CaviTrace : Hydrodynamic Cavitation-Based Rapid Gram Classification

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Priority Topic Area: **Health and Wellbeing**

1 – Aim/planned deliverables – Bridging the Diagnostic Gap in Antimicrobial Resistance Detection

Antimicrobial resistance (AMR) remains a global health challenge which has resulted in the deaths of about 5 million people worldwide. Current rapid molecular diagnostics though effective, remain costly, while conventional culture-based workflows exceed 18-hour turnaround times, delaying treatment. This study looks into developing CaviTrace, a hydrodynamic cavitation–based triage screening platform designed to rapidly classify bacteria as Gram-positive or Gram negative, information that is immediately actionable for antibiotic selection. Gram classification exploits the documented structural differences between the two cell wall types providing an acoustically detectable signal.

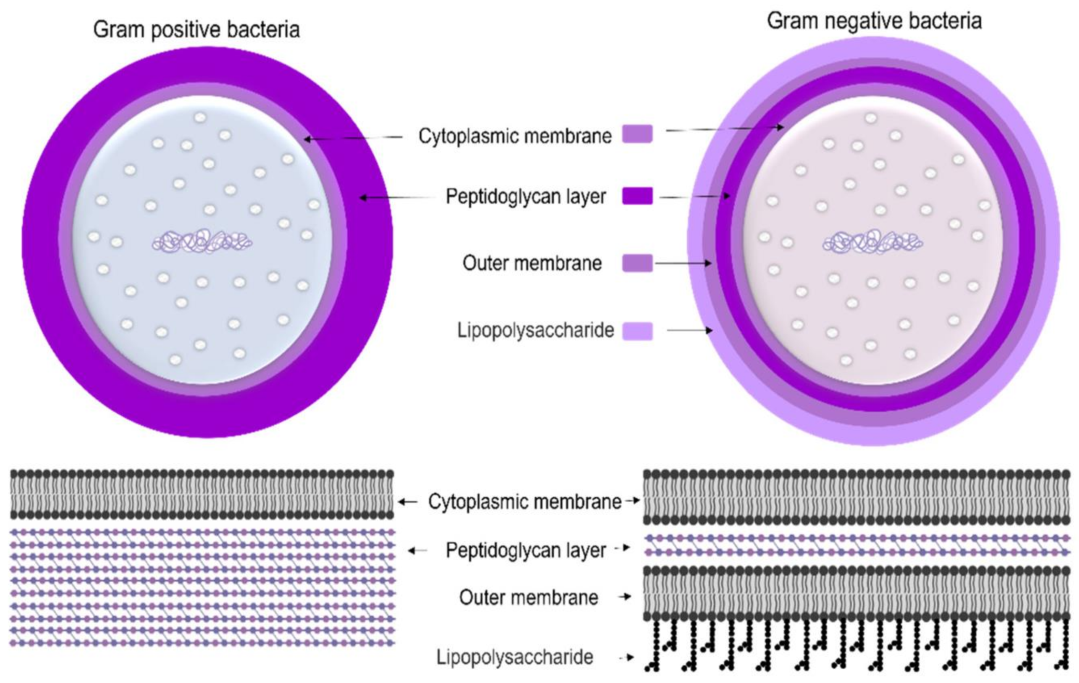


Figure1: Structural comparison of Gram-positive and Gram-negative bacterial cell walls

