrochemical capacitors
- batteries, fuel cells, novel membrane systems and many more

There are many roadblocks in bridging the gap between academic research and the market place.
Highlights

- Operational definitions
  - Category 1 nanosensor
  - Category 2 nanosensor

- Case studies-
  - *Ultra-sensitive Portable Capillary Sensor (U-PAC™)*
  - CeO₂, Fe₂O₃, TiO₂, ZnO, and fullerenes

- Testbeds and performance metrics

- Bridging the gap
  - a proposal for moving forward
How do you bridge the gap between research and commercialization?

Answer the two key questions of successful innovation:

- Can you make a product?
- Can you get anyone to buy it?
Trivia Questions

Who was:

- The first innovator of electrochemist instruments?
- The person who founded Shockley Semiconductor Laboratory creating Silicon Valley and electronics innovation?
Arnold Orville Beckman (April 10, 1900 – May 18, 2004) was an American chemist who founded Beckman Instruments based on his 1934 invention of the pH meter, a device for measuring acidity. He also funded the first transistor company, thus giving rise to Silicon Valley.
Beckman’s pH meter

“maybe you want to call it entrepreneurship or invention, I don’t know. But anyway, I thought, well, heck, lets make a complete instrument then. Get rid of the stuff spread on the desktop and make it a compact unit”.

Beckman’s first pH meter - predecessor of Model G. This is a picture of original model made in 1934 and patented. Picture courtesy of Beckman Coulter, Inc

Model G pH meter. Device was closed in wooden box 12" wide by 8" deep by 9" high. - was hardly portable, weighting almost 8 kilograms.
Nanosensor Classification

- **Type 1 Nanosensors:**
  Nanotechnology-enabled sensors or sensors that are themselves nanoscale or have nanoscale materials or components

- **Type 2 Nanosensors:**
  Nanoproperty-quantifiable sensors that are used to measure nanoscale properties


Category 1 Nanosensors

- Hundreds of research articles using nanomaterials for chemical & biosensors have been published. There are dozens of reviews available which partly deal with use of nanomaterials for electrochemical nanobiosensors

- Nanoparticles
- Nanowires
- Nanoneedles
- Nanosheets
- Nanotubes
- Nanorods

*Biosensors & Bioelectronics, 24, 2749-2765, 2009.*
Metal-Enhanced Electrochemical Detection (MED)


\[ \text{Ag}_s + \text{H}_2\text{O}(l) \rightarrow \text{AgOH}_{\text{ads}} + \text{H}^+_{\text{aq}} + e^- \]
SUNY-Binghamton scientists and engineers have developed a portable, fully autonomous, and remotely operated sensing device, called Ultra-Sensitive Portable Capillary Sensor (U-PAC™)

5. Analytical Chemistry, 74,713-719, 2002
UPAC instrument

Bench-top System (Developed by Sadik Group in conjunction with the Naval Research Lab\textsuperscript{1,2})

Use proven immobilization and fluorescent chemistry to study and optimize the capillary geometry

### Performance Characteristics

<table>
<thead>
<tr>
<th>Technique</th>
<th>LOD</th>
<th>Response Time</th>
<th>Sample Preparation</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPAC Biosensor</td>
<td>112 spores/ml</td>
<td>30 min</td>
<td>Minimal</td>
</tr>
<tr>
<td>Standard ELISA</td>
<td>4269 spores/ml</td>
<td>6hrs</td>
<td>Extensive</td>
</tr>
<tr>
<td>Standard PCR</td>
<td>250 spores/ml</td>
<td>12 hrs</td>
<td>Extensive (PCR extraction)</td>
</tr>
<tr>
<td>Optical Leaky Clad waveguide biosensor</td>
<td>10,000 spores/ml</td>
<td>40 min</td>
<td>Autonomous</td>
</tr>
<tr>
<td>DOX</td>
<td>Qualitative</td>
<td>30 min</td>
<td>Minimal</td>
</tr>
</tbody>
</table>
Few sensors exist to measure nanoscale properties including mechanical, electronic, photonic, and magnetic properties

