Low Temperature Physics/Fizika Nizkikh Temperatur, 2021, vol. 47, No. 12, pp. 1139–1147

Development of experimental techniques for antibiotics detection in aqueous solutions: real-time microwave dielectrometry and UV-Vis spectrophotometry study

Z. E. Eremenko[1], V. A. Pashynska[1,2], K. S. Kuznetsova[1], and A. V. Martunov[3]

[1]*O. Usikov Institute for Radiophysics and Electronics of NAS of Ukraine, Kharkiv 61085, Ukraine*
E-mail: zoya.eremenko@gmail.com

[2]*B. Verkin Institute for Low Temperature Physics and Engineering of NAS of Ukraine, Kharkiv 61103, Ukraine*

[3]*Mechnikov Institute of Microbiology and Immunology of the National Academy of Medical Sciences of Ukraine Kharkiv, Ukraine*

Received July 13, 2021, published online October 25, 2021

Microwave dielectrometry and UV/Vis spectrophotometry methods have been used to study the aqueous solutions of selected antibiotics of different classes: lincomycin hydrochloride, levofloxacin hemihydrate, amikacin sulfate, gentamicin sulfate. The microwave dielectrometry technique demonstrates high sensitivity of complex permittivity values of antibiotics water solutions from antibiotics concentration in such solutions. In our study, the microwave dielectrometry data are validated by the UV-Vis spectrophotometry results for levofloxacin and lincomycin aqueous solutions. The Fisher's correlation coefficients for the electromagnetic waves absorbance values, obtained by the different methods, are close to unity for the mentioned antibiotics. The obtained experimental results confirm that the developed by us microwave dielectrometry method is prospective to be applied for antibiotics determination in aqueous solutions including environmental water samples.

Keywords: microwave dielectrometry, UV/Vis spectrophotometry, aqueous solutions, antibiotics, electromagnetic waves, microwaves, complex permittivity.

1. Introduction

The problem of pollution of the environment and, in particular, environmental water sources by pollutants from the food, pharmaceutical, chemical industries and agricultural production is one of the most urgent ecological problems in the world. For instance, a significant amount of antibiotic contaminants are registered everywhere in water runoff and in untreated water, because of during last century antibiotics have been used widely as the main treatment agents against bacterial infections in humans, pets or livestock animals [1–3]. As antibiotics are used not only for treatment but also for disease prevention in animal husbandry and, in particular, in poultry farms, at present the antibiotics consumption by humans and livestock animals increases sharply, that raises the great global problem of antibiotic resistance. In order to reduce the antibiotics pollution and make our environmental safety, we need to provide effective permanent monitoring of the antibiotics presence and amount in environmental water samples and water wastes from industrial activities [4]. So, the development of effective techniques and devices for analyzing of antibiotics aqueous solution is urgent problem for today. Such devices must be extremely sensitive, robust in usage and operate in real time.

At present, there are the following methods of the antibiotics detection in water runoff, such as high-performance liquid chromatography (HPLC), ultra-high-performance liquid chromatography-tandem mass spectroscopy (UPLC-MS/MS), polymerase chain reaction (PCR), and tandem mass spectroscopy (MS/MS) [5]. All these methods and techniques are highly sensitive and effective. However, they have some disadvantages such as very high price of equipment which is not portable. So, these methods have limitations to analyze the waste water samples directly on the location of detection. Moreover, their analysis takes a long time, and the operators need to be highly qualified.

© Z. E. Eremenko, V. A. Pashynska, K. S. Kuznetsova, and A. V. Martunov, 2021

In [2], the authors made an overview of selected experimental methods [6, 7] used for antibiotic detection in water samples and presented the data of the antibiotics pollution determining in environmental water. It is known that trace concentrations of antibiotics in waste water and even in drinking water can be found everywhere in the world. For example, as mentioned in [8], the concentration of lincomycin in ground water was found to be 0.36 μg/l [8, 9]. The most frequently detected antibiotic was ciprofloxacin with the highest concentration of 1.270 μg/l in the raw water [10]. In Ref. 2, the researches also compared three different techniques, such as electromagnetic wave spectroscopy, ultraviolet-visible (UV-Vis) spectrophotometry, and capacitance sensing system for the real-time monitoring and detection of antibiotics concentration in water [6]. The electromagnetic wave spectroscopy (with microwave sensor) technique uses a vector network analyzer (VNA) connected to a planar interdigitated electrode (IDE) sensor. The VNA displays real-time spectra of the IDE sensor [6].

