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MEDICAL ASPECTS OF BACTERIAL STIGMERGY

The article highlights current data on the medical aspects of bacterial stigmergy problem, which is considered a phenomenon of collective self-organization of bacterial communities in response to the influence of adverse environmental factors. The transformation of bacteria into various adaptive forms is a phenomenon that is not only repeated in in vitro experiments but also is quite often a form of bacterial existence in the human body. A number of forms of bacterial stigmergy are discussed, such as biofilm formation, uncultivated forms of bacteria, microorganisms with a defect in cell wall synthesis, and a motile colony morphotype that can exist in the patient's organism at different stages of the infectious process. Analysis of clinical data shows that under most diseases, pathogens can acquire certain forms of resistance, while in some cases, for example, in typhoid fever, the origin of multifactorial protection is observed with the formation of uncultivated and L-forms, as well as a “motile” morphotype of colonies. The role of adaptively modified forms in the development of chronic and recurrent infections is considered.

Keywords: bacterial stigmergy, biofilm formation, uncultivated forms of bacteria, microorganisms with cell wall synthesis defects, motile colony morphotype.

The ability of microorganisms to quickly adapt and counteract the effects of adverse environmental factors underlies the ability of pathogens to persist for a long time in a new ecological niche and their influence on the development of both infectious and epidemic processes (Guzmán-So-

to et al., 2021). This pattern is especially relevant among infectious disease pathogens that are isolated in hospitals (Arbune et al., 2021). It should be noted that all microorganisms that enter from patients, medical personnel, or the external environment under the selective pressure of anti-

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biotics widely used in medical institutions can develop resistance to them (De Oliveira et al., 2020). As a result, pathogens that have adapted to adverse living conditions colonize most of the medical institution biotopes (Horcajada et al., 2019). They repeatedly contact a wide range of antibiotics, resulting in the origin of poly-, multi-, and pan-resistant strains (Potron et al., 2015). The described trend is global in nature and is considered a significant threat to humanity due to the possible loss of effectiveness of antibiotics in the future (Habboush & Guzman, 2023; Antimicrobial, 2022). However, this pattern is observed not only in medicine (Urban-Chmiel et al., 2022). It is known about the development of *Staphylococcus* spp. resistance to antimicrobial drugs in cattle breeding, *Enterococcus* spp. in veterinary medicine, *Campylobacter* spp. in poultry farming, *Pseudomonas syringae* in crop production, etc. (Wieczorek & Osek, 2015; John, 2020; Stępień-Pyśniak et al., 2021; Balko et al., 2024). Natural resistance to metals has also been revealed in extremophilic bacteria isolated from ecotopes that have not been influenced by humans, such as Antarctica (Kotsofliak et al., 2004). The above indicates that the development of resistance in microorganisms is a natural phenomenon that can always develop in any microbial population.

Currently, there is a transition from traditional views of bacteria as purely single-celled organisms to the idea of microbial communities in holistic structures (Fernández-Billón et al., 2023; Nadell et al., 2016). In response to adverse factors, bacterial cells form a variety of multicellular structures that regulate their behavioral responses to changes in the living conditions (Qin et al., 2020). Due to a complex coordination mechanism, microorganisms maintain the population's ability to survive in the external environment. However, survival is not always associated with the development of resistance, which is considered too energy-intensive for a bacterial cell. It is known that in prolonged absence of antibiotics in the environment, bacteria can lose resistance genes and return to their

original, sensitive phenotype (Guliy et al., 2014). Therefore, understanding the organization of bacterial communities and the patterns of interaction between microorganisms within them can provide tools to combat antibiotic resistance in pathogens and indicate ways to prevent it.

The term “stigmergy” was introduced in 1959 by French entomologist Pierre-Paul Grasse to describe the behavior of termites during the construction of termite colonies (Oberst et al., 2020). The principle of stigmergy describes self-organized phenomena that arise as a result of mediated communication among individuals in a group through the generation of constant signals to the external environment (Boldini et al., 2024). Stigmergy is used to describe various group activities, such as pheromone trails laid by ants, gregarious migration of animals, in some aspects of human activity, robotics and computing, and even in substantiating the patterns of development of multicellular tissues (Bánó et al., 2024; Tonello & Vallortigara, 2023; Gallo & Chittka, 2021). However, the application of the concept of stigmergy to describe the collective behavior of bacteria has only recently been proposed (Gloag et al., 2015).