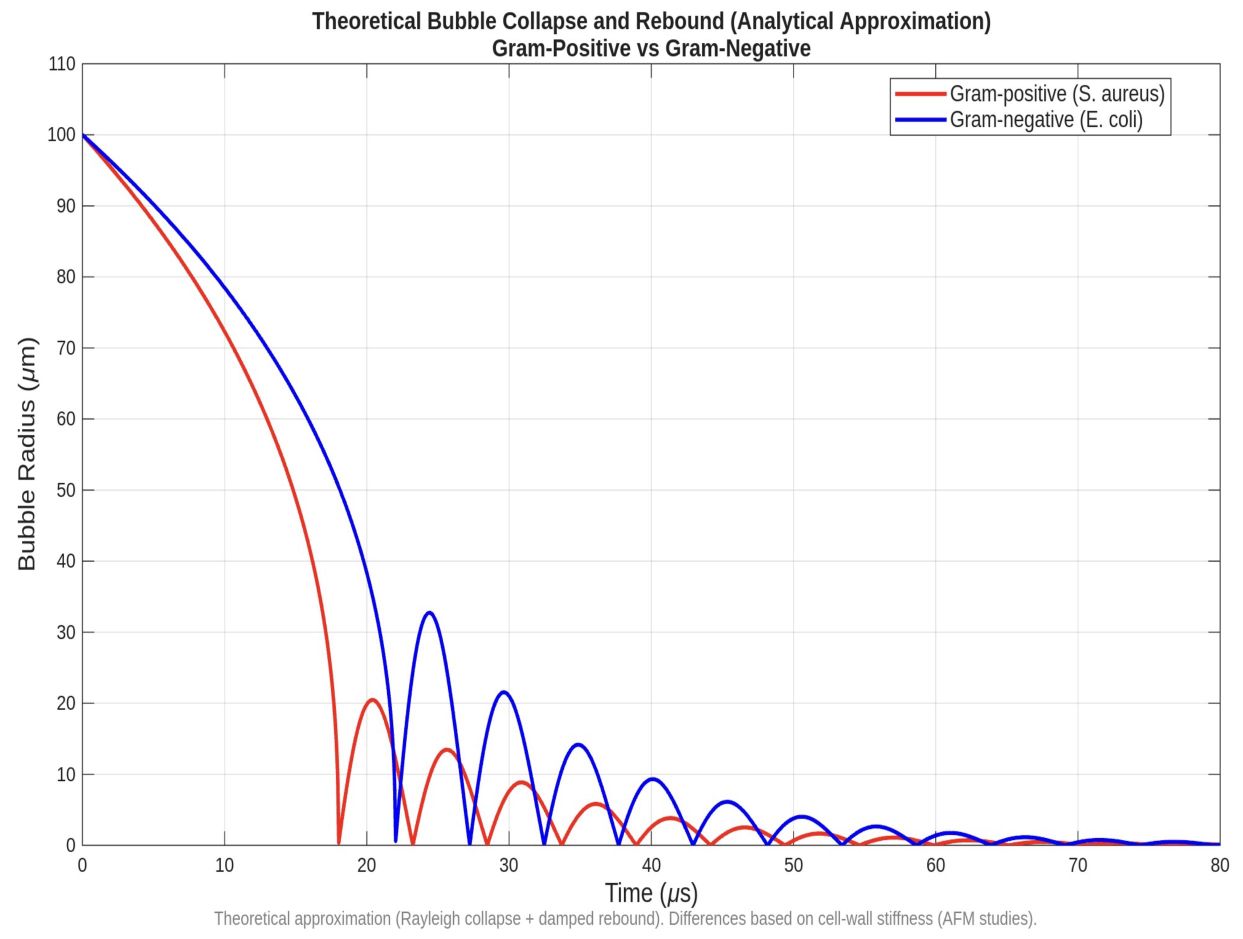
2 – Methodology : Translating Cell Wall Biophysics into a Diagnostic Signal

CaviTrace passes bacterial samples through a cavitation chamber where controlled pressure differentials induces membranes stress.

Gram- positive cells (which have substantially thicker peptidoglycan cell walls) and Gram negative cells exhibit distinct cavitation collapse thresholds and acoustic emission profiles as evidenced by AFM stiffness differential. Piezoelectric sensors capture the emissions across frequency and amplitude domains from which interpretable physical features feed a lightweight classifier trained on relevant reference strain. An internal control normalises concentration and growth phase variability. Temperature is also kept with ±1°C. When multiple organisms are present, their acoustic signatures will overlap, producing a blended signal that cannot be reliably classified thus such samples are flagged as inconclusive. A PID controller regulates pressure and outputs a binary gram classification for treatment triage

3 – Findings : Computational Modelling of Gram – Differential Cavitation Behaviour

Computational models developed in MATLAB were used to access the theoretical feasibility of Gram classification via cavitation acoustics. Each model addresses a distinct aspect of the proposed classification mechanism.



- **Cell Wall Stiffness and Collapse Dynamics**

Gram- positive bacteria possess peptidoglycan layers of 20 -80 nm with a spring constant of 0.41 ± 0.01 N/m, compared to 2-7 nm and 0.23±0.02 N/m in Gram-negative organisms.
This stiffness differential predicts faster collapse with small rebounds for Gram-positive cells, and a slower collapse with Larger rebounds for Gram-negative cells.
The bubble collapse graph illustrates these predicted dynamics using an analytical collapse based on Rayleigh –Plesset bubble dynamics.