Understanding the importance of development of robust and non-invasive methods for ecological control of water samples, we propose to use for the purpose of detection of antibiotics in water samples a dynamic control method based on microwave dielectrometry of aqueous solutions of biologically active substances. In the current study, we apply and adapt the method and a unique dielectrometer device, developed and designed in Usykov IRE NASU [11–22], to obtain the complex permittivity (CP) of aqueous solutions of a number of antibiotics, such as lincomycin, levofloxacin, gentamycin, and amikacin. The adapted method is based on determining the dielectric parameters (real ε' and imaginary ε'' parts of CP) of high loss aqueous solutions of studied compounds in the millimeter range of electromagnetic wavelengths. Aqueous solutions of the substances are characterized by strong absorption in the microwave range, where the region of maximum frequency dispersion of CP of water is located. Intermolecular interactions of dissolved biologically active molecules with water molecules directly affect the absorption of the electromagnetic wave by the solution under study. As a result of such interactions, called by hydration, a layer of bound water molecules is formed on the surface of the dissolved molecules, which is characterized by a relaxation time (the time for establishing the thermodynamic equilibrium) much longer than that of ordinary water molecules. Hydration of dissolved molecules leads to a decrease in the CP of the solution. Dielectrometric measurements of CP of water and water solutions in the frequency region of the maximum of its dispersion allow to obtain information about the state of free water in the systems studied.

Another approach to examine the model systems of aqueous solutions of antibiotics is the usage of UV/Vis spectrophotometry for the investigation of solutions, which can give information about the state of dissolved molecules of biologically active compounds in the systems. We also use this spectrophotometry method to support the microwave dielectrometry measurements of our model systems and to add the physicochemical information about dissolved biologically active molecules in the solutions. The method is based on the absorption of a passing electromagnetic wave by solution of antibiotics in the ultraviolet and visible region. The absorption intensity of many substances correlates with a substances concentration in solution.

2. Materials and methods

2.1. Objects under study

In the current study, aqueous solutions of some selected widely used antibiotics of different classes were probed by microwave dielectrometry and UV-Vis spectrophotometry methods. The following pharmaceutical aqueous solutions of antibiotics were used as stock solutions to prepare the model solutions for experimental measurements: lincomycin hydrochloride C = 300 mg/ml (Darnitsa, Kyiv), levofloxacin hemihydrate C = 5 mg/ml (Infuzia, Kyiv), gentamicin sulfate C = 40 mg/ml (Arterium, Kyiv), amikacin sulfate C = 250 mg/ml (Lekhim, Kharkiv). Note that the short commercial names of the studied antibiotics are used below to call the appropriate drug (e.g., the amikacin sulfate is named below as the amikacin). Chemical structures of the studied antibiotics are presented in Table 1.

The concentrations of the antibiotics aqueous solutions (prepared by dilution of the stock solutions using distilled water) for the microwave dielectrometry measurement are presented in Table 1 as well. All dielectrometry measurements were performed on the same day when the samples were prepared. The mentioned above stock solutions of the antibiotics were also diluted to the concentration of 1 mg/ml using distilled water for the initial UV-Vis spectrophotometry measurements.

2.2. Microwave dielectrometer method

The used microwave dielectrometry method [11–22] is based on the dependence of the complex propagation coefficient (CPC) ($h = h' + ih''$) on the complex permittivity (CP) of the liquid under test. The CPC real and imaginary parts correspond to a wave phase and its amplitude of the electromagnetic wave passing through measured liquid samples per unit of length, respectively. The operating frequency of our dieletrormeter is 31.82 GHz. This frequency was selected into the region of the maximum of the frequency dispersion of real and imaginary CP of water and water solutions [23]. Using the dieletrometer, we obtain the CP of high loss liquids, i.e., the liquids with the ratio of the real and imaginary parts of CP such as $\varepsilon_2'' / \varepsilon_2' \approx 1$.

The microwave circuit of our dielectrometry setup is presented in Fig. 1.