Bacterial stigmergy explains the principle of self-organizing multicellular collective behavior of bacteria. This phenomenon has been reproduced in *in vitro* experiments and becomes apparent by the existence of bacteria in biofilms, uncultivated and L-forms, cultures with a “motile” morphotype (Gloag et al., 2017). Thus, the rapid response of bacteria to environmental changes, which contributes to their survival, is currently considered a stigmergic self-organization of bacterial communities (Gloag et al., 2015).

Within the framework of the study of the bacterial stigmergy phenomenon, two interrelated aspects can be distinguished: general biological and medical. The general biological aspect is aimed at studying the fundamental possibility of the existence of most bacterial species in various structural and organizational forms and the use of various methods of protection against the ad-

verse effects of environmental factors (Gloag et al., 2015). It should be noted that the perception of changes in the external environment by individual microorganisms and the organization of the collective response of the bacterial population to these changes is performed by systems of Quorum sensing (QS) (Moreno-Gámez et al., 2023). These systems are complexly organized, can be hierarchically subordinated, and are represented by signaling molecules and regulatory proteins (Wu & Luo, 2021). For example, in *Pseudomonas aeruginosa*, the simultaneous functioning of four quorum-sensing systems has been described: *LasI/R*, *RhlI/R*, *PqsABCDH/R*, and, possibly, *IQS* (Miranda et al., 2022). Among those described, the main role is played by the *LasI/R* system, while others are subordinate to it and are activated only under certain conditions (Simanek et al., 2023). The medical aspect should be interpreted as an applied derivative of the general biological aspect, since it is determined by the role that various multicellular bacterial structures capable of collective self-organization can play in the infectious process. In this aspect, it is necessary to pay attention to the problem of microorganism persistence as the ability of pathogenic microbes to survive for a long time in the host organism under the active influence of immune system factors (Pan et al., 2023). This phenomenon is complex and, probably, cannot be solved unambiguously, since different pathogens are able to adapt differently to the influence of aggressive factors of the human organism (Balaban et al., 2019). As an example, several bacterial adaptive forms can be cited that play an important role in the development of chronic and recurrent infections.

Biofilm formation. A special form of stigmergy is the ability of microorganisms to form biofilms (Gloag et al., 2017). Biofilm formation is determined by adaptive reactions to the influence of external environmental conditions and consists in the ability of bacteria to synthesize a number of protective substances and virulence factors in response to environmental signals (Tuon et

al., 2022). According to available data, 65—80% of human infections are caused by bacteria in a biofilm form (Jamal et al., 2018). These diseases were previously associated only with the use of implanted medical equipment — catheters, lenses, prostheses, or artificial heart valves (Hall et al., 2014). However, it has also been shown that biofilms can form without attachment to a solid surface and are capable of forming within mucus (Bjarnsholt et al., 2009). Therefore, the conversion of bacteria to biofilm form is associated with one of the mechanisms of a chronic infectious process and the development of such chronic infections as otitis media, rhinosinusitis, nephrolithiasis, osteomyelitis, biliary and urinary tract infections, chronic wounds, etc., which are difficult to treat (Fernández-Billón et al., 2023).

A biofilm is a highly organized, structured microbial community formed by bacteria of one or more species, which are surrounded by extracellular polymeric substance (EPS) synthesized by them and attached to a tissue or dense surface (Wang et al., 2020). During biofilm formation, bacterial cells convert from a mobile planktonic form into an attached state as part of cell groups with multicellular behavior. When bacterial cells turn into a biofilm form, significant changes occur in their intensity of protein synthesis, gene expression, and phenotype (Olaimat et al., 2024).

