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BACTERIAL NANOMECHANICAL VIBRATIONS AS A DIAGNOSTIC TOOL: A NARRATIVE REVIEW OF EVIDENCE, TERMINOLOGY, AND LIMITATIONS

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ABSTRACT

Introduction. Atomic force microscopy (AFM) and graphene-based nanomechanical resonators show that bacterial cells generate detectable nanoscale mechanical oscillations ("nanomotion") linked to flagellar rotation, pilus activity, and metabolism. These signals have been proposed for rapid antimicrobial susceptibility testing (AST), but are often discussed together with mechanistically unrelated phenomena, including ultrasound imaging of gas-vesicle reporter bacteria, quorum sensing, and the effects of external sound or electromagnetic fields on bacterial growth.

Aim. To critically review the evidence for bacterial nanomechanical vibrations as a diagnostic tool, with an emphasis on rapid AST, and to clarify the terminological and mechanistic boundaries between nanomotion detection and related but distinct acoustic phenomena.

Materials and methods. A narrative review was conducted using PubMed, supplemented by Google Scholar, with combinations of the search terms "bacterial nanomotion", "AFM bacteria", "graphene resonator bacteria", "bacterial vibration antibiotic susceptibility", and "acoustic reporter genes", restricted to English-language studies. Titles and abstracts were screened for relevance to mechanical, acoustic, or ultrasound-based detection of bacterial activity; unrelated sources were excluded.

Results. AFM- and graphene-drum-based nanomotion assays can distinguish metabolically active from antibiotic-killed bacteria within hours in single-species proof-of-concept studies, but large-scale validation across multiple bacterial species and antibiotics against reference MIC testing remains limited. Ultrasound imaging of acoustic reporter genes, quorum-sensing regulation of biofilm formation and virulence, and the effects of external sound or electromagnetic exposure are supported by separate, non-overlapping evidence. Proposed industrial, environmental, and space microbiology applications remain largely hypothetical, with no clinical, regulatory, or industrial validation identified.

Conclusions. Nanomechanical vibration detection is a promising but early-stage diagnostic approach, supported mainly by proof-of-concept studies. Multicenter validation, standardized terminology, and clear separation from mechanistically distinct phenomena are needed before broader translational claims can be justified.

Keywords: bacterial nanomotion; atomic force microscopy; antimicrobial susceptibility testing; graphene resonator; acoustic reporter genes

INTRODUCTION

Bacterial cells are not passive with respect to mechanical energy: their flagellar rotation, pilus activity, and metabolic processes generate nanoscale mechanical oscillations that can be detected with sufficiently sensitive instrumentation [1, 2]. These oscillations, commonly termed "nanomotion" or "nanomechanical vibrations," are distinct from audible sound and require dedicated transducers – most notably atomic force microscopy (AFM) cantilevers and graphene nanomechanical drums – for detection and quantification.

Graphene-drum resonators loaded with single bacterial cells convert cellular nanomotion into a measurable mechanical signal, as illustrated in Figure 1 [3]. This approach has been used to distinguish metabolically active bacteria from bacteria killed by antibiotic exposure, since motion amplitude decreases markedly once cells lose viability [3].

It is important to distinguish this phenomenon from several related but mechanistically different areas of research that are sometimes discussed under the same umbrella term of "bacterial sounds": (i) nanomechanical vibrations of individual cells detected