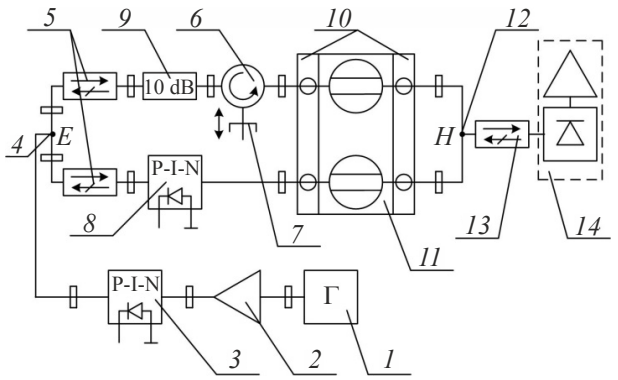


Fig. 1. Circuit of the microwave dielectrometer: frequency synthesizer (*1*); power amplifier (*2*); regulating *p-i-n* attenuator (*3*); *E*-plane tee splitter (*4*); ferrite valves (*5*); *T* circulator (*6*); measuring short-circuit piston (*7*); measuring *p-i-n* attenuator (*8*); 10 dB attenuator (*9*); matching plates (*10*); cuvette block (*11*); *H*-plane tee signal adder (*12*); ferrite valve (*13*); detector with low noise amplifier (*14*).

The principle of operation of our dielectrometry setup involves the division of the output power into two channels: the reference channel and the measuring one, respectively. To reduce the total length of the microwave path, the circuits are split into two different channels, in each of which the wave phase shift and amplitude change are measured.

The dielectrometer measurement cavity is a differential cavity (*11*) (Fig. 1) and consists of two identical cells made of copper. The first cell is for the reference liquid like distilled water and the second one is for the liquid under test. The electromagnetic wave propagates along quartz cylinders of the radius $a = 0.25$ cm (CP of the quartz cylinders $\varepsilon = 3.8 + i0.0001$), which are placed inside the cell. The cell diameter b is equal to the cell length l = 2cm. The reference liquid and the liquid under test are placed in the space between cell border and quartz cylinder with the size $b - a$. The operating type of wave propagating along the cells is HE_{11} which is exited in the quartz rod by input rectangular waveguides with H_{11} basic wave types.

To obtain the solution of the electromagnetic problem for the layered waveguide cell with the dielectric rod and high-loss liquid surrounded it, the Maxwell' equations were solved by the methods of separation of variables in cylindrical coordinates (r, φ, z) [18, 19]. After fulfilling the boundary conditions in our layered waveguide cell, we obtain complex implicit characteristic equation, which is used to obtain the CP of the liquid under test. CP calculation technique of the tested liquid was described in [11, 18]. Knowing the CP of reference liquid ($\varepsilon_r = \varepsilon_r' + i\varepsilon_r''$) and solving the characteristic equation obtained for the layered waveguide with rod and the surrounding liquid, we find the phase coefficient h_r' and the attenuation coefficient h_r'' of the reference liquid as real and imaginary parts of CPC, respectively. The phase differences $\Delta\varphi$ and the amplitude differences ΔA are measured in two cells of the dielectrometer measurement cavity, if one of the cells filled with the reference liquid and another cell filled with the liquid under test. The wave phase and attenuation coefficients calculated for tested liquid as $h_t' = h_r' + \Delta\varphi$ [rad/cm] and $h_t'' = h_r'' + \Delta A$ [dB/cm], respectively. Knowing the values h_t', h_t'' and again using the characteristic equation, we can find the CP of the tested liquid as $\varepsilon_t = \varepsilon_t' + i\varepsilon_t''$.

The CP measurement errors of the reference liquid were estimated in [11, 18, 19]. The differential sensibility of our differential dielectrometer are estimated as $\delta(\Delta\varphi) \approx \pm 0.025$ deg/cm for the phase shift $\Delta\varphi$ and $\delta(\Delta A) \approx \pm 0.0005$ dB/cm for the amplitude difference ΔA using the root-mean-square random measurement errors technique. The total relative errors for the real and imaginary CP parts for the tested liquid were obtained as 0.156 and 0.52%, respectively.

2.3. Ultraviolet-visible spectrophotometry method

The spectrophotometry in the ultraviolet-visible range is one of the most widely used laboratory techniques in biomedical analysis [24]. It is known that the base principle of UV-Vis spectrophotometry is the absorption of the electromagnetic waves in ultraviolet or visible ranges by molecules of chemical compounds. The UV-Vis method measures the attenuation (absorbance) of a radiation beam passes through a cuvette containing solution of the test compounds.