When forming a biofilm, microorganisms go through some stages (Tasneem et al., 2018). First, bacteria attach to the surface, and basic components are formed. Traces, rosettes, and conglomerations have been referred to as base *P. aeruginosa* biofilm components (Balko & Avdieieva, 2010). These structures are combined into a net structure, islands, which subsequently form a continuous monolayer. These components are found in biofilm composition both at the stage of formation and at the stage of degradation, regardless of the source of the microorganism isolation and their strain characteristics (Balko et al., 2013a). Bacteria in the monolayer composition exist as a functional community, after which planktonic

cells detach and move to new locations, and the cycle repeats (Bai et al., 2021). Thus, microorganisms are characterized by a three-stage biofilm formation: initial formation, subsequent partial degradation, and repeated accumulation of biomass, which determines their stability in the external environment (Balko et al., 2013b). At the same time, the intensity of biofilm formation directly depends on the degree of deviation of the cultivation conditions from the optimal ones for a given strain (Balko & Avdeeva, 2009).

Biofilms can be the result of a natural survival strategy (Ma et al., 2021). Biofilm consists of bacterial cells surrounded by EPS, which provides stability and increases their resistance to stress factors (Bamford et al., 2023). EPS contains polysaccharides, such as cellulose, as well as nucleic acids, proteins, and lipids. This substance also includes bacterial structures such as pili, flagella, and fimbriae. The main functions of EPS are providing stable attachment of bacteria to dense surfaces, distribution of substrates necessary for bacterial growth, protection from antimicrobial agents, and increasing antimicrobial resistance through the formation of compounds such as catalase (Olaimat et al., 2024). It should be noted that the regulation of EPS synthesis provides the bacterial community with many advantages, including adaptation to a wide range of antimicrobial substances and environmental influences, and the ability to attach to various surfaces (Jennings et al., 2021).

Bacterial cells in a biofilm have a significant advantage over analogous bacteria in a planktonic form, as the biofilm provides microorganisms with an aqueous environment that concentrates nutrients near a solid surface and creates better access to them (Penesyan et al., 2021). This increases the general adaptability of bacteria to adverse environmental factors, and due to the high level of gene exchange within the biofilm, significant genetic diversity of bacterial cells is achieved (López-Causapé et al., 2023; Flemming et al., 2016). In addition to its protective function, the

biofilm serves as a deposit formation that ensures the maintenance of a stable number of bacteria in the planktonic form. Therefore, it is possible to eliminate the spread of microorganisms only after eradicating the biofilm nidus from the corresponding biotope (Balko et al., 2018). Furthermore, the most important aspect of biofilm formation is antimicrobial resistance. The EPS matrix is the first barrier that contacts with antibiotics or other antimicrobial agents, after which various biopolymers in its composition can bind to these substances and lead to partial or complete loss of their activity (Flemming et al., 2016). Another defense against antimicrobial action on bacteria in the biofilm is substances that are secreted by the cells and diffuse through the EPS. Such substances include catalase and antioxidants, which are able to protect bacterial cells jointly, often even synergistically (Olaimat et al., 2024). It has been shown that through the secretion of catalase by cells, the biofilm protects bacteria from the effects of hydrogen peroxide (Stewart & Owkes, 2023). Thus, a lethal concentration of hydrogen peroxide to planktonic cells does not affect the bacteria in the biofilm, and the biofilm itself only thickens after the mentioned exposure. When studying the biofilm of *Salmonella* sp., it was found that to affect cells in a biofilm form, the chlorine concentration must be at least 10 times higher to produce a similar inhibitory effect as on free-floating planktonic bacterial cells (Trmcic et al., 2018). In contrast, the increase in the resistance of bacteria in a biofilm form to antibiotics can rise by 100-1000 times (Mah, 2012). It has been shown that the resistance to antimicrobial agents develops as early as 15 min after bacteria attach to a solid substrate (Balko et al., 2017).