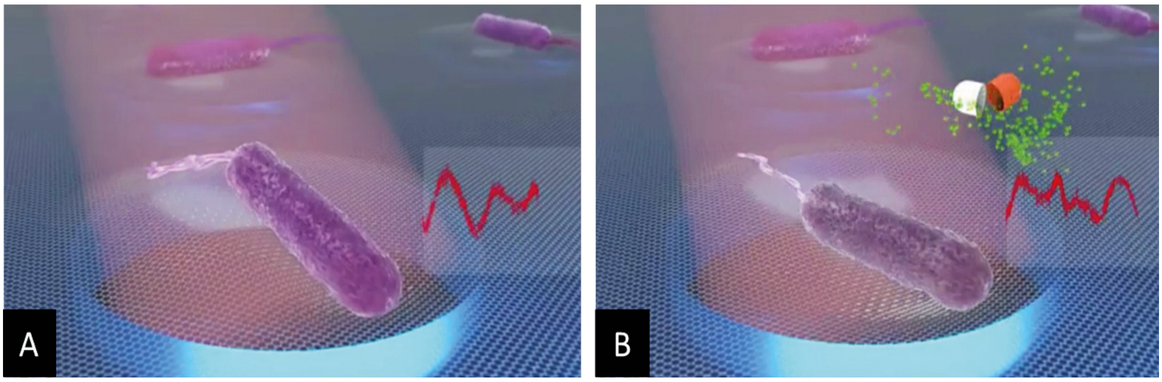

Fig. 1. Schematic illustration of a graphene-drum resonator detecting nanomotion of a single bacterium. (A) A metabolically active bacterium generates continuous nanomechanical vibration. (B) Vibration amplitude decreases markedly following antibiotic exposure, consistent with loss of viability. Adapted from the graphene-drum nanomotion assay described by Roślń et al. [3]; original source and reproduction permission to be confirmed by the corresponding author prior to submission

by AFM or graphene resonators; (ii) ultrasound imaging of genetically engineered bacteria expressing gas vesicles ("acoustic reporter genes"), used for in vivo visualisation rather than single-cell diagnostics; (iii) chemical quorum-sensing communication, which is not itself an acoustic or mechanical phenomenon but is occasionally conflated with it in the popular literature; and (iv) studies of how external audible sound or electromagnetic fields affect bacterial growth and antibiotic susceptibility, which examine bacteria as a target of external stimuli rather than as a source of a diagnostic signal. These four bodies of work differ in mechanism, instrumentation, and level of supporting evidence, and are treated separately throughout this review.

Interest in nanomotion detection stems largely from its potential to accelerate antimicrobial susceptibility testing, a task of direct relevance to the global challenge of antimicrobial resistance [4, 5]. Related, more speculative interest concerns environmental and industrial monitoring of microbial activity [6, 7] (Figure 1).

AIM

The aim of this review is to critically evaluate the evidence for bacterial nanomechanical vibrations, principally as detected by AFM- and graphene-resonator-based methods, as a tool for rapid antimicrobial susceptibility testing, and to clarify how this phenomenon differs mechanistically and in evidentiary strength from ultrasound-based bacterial imaging, quorum-sensing communication, and bacterial responses to external sound or electromagnetic exposure. Environmental and industrial applications are discussed only to the extent that they are directly supported by the reviewed sources, and are explicitly flagged where evidence is currently limited to hypothesis or extrapolation.

MATERIALS AND METHODS

This is a narrative review. The literature search was performed in PubMed, with cross-checking in Google Scholar, and covered publications up to 2024. Search terms included combinations of "bacterial nanomotion", "atomic force microscopy bacteria", "graphene resonator bacteria", "bacterial vibration antibiotic susceptibility", "acoustic reporter genes", "sonogenetics", and "sound electromagnetic bacterial growth".

Inclusion criteria were: (1) direct measurement or manipulation of bacterial mechanical, acoustic, or ultrasound signals; (2) bacterial species as the object of study rather than incidental mention; and (3) availability of a verifiable digital object identifier (DOI) or indexed record. Exclusion criteria were: studies concerning non-bacterial organisms unless directly comparative; general acoustic-engineering studies without a bacterial component; and sources that could not be verified against PubMed or Crossref at the time of writing. Reference verification against PubMed and Crossref led to the removal of several sources present in an earlier draft that were found to concern unrelated topics, including sound-absorbing building materials, shore-crab behaviour, and urban aerobiome stratification. These exclusions are noted where relevant to ensure transparency. No formal quality-assessment instrument was applied, consistent with the narrative (non-systematic) design of this review; this is acknowledged as a limitation below.