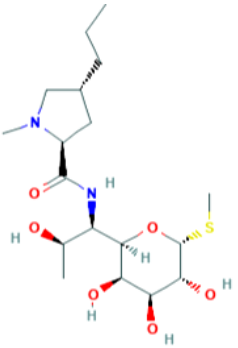
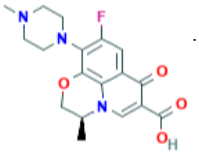
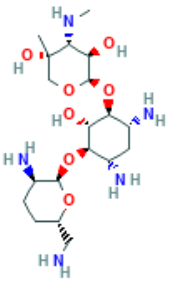
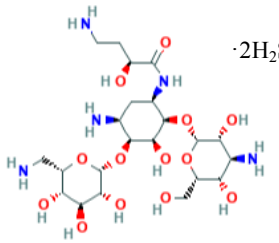
For the last few decades, UV-Vis spectrophotometry has been actively applied for study of organic compounds solutions with the purposes to determine some physical parameters of the solutions, for example, absorption coefficient, absorption ratios, spectral slopes, etc. [25]. In the present study, the Biochrom GeneQuant 1300 Spectrophotometer (USA, General Electric) for the UV-Vis spectrophotometry measurements is used with the standard measurement technique [24, 25, 27, 28].

3. Results and discussion

3.1. Microwave dielectrometry measurements

We carried out the measurements of aqueous solutions of antibiotics with different concentrations (Table 1) using our dielectrometer setup. Figure 2 shows the measured wave phase shift $\Delta\varphi = \varphi_{\text{liquid}} - \varphi_{\text{water}}$ and wave amplitude difference $\Delta A = A_{\text{liquid}} - A_{\text{water}}$ dependences for the studied solutions on their concentrations. The measured wave amplitude value depends on the wave attenuation (wave absorbance) value in the liqiud under test. The larger wave amplitude corresponds to the smaller its attenuation. According to the procedure described in Sec. 2.2., we obtain the real and imaginary parts of CPC (Fig. 3) of the studied aqueous solutions using measured data such as the wave phase shift $\Delta\varphi$ and the amplitude difference ΔA between two cells: the cell for a reference liquid containing the distilled water; and the cell for the testing liquid containing solved antibiotics. Figure 4 shows the dependences of the

Table 1. Chemical structures of the antibiotics under study and their concentrations in the aquaus solutions for the dielectrometry experiments

Sample	Molecular formula	Structural formula	Concentrations, mg/ml
lincomycin hydrochloride	$C_{18}H_{35}ClN_2O_6S$	 ·HCl	0.9375 1.875 3.75 7.5 15
levofloxacin hemihydrate	$C_{36}H_{42}F_2N_6O_9$	 ·1/2 H_2O	0.1825 0.3625 0.625 1.25 2.5 5
gentamicin sulfate	$C_{60}H_{125}N_{15}O_{25}S$	 ·1/3H_2SO_4	0.00235 0.0047 0.01953 0.039 0.3125 0.625 1.25 2.5 5 10
amikacin sulfate	$C_{22}H_{47}N_5O_{21}S_2$	 ·2H_2SO_4	0.2441 0.48825 0.9765 1.953 3.906 7.8125 15.625 31.25 62.5 125

real and imaginary part of CP, and Fig. 5 presents the module of CP for the studied pharmaceutical solutions.

The analysis of the presented data shows that the wave phase shift and the wave amplitude difference values increase for the majority of tested drugs solutions with the growing of their concentrations (curves *1–4* in Fig. 2), except of the gentamicin (curve *5* in Fig. 2). The similar behavior we obtain for the real and imaginary parts of CPC for the studied solutions (Fig. 3). At the same time, we can observe the decreasing of the real and imaginary parts of CP (Fig. 4) and, as a result, decreasing of CP module (Fig. 5) for majority of studied antibiotics with the growing of their concentrations in the solutions, except of the gentamicin (curves *5* in Figs. 4 and 5).

Obtained results for the CPC of the studied solutions reveal that the wave phase h' and attenuation coefficients h'' increase (Fig. 3) with increase in antibiotics concentration in water solutions for the majority of tested drugs, except of the gentamicin solution. This means that the wave absorbance (attenuation) and the phase shift in the probed solutions are getting bigger with the concentration growing in comparison with the data for pure distilled water. The data on CPC we have used to obtain the CP values of the tested antibiotics aqueous solutions.