- ROS production

Characterization methods
- Not high-throughput
- Not mass quantitative

Electron microscopy
- Size, shape, composition

Crystallinity
- XRD, XPS, Raman

Size in liquid
- DLS

(Auffan et al., 2009)
Conventional and emerging tools for characterizing engineered nanoparticles

SP-ICP-MS = Single Particle Inductively Coupled Mass Spectrometer,
FFF-ICP-MS = Fluid Flow Fractionation Inductively Coupled Mass Spectrometer,
EC-TFF = Electro-Chemical Tangential Fluid Flow,
DOX-EC = Dissolved oxygen Sensor coupled with Electrochemical technique,
DLS = Dynamic Light Scattering.
A single-use quantity of cosmetic (0.5 g) may contain up to 0.6 µg of C₆₀ and demonstrates a pathway for human exposure to engineered fullerenes.

Benn et al., Environ. Poll. (2011)
Nanosensor Responses

- Active sensing electrode surface area of 0.196 cm², an equivalent of $2.02 \times 10^{12}$ beta-CDs should fit on the QCM sensor.

- At low concentrations, the ratio of beta-CD/C₆₀ molecules was $\sim 1.12$ C₆₀/cavity which is consistent with the host-guest chemistry of beta-CD-C₆₀ 1:1 inclusion chemistry.

ES&T 2011, 45, 5294 – 5294.
Category 2:
Capture and Detection of Aerosol Nanoparticles using Poly (amic) acid, Phase-inverted Membranes

1SUNY-BINGHAMTON, NY
Harvard’s VENGES
New Platform for pulmonary and cardiovascular toxicological characterization of inhaled ENMs

Nanotoxicology, 2011; Early Online, 1–11
Surface Characterization
Proposal for Going Forward

- Develop the necessary calibration and validation tools
- Develop SRMs and the analytical quality control tools
- Develop acceptable standards testbeds & characterization centers
Overcoming Present Challenges

- Develop acceptable SRMs
  - Depends on testbeds
- Calibration/validation tools
- Standardization and Testing Centers
- Develop training manuals & SOPs
- Define measures of success
Test beds depend on the application

- Health
- Food
- Pharmaceutical
- Process
- Environmental
- Defense & Security
Testbed Specifications

- Environmental sensor should be sensitive, specific, provide fast response, must be reliable, flexible and capable of rapid and direct detection of toxic compounds.

- Additionally, there should be no need for sample preparation steps when analyzing environmental matrices or point-of-care biomedical samples.

- The sensor should be capable of convenient signal processing that will allow immediate remedial actions to be taken after detection.
Environmental and Clinical Requirements

- Precision, accuracy, measurement range, total error
- Interference
- Reference
- Response time
- Calibration
- Manufacturing
- Single use Vs. multi-use
Nanosensor Performance Metrics-EPA QA/QC

- Data quality parameters
  - Precision, accuracy, LOD, robustness etc

- Method Determination
  - Method positive control, matrix spike, negative control (buffers, blanks, reagent water)

- Frequency
  - With every field sample, 1/batch or 20 samples, 10% of field samples, all standards, blanks, samples

- Quality objective & Comparability
  - % RSD, MDL, intended use of data

Designated Analytical Levels.

Performance Metrics

- Experimental variables should be defined
  - Sensitivity should be defined
  - Selectivity and reliability (false positives and false negatives) should be assessed using SOPs.
  - Optimization of experimental variables influencing sensor selectivity and sensitivity as well as the transfer to manufacturing platforms.
- Comparable to standard EPA, AOAC or FDA methods.
Conclusions - Needs of the Community

- Manufacturing must produce stable sensors with uniform and non-distortable signals across sensing area.
- Sensor layers must be mounted with a suitable transducer that does not distort them.
- Unpreventable calibration errors in the devices must be reduced to an acceptable level.
- Developing QC for the sensor industry requires the collaboration between the manufacturing, government, and research laboratories.