RESULTS

Terminology and Definitions

For clarity, the following terms are used consistently throughout this review. "Nanomechanical vibration" or "nanomotion" refers specifically to sub-nanometre- to nanometre-scale mechanical oscillations of individual bacterial cells detected by AFM cantilevers or graphene-based nanomechanical drums. "Acoustic reporter genes" refers to genetically encoded gas vesicles that scatter ultrasound and enable in vivo imaging of bacterial populations; this is an ultrasound imaging method, not a measurement of intrinsic bacterial vibration. "Quorum sensing" refers to chemical signaling between bacteria and is not an acoustic phenomenon. "External sound/ electromagnetic exposure" refers to studies in which bacteria are the targets, rather than the sources, of an applied acoustic or electromagnetic stimulus. Where the literature uses the informal term "bacterial sounds," this review treats it as an umbrella term requiring further specification rather than as a defined technical category.

Biophysical Mechanisms of Nanomechanical Vibrations

Nanomechanical vibrations of bacterial cells are attributed to flagellar rotation, pilus retraction/ extension, and metabolically driven cytoplasmic and membrane fluctuations [1, 2]. When a bacterium is mechanically coupled to a sufficiently sensitive resonator – an AFM cantilever tip or a suspended graphene membrane – these sub-cellular movements produce a measurable change in resonance frequency or deflection amplitude [3]. Because the signal reflects ongoing cellular activity, it decreases when metabolism is arrested, which is the basis for its proposed use in viability and antimicrobial-susceptibility assessment [3, 8].

Detection Methods

Table 1 summarises the principal methods used to detect bacterial nanomechanical or acoustic signals, together with their measured parameter, approximate operating ranges, and current level of practical implementation, based on the sources reviewed. Several of these methods (ultrasound imaging, optical tweezers) do not measure intrinsic bacterial "sound" directly but rather force, displacement, or an

Table 1. Methods used to detect bacterial nanomechanical or acoustic signals, with measured parameter, approximate range, level of implementation, and key limitation

Method	Physical Principle / Measured Parameter	Approximate Range / Resolution	Level of Implementation	Key Limitation
Atomic Force Microscopy (AFM)	Cantilever deflection from nanomechanical cell motion; sub-nm displacement	Sub-nm to nm amplitude; Hz–kHz frequency	Single-cell, research-laboratory stage [3, 9]	Low throughput; requires trained operators and controlled sample mounting
Graphene nanomechanical drums	Resonance-frequency shift of a suspended graphene membrane loaded with a single bacterium	nm-scale displacement; kHz–MHz resonance	Proof-of-concept, single/few-species studies [3]	Not yet validated across broad panels of species/antibiotics
Piezoelectric sensors	Conversion of mechanical vibration into an electrical signal	Sensor-dependent; typically kHz range	Laboratory prototypes	Limited specificity to individual-cell signal versus bulk noise
Ultrasound imaging (acoustic reporter genes)	Ultrasound scattering from genetically expressed gas vesicles; an imaging contrast method, not intrinsic vibration	MHz ultrasound frequencies; population-level, not single-cell	In vivo animal-model studies [10]	Requires genetic modification; not applicable to unmodified clinical isolates
Optical tweezers	Laser-trap force measurement used to infer mechanical properties, not direct sound detection	pN-scale force resolution	Specialised biophysics laboratories	Low throughput; high equipment cost
Laser Doppler vibrometry (LDV)	Non-contact optical measurement of velocity/displacement	nm-scale displacement	Experimental / early-stage for bacterial applications	Requires stable, non-contact optical access to the sample
Microelectromechanical systems (MEMS)	Integrated mechanical–electrical transducers	Device-dependent	Early-stage portable prototypes	Lower resolution than AFM; limited published validation

engineered acoustic contrast agent; this distinction is indicated in the table.