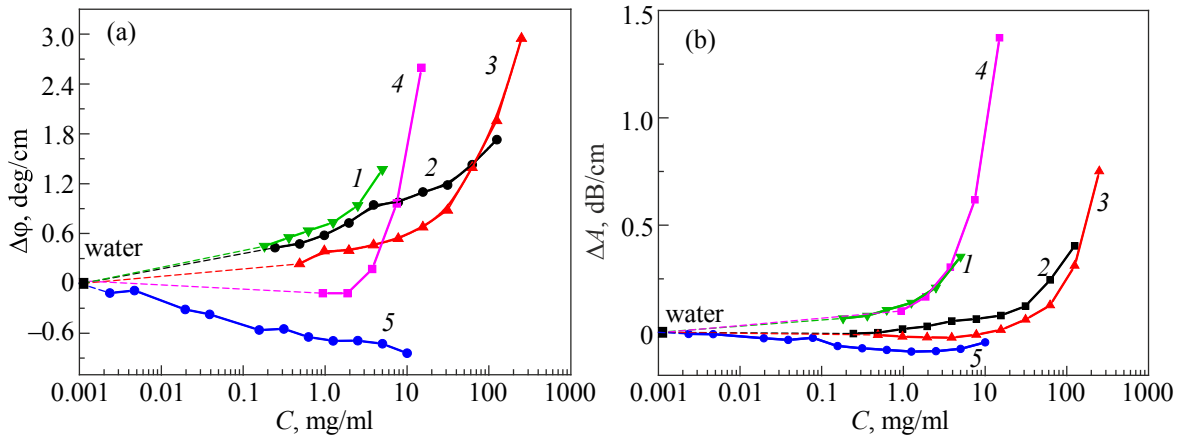


Fig. 2. The dependences of wave phase shift (a) and amplitude difference (b) on the concentration of aqueous solutions of drugs indicated as: levofloxacin hemihydrate (*1*), amikacin sulfate (*2*), Mg sulfate (*3*), lincomycin hydrochloride (*4*), gentamicin sulfate (*5*). Black square corresponds to the distilled water.

Analyzing the data on CP for the studied liquids (Fig. 4), we see that the values of the real and imaginary parts of CP for the studied aqueous solutions of drugs are less than the appropriate values of a pure water, except for the gentamicin-water solution (curve *5*, Fig. 4). If the real CP part of a water solution is less than the real CP part of pure water, we can conclude that the free water part in the solutions is getting smaller due to the water molecules are bound with the drug ones in a result of hydration process. The higher concentration of the antibiotic in the aqueous solution, the less free water remains in it. The dependence of CP module on drugs concentration for the studied solutions has similar behavior (Fig. 5): the values of CP modules for the majority of tested antibiotics solutions are going down with increasing of the concentration, and the CP module values are less than the CP module value for pure water, except of the gentamisin-water solution. For better understanding of the concentration dependences for amikacin sulfate and gentamicin sulfate solutions, we additional measured Mg sulfate solution as a simple sulfate compaund with the concentrations 0.4875; 0.975; 1.95; 3.9; 7.8125; 15.625; 31.25; 62.5; 125; 250 mg/ml. It turned out that the behavior of CP values of Mg sulfate (curves *3*, Figs. 4 and 5) is similar to the behavior of the amikacin sulfate solution (curves *2*, Figs. 4 and 5), but is different from the behavior of CP of the gentamicin sulfate solutions (curves *5*, Figs. 4 and 5).

The concentration dependences of the gentamisin aqueous solution (curves *5* in Figs. 2–5) is atypical ($\Delta A < 0$) comparising with the above described other studied antibiotics and Mg sulfate aqueous solutions ($\Delta A > 0$). Obviously, we cannot explaine this result for the gentamicin solution by concentration-dependent the change in the amount of a free water. So, we explain this phenomenon with the absorption of the microwaves. The amplitude values of the electromagnetic wave after the passage of

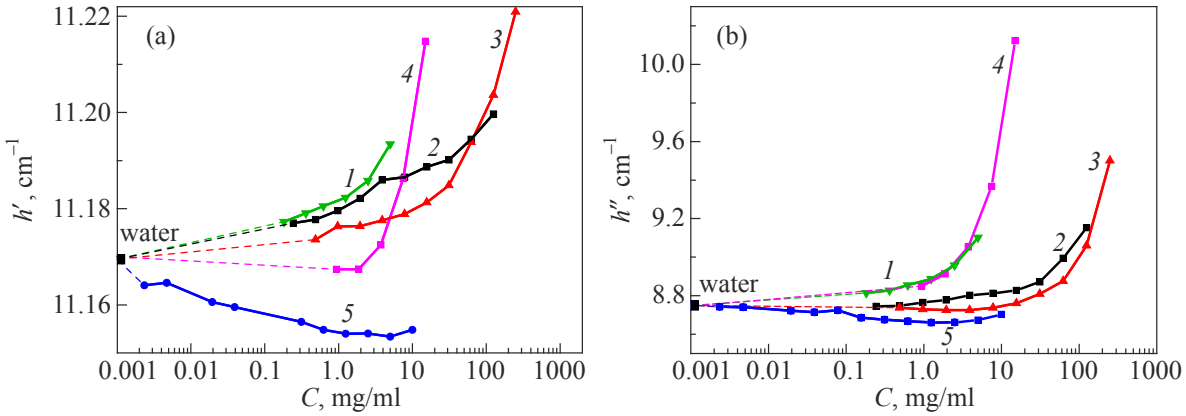


Fig. 3. The dependences of the real (a) and imaginary (b) parts of CPC on the concentration of drugs in aqueous solutions. The numbering is as in Fig. 2.