Bacteria in biofilm forms are able not only to protect themselves from the effects of adverse environmental factors but also to secrete substances that help them to colonize certain niches and actively compete with other microorganisms. Bacteriocins can be classified as such substances (Yang et al., 2025; Balko, 2012). Bacteriocins

are analogs of antibiotics, they are synthesized by most microorganisms and have a narrow spectrum of action, which is directed at representatives of related taxa (Balko et al., 2020; Versluis et al., 2018). Thus, *Pseudomonas aeruginosa* bacteriocins (S5 pyocins) are able to inhibit the growth of phytopathogenic strains of *Pseudomonas syringae* (Balko et al., 2024). Bacteria can synthesize several types of bacteriocins (Zareen et al., 2025; Charkhian et al., 2024). As for *P. aeruginosa*, it has been described to produce high molecular weight structures — analogs of phage tail, low molecular weight proteins, and microcin-II-like bacteriocins (Balko & Avdeeva, 2012; Balko, 2019). Moreover, bacteriocins of different types can combine with each other, which leads to their stabilization and enhanced antimicrobial activity (Cubillo-Komarovova et al., 2024; Balko, 2021). It has been shown that the producer cultures are capable of isolating bacteriocins with varying intensity depending on the cultivation temperature. Thus, microorganisms isolated from soil synthesize substances more actively at 28 °C, while clinical isolates — at 37 °C (Balko et al., 2013c). However, a slight increase in temperature to 30–40 °C stimulates the intensity of bacteriocin production by soil isolates, increasing their activity up to 16 times (Balko et al., 2019). When added to poor culture medium, bacterial cells in biofilm do not synthesize bacteriocins, as the main emphasis in this case is on protecting population through enhanced biofilm formation (Pisarenko & Balko, 2013). These cultivation conditions should obviously be considered a stress factor for producer cells, which necessitates the intensification of the struggle for survival. Thus, biofilm formation and bacteriocinogeny can be regarded as interrelated bacterial survival strategies.

Uncultivated forms of bacteria (cells in the VBNC state). In the natural environment, microorganisms are exposed to a variety of stress factors that can potentially destroy whole populations. To counteract this, several strategies are used to maintain tolerance to harmful conditions

(Pazos-Rojas et al., 2024). Some microorganisms are able to form spores and remain viable under extreme conditions (Voitsekhovskiy et al., 2024a). Another form of survival is cysts, which are found in certain Gram-negative bacteria, for example, in members of the *Azotobacter* genus (Voitsekhovskiy et al., 2024b). Other microorganisms that are not capable of spore and cyst formation can go into a latent state (Zhang et al., 2021). For example, it is known that one of the most important factors for bacterial survival is the availability of nutrients in the environment. When bacterial cells are starved, they can shrink in size and become more resistant to adverse environmental conditions (Pinto et al., 2015). Another response variant is transition to a state in which uncultured cells or spore-like structures are formed (Trevors, 2011). This state is referred to as viable-but-non-culturable (VBNC) or simply unculturable forms of microorganisms (Pazos-Rojas et al., 2024).

VBNC bacteria are unable to grow and form colonies, but remain alive and can resume their metabolic activity (Zhang et al., 2021). Cells in this state usually have a reduced level of metabolic activity. Nutrient transport, the rate of respiration, and macromolecular synthesis slow down, and bacteria are able to form stable structures similar to spores (Pazos-Rojas et al., 2019). Many bacterial species reduce their size, transforming into coccoid-shaped cells with an enlarged periplasmic space. A decrease in the ratio of cell surface area to volume helps cut down energy requirements (Bodor et al. 2020). Furthermore, cells in the VBNC state typically contain reduced concentrations of cytoplasm, total proteins, and membrane fatty acids, but relatively high levels of ATP exhibit high membrane potential, increased O-acetylation, and crosslinking in cell wall peptidoglycans (Pinto et al. 2015). Lessened superoxide dismutase activity and increased oxidative damage were also noted. A unique feature of bacteria in the VBNC state is the continuous expression of genes in the cells (Trevors, 2011). Due to these changes,

cells acquire increased resistance to antibiotics and the effects of physical and chemical stresses. The virulence potential among pathogens in an uncultured form is ambiguous. Some infectious agents are unable to cause disease until they are transformed into a cultivated form, while others remain potentially pathogenic because they continue to produce toxins (Dong et al. 2020).