Antimicrobial Susceptibility Testing: Evidence and Limitations

The strongest evidence for a diagnostic application of nanomechanical vibrations concerns antimicrobial susceptibility testing. In graphene-drum- and AFM-based assays, cessation or marked reduction of nanomotion following antibiotic exposure has been used as an indicator of bacterial killing, whereas continued vibration has been associated with survival or resistance in the specific strains and antibiotics tested [3, 8]. However, the sources reviewed do not establish that this relationship holds universally across bacterial species, antibiotic classes, or resistance mechanisms; nor do they report large-scale, multicentre comparisons against reference broth microdilution MIC testing with defined sensitivity and specificity values. The number of clinical isolates evaluated in the available proof-of-concept studies is small, and turnaround-time claims (typically minutes to a few hours) have not been independently reproduced across multiple laboratories in the identified literature. Continued bacterial vibration should therefore not be equated with resistance, nor should cessation of vibration be interpreted as confirmed clinical treatment efficacy without additional validation. These findings remain correlational and derive from early-stage studies rather than established diagnostic criteria.

Bacterial Communication and Collective Behaviour: Distinguishing from Nanomotion

Separately from nanomechanical vibration, quorum sensing – a chemical, not acoustic, signalling process – is well established as a regulator of biofilm formation and virulence-factor expression [11, 12]. Some sources additionally report that bacterial growth, metabolism, or biofilm formation can be affected by externally applied sound frequencies or electromagnetic fields [13-16]. These findings describe bacteria as recipients of an external physical stimulus, and do not, on their own, demonstrate a universal acoustic channel of bacterial-to-bacterial communication analogous to quorum sensing. Causal claims linking nanomechanical vibration itself to intercellular communication are not directly supported by the sources reviewed and are presented here as a hypothesis rather than an established mechanism.

Proposed Environmental, Industrial, and Medical Applications

Table 2 lists proposed applications identified in the literature, together with an explicit evidence-

Table 2. Proposed applications of bacterial nanomechanical or acoustic phenomena, by domain, representative source(s), and evidence level

Proposed Application	Domain	Representative Source(s)	Evidence Level	Notes / Limitations
Rapid antimicrobial susceptibility testing	Medical	[3, 8]	Early-stage experimental	Single/few-species proof-of-concept; not validated against reference MIC testing at scale
In vivo imaging of engineered bacteria via gas-vesicle ultrasound reporters	Medical / research	[10]	Established (in animal models)	Requires genetic engineering of the bacterial strain; not applicable to native clinical isolates
Biofilm and virulence regulation via quorum sensing	Medical / microbiology	[11, 12]	Established (chemical signalling, not acoustic)	Frequently miscategorised as an "acoustic" phenomenon in secondary literature
Effect of external sound/ electromagnetic fields on bacterial growth or antibiotic susceptibility	Basic research	[13-16]	Experimental, strain-specific	Effect sizes and mechanisms vary by study; not yet a validated clinical or industrial tool
Industrial fermentation, wastewater, and food-quality monitoring via bacterial vibration	Industrial / environmental	—	Hypothetical / extrapolated	No industrial implementation, regulatory approval, or peer-reviewed validation identified
Space-microbiology monitoring (e.g., aboard the ISS)	Environmental / aerospace	—	Hypothetical / extrapolated	No specific primary source identified for bacterial-nano-motion monitoring in this context
AI-assisted analysis of vibrational/acoustic data	Cross-cutting	—	Emerging concept	Proposed direction for future research rather than a demonstrated application