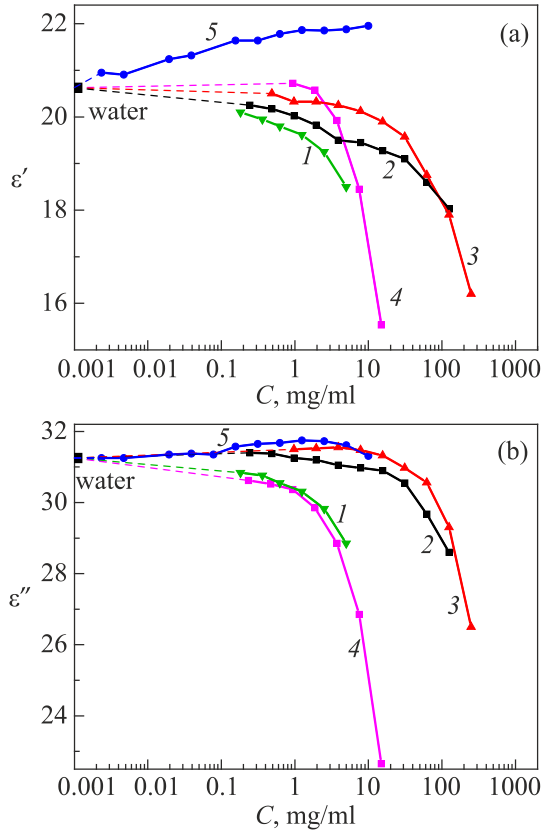


Fig. 4. The dependences of the real (a) and imaginary (b) parts of CP on the concentration of drugs in aqueous solutions. The numbering is as in Fig. 2.

the gentamicin solution are lower than the wave amplitude for water (Fig. 2), that indicates their greater attenuation in the gentamicin solution. This phenomenon may be related to the structural features of the gentamicin sulfate in comparison with other tested antibiotics, but should be investigated more deeply in the future.

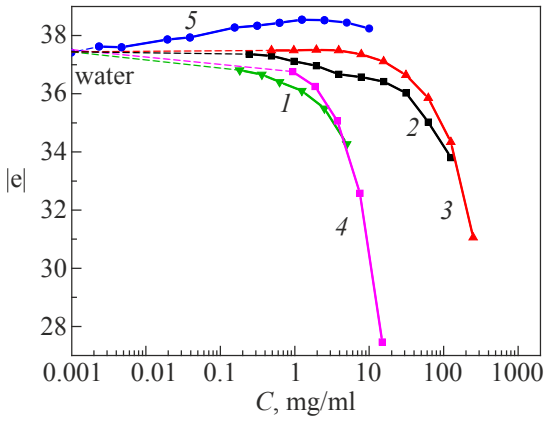


Fig. 5. The dependences of the CP module on the concentration of drugs in aqueous solutions. The numbering is as in Fig. 2.

3.2. Measurement using the UV/Vis spectrophotometry technique

For the proof of the microwave dielectrometry measurements, a widely used method of determining the antibiotics concentration in water solutions is necessary and the effectiveness of which is well known. We applied the UV/Vis spectrophotometry method for this purpose. For all antibiotics, the dependence of absorbance spectra on the optical wavelengths was measured. For the lincomycin and the levofloxacin aqueous solutions, the absorption bands were determined (Figs. 6 and 7). Figure 6(b) shows a fragment of the absorbance spectrum of the lincomycin solution in the region of 200–230 nm. For the lincomycin solutions, this is the absorption band at 225 nm, and for the levofloxacin solutions, the absorption band is determined at 284 nm. As seen in Fig. 6, for the lincomycin the absorption band at 225 nm is the most distinguished. In most cases, the absorbance intensity of the band in UV region depends on the substance concentration in the solution.