Microorganisms can transform into uncultivated forms in response to natural stresses: starvation, extreme temperatures, high osmotic or oxygen concentrations, and light effect (Pazos-Rojas et al., 2024). However, if optimal conditions are restored, cells can return from the VBNC state to a metabolically active and cultured state (Dong et al., 2020). Thus, VBNC bacteria often retain their cellular integrity and potential for replication (Pinto et al., 2015).

Studies of the VBNC state have shown that it is a universal survival strategy for a wide range of Gram-negative bacteria, a smaller number of Gram-positive bacteria, and some fungal species (Zhang et al., 2021). Among them, a significant part of the bacterial species is represented by human pathogens: *Burkholderia pseudomallei*, *Campylobacter jejuni*, *Escherichia coli*, *Francisella tularensis*, *Helicobacter pylori*, *Klebsiella pneumoniae*, *Legionella pneumophila*, *Listeria monocytogenes*, *Mycobacterium tuberculosis*, *Pseudomonas aeruginosa*, several species of genera *Salmonella* and *Shigella*, numerous representatives of the *Vibrio* genus, and also *Yersinia pestis* (Pazos-Rojas et al., 2024; Zhang et al., 2021). The existence of pathogenic bacteria in such dormant forms can explain the disease relapses that occur in patients after courses of antimicrobial therapy (Dong et al., 2020).

It should be noted that the transition to the VBNC state can be caused not only by environmental stress factors but also by other processes. It was found that inducers of the appearance of uncultivated forms can be pasteurization of milk, chlorination of wastewater, and the use of food preservatives such as potassium sorb-

ate and sodium benzoate (Pazos-Rojas et al., 2024). Cells of some bacteria (*M. tuberculosis*, *C. jejuni*, *H. pylori*) can convert into a non-replicating cocci-like state under microaerophilic conditions (Zhang et al., 2021). It has also been established that transformation into uncultivated forms is possible as a response to the effects of therapeutic drugs, in particular, antibiotics (Austin & Austin, 2016). However, such forms of bacteria can be activated by signaling molecules of the QS system: autoinducer 2(AI-2) in *E. coli* O157:H7 and in *V. vulnificus* (Ayrapetyan et al., 2014). These inducers can stimulate catalase expression, which can also provoke the recovery of *S. typhimurium* VBNC cells, even independently of the OxyR regulon (Liao et al., 2019). The above indicates that QS plays an important role in the process of the reversion of microorganisms to a cultured form and their potential possibility for pathogenicity acquisition (Zhang et al., 2021).

Microorganisms with cell wall synthesis defects (CWD forms). Quite often, the form of existence of bacteria is their structural formations with a defect in cell wall synthesis and a pronounced ability for long-term persistence. Bacteria usually have a relatively low osmolarity, and a strong and elastic cell wall performs an osmoprotective function (Auer & Weibel, 2017). In its deficiency or absence, cells will undergo lysis in most environments, but under isoosmotic conditions, which are characteristic of many human tissues and fluids (e.g., urine), they can survive and, in some cases, even grow (Emami et al., 2023). Microorganisms that have lost part or all cell wall peptidoglycan but remain viable are referred to as cell wall deficient (CWD) variants or cells in a CWD state (Lazenby et al., 2022). Many terms have been used to refer to CWD bacteria: L-forms, L-phase, L-organisms, round forms, round bodies, ovoid cells, S-cells, and spherical cell morphotypes. Among the above variants, the most famous are the L-forms, however, some researchers recommend limiting the use of this term only to CWD cells that are capable of prolifer-

eration in this state (Allan et al., 2009). Therefore, in the absence of clear evidence of replication capacity, it is recommended to use the term the CWD form (Lazenby et al., 2022). It is important to note that CWD variants do not include members of the *Mollicutes* class, such as *Mycoplasma* and *Phytoplasma*, which have evolved to exist without a cell wall (Chen et al., 2012).