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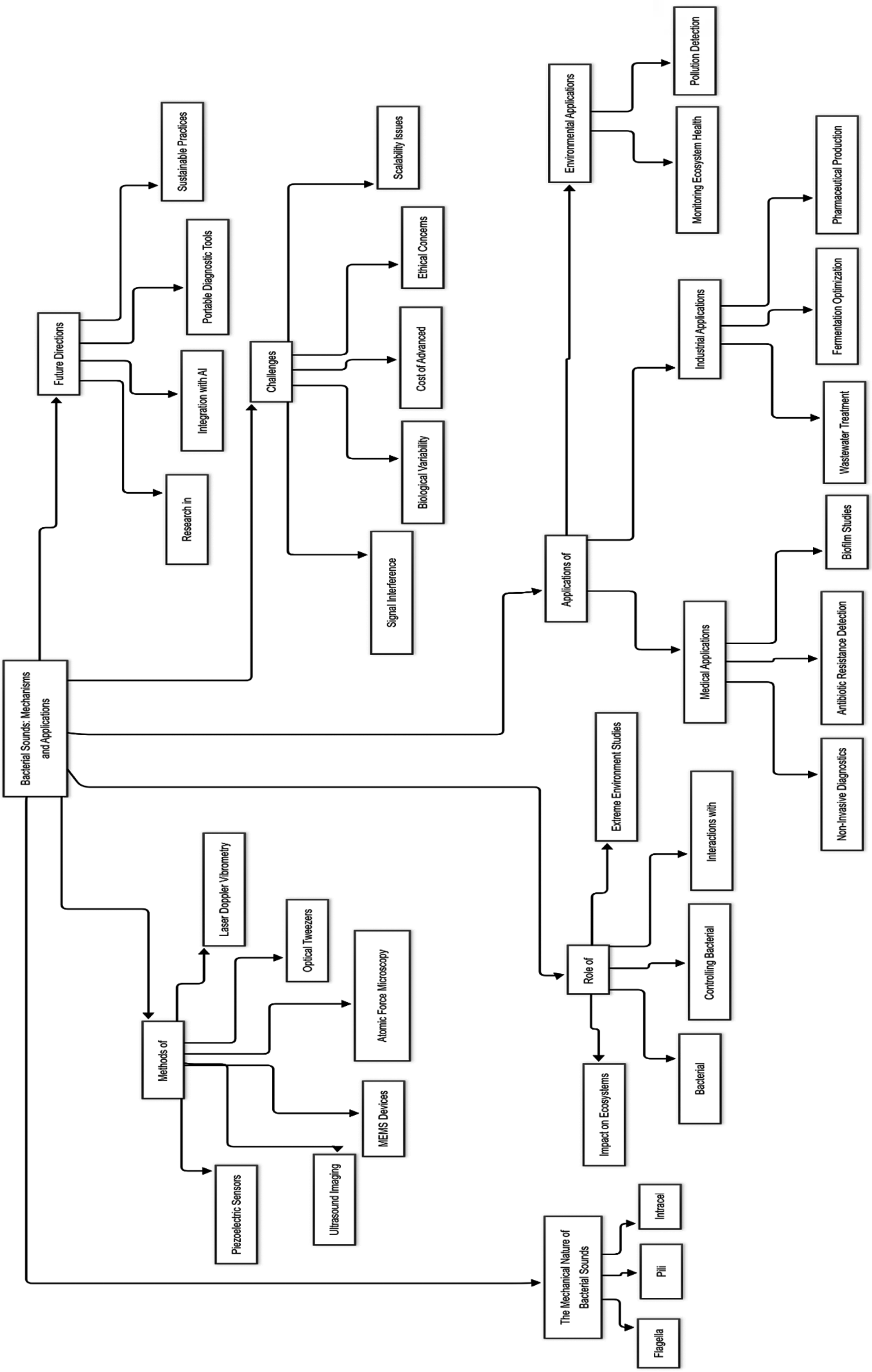

Fig. 2. Overview diagram linking proposed mechanisms, detection methods, and application domains discussed in this review. Relationships shown reflect the evidence-level distinctions described in Table 2; hypothetical applications are not intended to represent established clinical, industrial, or regulatory practice.

level rating. Applications rated "established" are supported by peer-reviewed experimental data specific to the stated use; those rated "hypothetical/extrapolated" are scenarios discussed in the literature or by extension from related findings, without direct experimental, clinical, or industrial validation identified in the sources reviewed. These relationships between mechanisms, detection methods, and application domains, and the evidence-level distinctions summarised in Table 2, are illustrated in Figure 2.