At the same time, for the gentamicin and amikacin solutions in their absorbance spectra (Figs. 8 and 9), there are no detectable certain absorption bands. This is probably

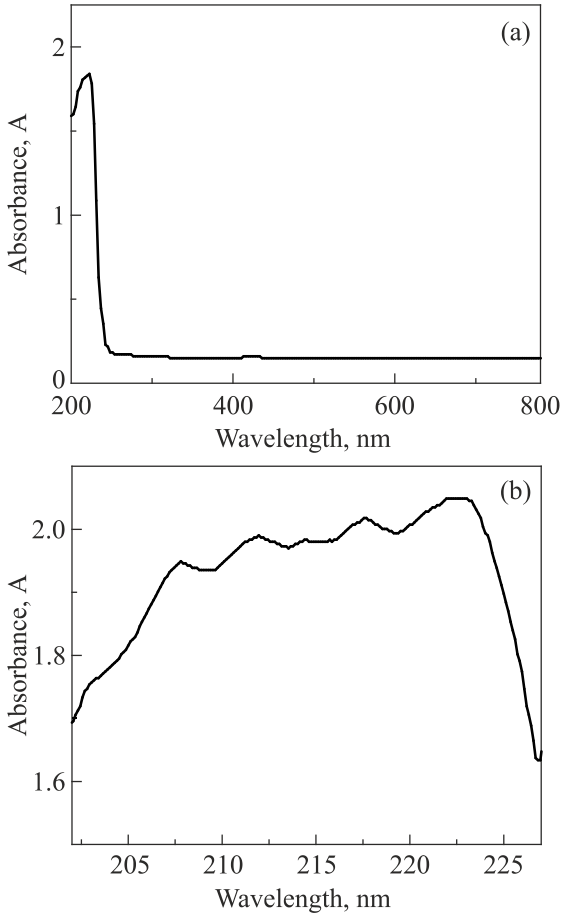


Fig. 6. UV/Vis absorbance spectrum for the lincomycin water solution (a) and the fragment of the absorbance spectrum in the narrowed region of 200–230 nm (b).

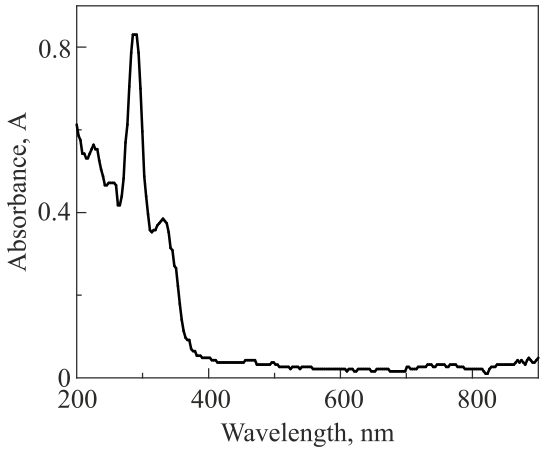


Fig. 7. UV/Vis absorbance spectrum for the levofloxacin water solution.

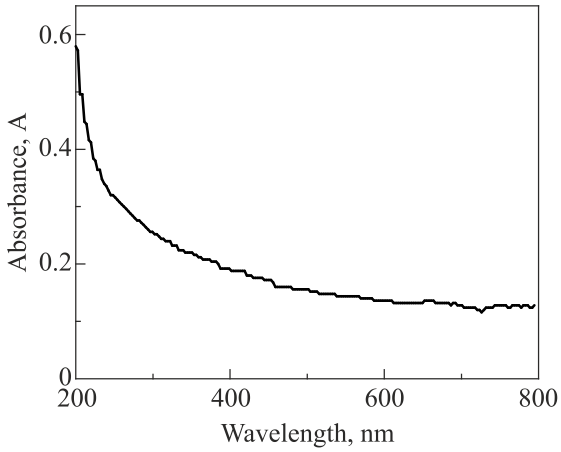


Fig. 9. UV/Vis absorbance spectrum for the amikacin water solutions.

due to the absence of double bonds and/or aromatic residues in the molecular structures of gentamicin and amikacin.

Figure 10 shows the absorbance dependences on the concentration of the lincomycin and the levofloxacin in the water solution.

Figure 10 presents close to linear absorbance intensity dependence on the lincomycin concentration in the range from 0.075 to 1.0 mg/ml (absorbance at 225 nm), and the similar dependence for levofloxacin at 284 nm using UV/Vis spectrophotometry. These almost linear dependences can be used in pharmaceutical analysis to validate a concentration measurement for lincomycin and levofloxacin aqueous solutions with the given microwave dielectrometric method according to State Pharmacopeia of Ukraine principles [27]. UV/Vis spectrophotometry is a well-known pharmacopeia method to analyze medicines. Up to now, the microwave dielectrometric method is not included in the list of pharmacopeia methods. In order to consider the following possible of including the developed microwave dielectrometric method to the pharmacopeia methods list, we need to compare it with a confirmed pharmacopeia method, that is, in our case, the UV/Vis spectrophotometry method. If the correlation coefficient between two methods is close to the one, then the tested method can be proposed as a pharmacopeia one after further numerous validating measurements of a number of medicines.