- **Theoretical Cavitation Number Thresholds :**

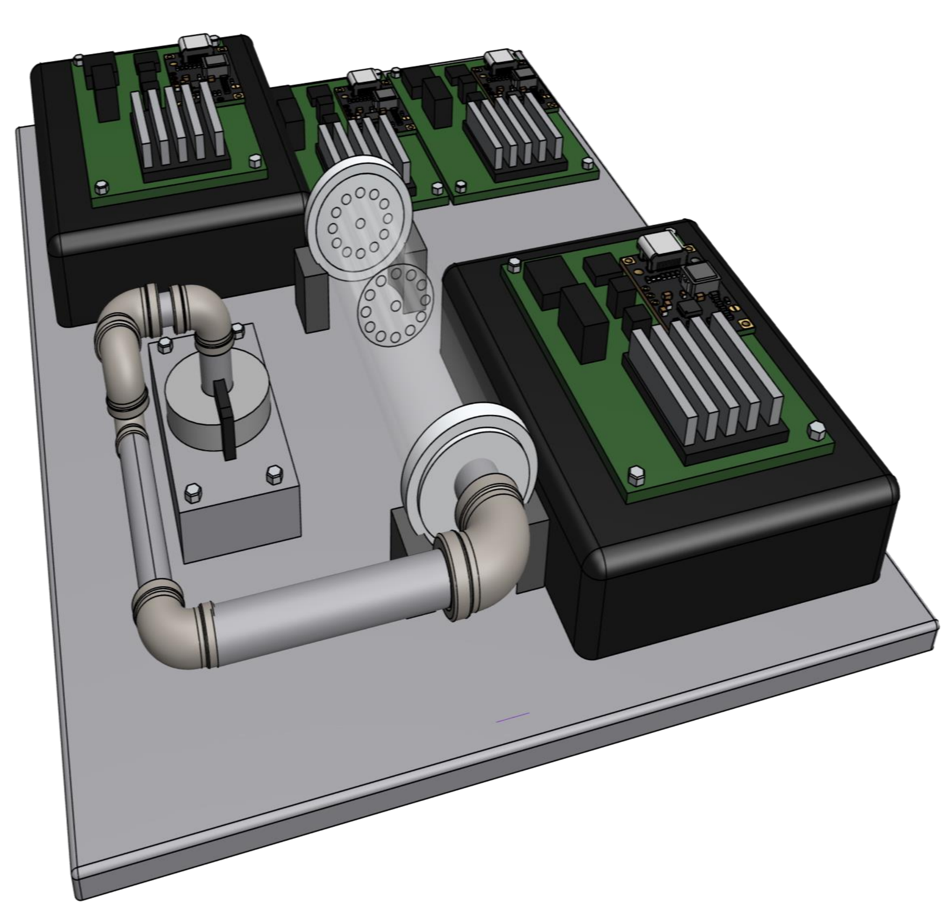
This simulation assumes lysis onset at σ =0.6-0.9 for Gram-positive cells and σ=1.2. -1.5 Gram-negative cells. The threshold separation of about $\Delta\sigma$=0.3 represents a substantial margin relative to typical pressure control precision under typical operating conditions, suggesting that two rupture events are theoretically resolvable as distinct signals.

- **Acoustic Emission Characteristics**

Bubble collapse generates a pressure wave detectable by a piezoelectric sensor. The magnitude of this wave is determined by bubble size, collapse intensity and sensor distance, all parameters that can be controlled through reactor design. Background hydrodynamic noise arises from fluid flow and bubble dynamics. Based on established cavitation physics, collapse-generated emissions are predicted to be sufficiently distinct for reliable detection. If validated experimentally, these acoustic signatures would provide the physical basis for a rapid reagent-free Gram-classification result to guide in antibiotic selection.

4 – Benefit to society: Transforming Frontline Diagnostics

CaviTrace targets antimicrobial resistance, one of the most pressing challenges in global health, which has caused approximately 5 million deaths worldwide according to the WHO.
By delivering a rapid Gram-classification result within 30 minutes, the device enables clinicians to make informed decisions before culture results are available, thus reducing inappropriate broad-spectrum prescribing.
Designed for low-resource settings where molecular diagnostics remain inaccessible, CaviTrace has the potential to strengthen diagnostic infrastructure where AMR burden is highest. Earlier, more targeted treatment improves patient outcomes, reduces treatment cost, and slows down the emergence of resistant strains, benefits that extend beyond individual patients to entire health systems.



5 – Next steps: From Simulation to Prototype

Immediate priorities include experimental calibration of cavitation thresholds against reference strains (S. aureus and E. coli), followed by prototype reactor development and acoustic sensor validation.
Performance will be benchmarked against Gram stain and culture standards. Successful validation would support a clinical pilot in UTI specimens across low-resource settings.

References/Acknowledgements
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