CWD bacteria differ significantly in the degree of the presence of cell wall material and are divided by this criterion into spheroplasts, which retain a certain amount of peptidoglycan, and protoplasts, which are completely devoid of peptidoglycan (Allan et al., 2009). Microorganisms with a defect in cell wall synthesis can also be classified as stable or unstable (transient). CWD-stable bacteria have genetic mutations that block them in this form, while CWD-unstable bacteria are considered genetically identical to their parent cells and have retained the ability for conversion to a normal cell wall shape after removal of the inductor (Lazenby et al., 2022).

Due to the loss of a rigid cell wall, CWD bacteria appear spherical, ovoid, or pleomorphic and may be sensitive to osmotic pressure and mechanical lysis (Emami et al., 2023). It is considered that for their cultivation, it is necessary to create special osmoprotective conditions or use various fluids, in most cases of biological origin, such as urine, rabbit cecal fluid, and human blood serum. However, it is known that CWD bacteria can be adapted to low osmolarity conditions (Osawa & Erickson, 2019). This suggests that not all CWD bacteria are identical and can be divided into osmotically sensitive variants that require special osmoprotective conditions and more stable variants that can be cultivated without osmoprotection (Lazenby et al., 2022).

The origin of microorganisms with a defect in cell wall synthesis is associated with the action of several factors: the influence of enzymes and compounds that destroy and inhibit cell wall biosynthesis; thermal, cryogenic, osmotic, and genotoxic stresses; nutrient limitation; the action

of antibodies, complement proteins, and bacteriophages; mutation of genes involved in cell wall biosynthesis (Mueller & Levin, 2020). However, in medical practice, the most common cause of CWD bacteria appearance is considered the effect of antibiotics, namely β -lactams (penicillins, cephalosporins, carbapenems, and monobactams), as well as fosfomycin and cycloserine, which affect peptidoglycan biosynthesis (Mercier et al., 2014). Antibiotics of other classes can also lead to the CWD form origin: trimethoprim in *P. vulgaris*, and aminopterin in *Serratia marcescens*. The development of spheroplasts in *E. coli*, *S. aureus*, and *P. aeruginosa* has been shown after the use of protein synthesis blockers — chloramphenicol, streptomycin, oxytetracycline, kanamycin, and tobramycin (Lazenby et al., 2022).

Different variants of CWD bacteria have been described for many species, including pathogens of some human infections. Such microorganisms include *Acinetobacter baumannii*, *Escherichia coli*, *Klebsiella pneumoniae*, *Listeria monocytogenes*, *Mycobacterium tuberculosis*, *Pseudomonas aeruginosa*, *Salmonella* sp., *Staphylococcus aureus*, and *Vibrio cholera* (Mercier et al., 2014). These microorganisms with a defect in cell wall synthesis can exist in the patient's organism during chronic infections or bacterial carriage and cause relapses of the disease (Emami et al., 2023). Thus, one of the most studied examples of a chronic infectious process is tuberculosis infection. Isolated from patients' cultures of *M. tuberculosis* in the L-form showed the ability to revert to the original morphotype. In general, using material from patients has shown the importance of L-forms in the persistence of some disease pathogens at different stages of the infectious process (Westblade et al., 2020). The mechanisms underlying typhoid and paratyphoid bacterial carriage are also actively discussed. Most researchers consider this issue exclusively in relation to bacterial forms, and only in some works, data on the isolation of the typhoid fever causative agent in the CWD form from patients are provided, including during the

relapse period (Yang et al., 2020). CWD bacteria have been identified for many microorganism species, the appearance of which was correlated with episodes of fever in bone marrow recipients during treatment with high doses of antibiotics. Relapses of *Haemophilus influenzae* infections after a course of penicillin have been explained by conversion and return from the CWD stage. Unstable CWD *E. coli* has been identified in the urine of patients with urinary tract infections treated with amoxicillin, cephalexin, or fosfomycin (Mickiewicz et al., 2019). The cells showed the ability to divide and reverse when transferred to an osmoprotective medium without fosfomycin. Thus, the conversion to the CWD form allows bacteria to avoid lysis due to the antibiotic effect, survive, and return to a pathogenic state, which can cause repeated persistent infections (Emami et al., 2023).