Limitations of the Current Evidence Base

Several limitations constrain the strength of the conclusions that can be drawn from the current literature. High-sensitivity instrumentation (AFM, graphene resonators, and MEMS) remains costly and requires specialised operator training. Environmental mechanical noise can complicate signal acquisition and interpretation. Vibrational patterns vary across bacterial species and strains, making standardisation challenging. Interpretation of complex vibrational datasets requires dedicated computational and, increasingly, machine-learning tools, whose validation remains at an early stage. The use of genetically engineered acoustic reporter bacteria raises regulatory and biosafety questions that require case-by-case evaluation. Finally, translation from single-centre proof-of-concept studies to reproducible and scalable clinical or industrial applications has not yet been demonstrated in the sources reviewed.

DISCUSSION

The evidence reviewed here supports a cautiously optimistic but clearly bounded view of bacterial nanomechanical vibration as a diagnostic signal. The clearest and most direct evidence concerns single-cell AFM- and graphene-resonator-based detection of viability loss after antibiotic exposure, which offers a plausible route toward faster antimicrobial susceptibility testing than conventional culture-based methods. This evidence, however, currently rests on a small number of proof-of-concept studies with limited species and antibiotic coverage, and has not been compared systematically against reference MIC methodology across multiple centres.

By contrast, ultrasound imaging of acoustic reporter genes, quorum-sensing-mediated communication, and bacterial responses to external sound or electromagnetic exposure are each supported by their own, distinct bodies of literature, but should not be treated as evidence for a single unified field of "bacterial bioacoustics." Conflating these phenomena risks overstating the maturity of any one of them and obscures the specific validation still required for each. Industrial, environmental, and space-microbiology applications discussed in secondary or promotional sources are, on the basis of the sources identified here, hypothetical extensions rather than demonstrated technologies, and should be labelled as such in future work.

Future research would benefit from standardised terminology distinguishing these phenomena; multi-centre studies directly comparing nanomotion-based AST against reference MIC testing, with reported sensitivity, specificity, and turnaround time; and transparent reporting of the technology readiness level of any proposed industrial or environmental application.

CONCLUSIONS

Bacterial nanomechanical vibration detection, principally via AFM and graphene-based nanomechanical resonators, is supported by proof-of-concept evidence as a marker of bacterial viability and a candidate tool for rapid antimicrobial susceptibility testing, although large-scale clinical validation against reference methods remains lacking. Ultrasound-based imaging of acoustic reporter genes and quorum-sensing-mediated communication are separately well-supported phenomena that should not be conflated with nanomechanical vibration. Proposed industrial, environmental, and space microbiology applications remain at a hypothetical or exploratory stage and require dedicated primary studies, technology-readiness assessment, and, where relevant, regulatory evaluation before they can be considered validated technologies. Priority directions for further research include multispecies, multi-antibiotic clinical validation studies; standardised terminology; and transparent grading of the evidence supporting proposed applications.

Article Declarations

Prospects for further research. Further studies should prioritise multi-centre, multi-species clinical validation of nanomotion-based antimicrobial susceptibility testing against reference MIC methodology, with reported sensitivity and specificity; development of standardised terminology distinguishing nanomechanical vibration, ultrasound-based imaging, quorum sensing, and external sound/electromagnetic exposure studies; and technology-readiness assessment of proposed environmental and industrial applications.

Study limitations. This is a narrative, non-systematic review. Its limitations relate to the predefined scope of the topic, the search period and study types included, and the availability of relevant sources. The literature search strategy included PubMed, supplemented by Google Scholar; a formal systematic-review protocol (e.g., PRISMA) was not applied, and no formal quality-scoring instrument was used to weight individual studies.