Motile colony morphotype. The formation of a complex colony structure is also considered a cooperative adaptive response of bacteria to adverse environmental influences. Colonies change their organization to optimize the growth and survival of microorganisms (Pipe & Grimson, 2008). The concept of “morphotype” was introduced to describe the structure of bacterial colonies. Three main morphotypes are known: tip-splitting (T), chiral (C), and vortex (V). Different species and strains of bacteria can belong to the same morphotype. The change in morphotype is adaptive in nature and can occur within several days (Ben Jacob et al., 1998).

The V morphotype of colonies, which is formed by bacteria capable of motile growth on meat-peptone agar, is actively discussed. The formation of this colony morphotype has been described for *E. coli*, *S. typhi*, *S. typhimurium*, and *B. subtilis*. It occurs under the influence of various stress factors such as changes in growth medium, increased temperature, the presence of antibiotics, disinfectants, hydrogen peroxide, etc (Budrene & Berg, 1995). In response to the action of these factors, bacteria enhance che-

moattraction. At that, the production of high concentrations of polysaccharides and peptide components is observed, which is the reason for the formation of larger vortices, in which, for example, an antimicrobial substance is diluted.

Thus, from the blood of six patients with clinical signs of typhoid fever, cultures with motile morphotype V, identified as *S. typhi*., were isolated. During their passage 5—8 stages in meat-peptone and bile broths, the studied strains formed “immobile” colonies. Two patients had relapses of the disease after the course of treatment, during which microorganisms with a motile colony morphotype were isolated from the blood, and from feces — with a non-motile one. This suggested that blood and stool cultures of *S. typhi* have different physiology at the stages of invasive (blood) and acute (feces) infections. Thus, for the first time, there were described microorganisms with a motile morphotype V (vortex), which are characterized by surface swarming on agar, the ability to reversion, and participation in the infectious process (Morozova et al., 2024).

Thus, the fundamental similarity of the adaptive forms of different bacterial species, in particular their ability to multiple antibiotic resistance, long-term survival under the influence of adverse factors, and the possibility of selection, raises questions about their role in the infectious process. Analyzing the above facts, it can be concluded that changes in the structural organization of bacteria in the process of adaptation to adverse factors from the position of stigmergy determine changes in their ecology *in vitro* and *in vivo*. Adaptively changed forms of bacteria may be important in the pathogenesis of many infectious diseases, but the most likely role of such forms is in the development of chronic and recurrent infections and bacterial carriage. The bacterial stigmergy in various infections requires further research and new findings, the discovery of which may contribute to the development of approaches to the diagnosis and treatment of infectious diseases.

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МЕДИЧНІ АСПЕКТИ БАКТЕРІАЛЬНОЇ СТИГМЕРГІЇ

У статті висвітлюються сучасні підходи до оцінки збудників інфекційних захворювань з позицій передусім медичних аспектів проблеми стигмергії бактерій, котра розглядається як феномен колективної самоорганізації бактеріальних спільнот у відповідь на вплив несприятливих для них факторів довкілля. Трансформація бактерій у різні адаптаційні форми являє собою феномен, який не тільки відтворюється в досліджах *in vitro*, але й досить часто є формою існування бактерій в організмі людини. Обговорюється ряд форм бактеріальної стигмергії: біоплівкоутворення, некультивовані форми бактерій, мікроорганізми з дефектом синтезу клітинної стінки, рухливий морфотип колоній, які можуть існувати в організмі хворого на різних стадіях інфекційного процесу. Аналіз клінічних даних показує, що з розвитком більшості захворювань патогени можуть набувати певних форм стійкості, тоді як в окремих випадках, наприклад, при черевному тифі, спостерігається виникнення багатофакторного захисту з утворенням некультивованих та L-форм, а також «рухливого» морфотипу колоній. Розглядається питання щодо ролі адаптивно змінених форм у розвитку хронічних і рецидивуючих інфекцій.

Ключові слова: бактеріальна стигмергія, біоплівкоутворення, некультивовані форми бактерій, мікроорганізми з дефектом синтезу клітинної стінки, рухливий морфотип колоній.