Primary data and materials. The authors confirm that no primary medical documentation, including medical records, outpatient records, examination protocols, individual patient laboratory or instrumental findings, or statistical databases, was used in this study.

Research ethics. This is a literature review that did not involve human participants, animal subjects, or identifiable medical data; formal ethics committee approval was therefore not required. If any component of the underlying work involved human participants, animals, or identifiable data, please replace this statement with the applicable approval details, including committee name and approval number.

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БАКТЕРІАЛЬНІ НАНОМЕХАНІЧНІ КОЛИВАННЯ ЯК ДІАГНОСТИЧНИЙ ІНСТРУМЕНТ: НАРАТИВНИЙ ОГЛЯД ДОКАЗОВИХ ДАНИХ, ТЕРМІНОЛОГІЇ ТА ОБМЕЖЕНЬ

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РЕЗЮМЕ

Вступ. Атомно-силова мікроскопія (AFM) та графенові наномеханічні резонатори демонструють, що бактеріальні клітини генерують детектовані наномасштабні механічні коливання («нанорух»), пов’язані з обертанням джгутиків, активністю пілів та метаболічними процесами. Ці сигнали розглядаються як потенційний інструмент швидкого визначення чутливості до антимікробних препаратів (AST), однак їх часто обговорюють разом із механістично не пов’язаними явищами, зокрема ультразвуковою візуалізацією бактерій-репортерів із газовими везикулами, кворум-сенсингом та впливом зовнішнього звуку або електромагнітних полів на ріст бактерій.

Мета. Критично проаналізувати докази щодо використання бактеріальних наномеханічних коливань як діагностичного інструменту, з особливим акцентом на швидкому визначенні чутливості до антимікробних препаратів, а також уточнити термінологічні та механістичні межі між детекцією наноруху та пов’язаними, але відмінними акустичними явищами.

Матеріали та методи. Проведено наративний огляд літератури з використанням бази даних PubMed із додатковою перевіркою в Google Scholar. Пошук здійснювали за комбінаціями пошукових термінів «bacterial nanomotion», «AFM bacteria», «graphene resonator bacteria», «bacterial vibration antibiotic susceptibility» та «acoustic reporter genes» з обмеженням до англомовних публікацій. Заголовки та анотації оцінювали на відповідність тематиці механічної, акустичної або ультразвукової детекції бактеріальної активності; нерелевантні джерела виключали.

Результати. Наномеханічні дослідження із застосуванням AFM та графенових барабанних резонаторів дають змогу протягом кількох годин відрізнити метаболічно активні бактерії від бактерій, загиблих під впливом антибіотиків, у межах доказових досліджень на окремих видах бактерій. Водночас широкомасштабна валідація на різних видах бактерій та за різних класів антибіотиків із використанням референтного визначення мінімальної інгібувальної концентрації (MIC) залишається обмеженою. Ультразвукова візуалізація акустичних генів-репортерів, кворум-сенсингова регуляція формування біоплівок і вірулентності, а також вплив зовнішнього звуку або електромагнітного випромінювання на бактерії мають окремі, незалежні доказові бази. Запропоновані промислові, екологічні та космічні мікробіологічні застосування залишаються переважно гіпотетичними; клінічної, регуляторної або промислової валідації таких технологій не виявлено.

Висновки. Детекція наномеханічних коливань є перспективним, але раннім за рівнем розвитку діагностичним підходом, доказова база якого переважно представлена дослідженнями підтвердження концепції (proof-of-concept). Для обґрунтування ширших трансляційних висновків необхідні багатоцентрова валідація, стандартизована термінологія та чітке розмежування цього явища з механістично відмінними феноменами.

Ключові слова: бактеріальний нанорух; атомно-силова мікроскопія; визначення чутливості до антимікробних препаратів; графеновий резонатор; акустичні гени-репортери.

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