To compare mentioned above methods, we use the absorbance data of two presented methods [Figs. 3(b) and 10] for two antibiotics under test: lincomycin and levofloxacin. We selected these antibiotics because they showed semi-linear dependences in the given wavelength range (200–900 nm) of our UV/Vis spectrophotometer (Fig. 10). For the other two antibiotics (gentamicin and amikacin), we did not observe any resonant picks in this wavelength range in our UV-Vis measurements.

The absorbance data of two methods were processed and validated statistically with the use of the Fisher's correlation coefficient relation below, in order to compare and link measured results obtained by means of two different

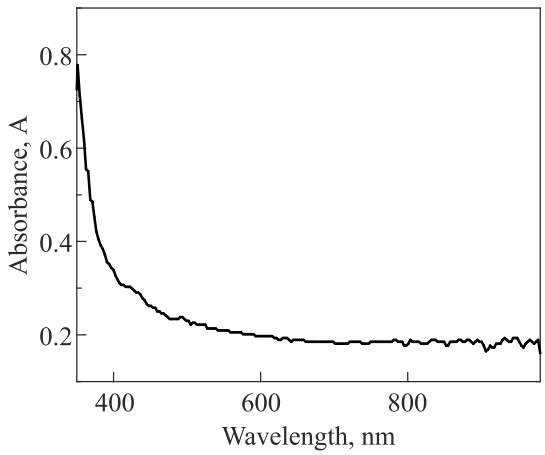


Fig 8. UV/Vis absorbance spectrum for the gentamicin water solution.

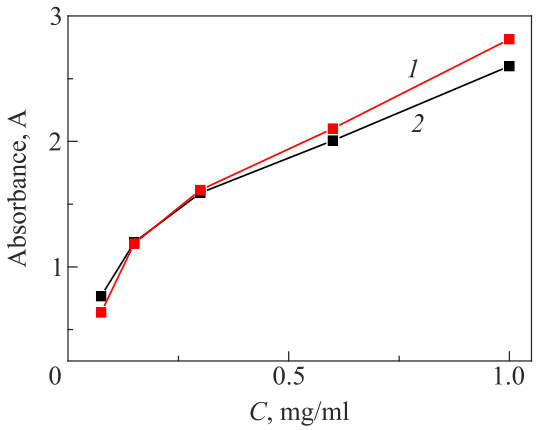


Fig. 10. The dependences of the lincomycin aqueous solution absorbance (*1*) on its concentration at 225 nm wavelength and the levofloxacin aqueous solution absorbance (*2*) on its concentration at 284 nm wavelength.

methods, such as the microwave dielectrometry technique and UV/Vis spectrophotometer ones.

As it is known, Fisher's correlation coefficient [28] is commonly used as an estimate of correlation in biometric studies, it has a form

$$F = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}},$$

where $x_i - \overline{x}$ and $y_i - \overline{y}$ represent deviation from their respective means. We take the wave attenuation (wave absorbance) values (h'') in our two measurements cells of the dielectrometer as x_i values and the absorbance values (A) obtained in the UV/Vis spectrophotometer as y_i ones.

So, for the levofloxacin-water solutions, the correlation coefficient for absorbance is F = 0.9708, for the lincomycin water solutions F = 0.9680. Thus, we have a good agreement of the measurement results of two presented methods.

4. Conclusion

In the current study, we applied the developed by us microwave dielectrometry setup and UV/Vis spectrophotometry method to study the aqueous solutions of selected antibiotics of different classes: the lincomycin hydrochloride, the levofloxacin hemihydrate, the amikacin sulfate, and the gentamicin sulfate. Complex permittivity (CP) values for the pharmaceutical aqueous solutions depending on antibiotic's concentration in the solutions were calculated based on the microwave dielectrometry results, comparative analysis of the CP values for the studied antibiotics solutions was performed. It was determined that values of the CP module for the lincomycin hydrochloride, levofloxacin hemihydrate, and amikacin sulfate solutions decreased with the drugs concentration increasing. Moreover, the CP module values for these antibiotics solutions were less than the CP module for distilled water due to the decrease in the part of free water with the increase in antibiotics concentration in the water solutions. For the gentamicin sulfate aqueous solution, the atypical CP behavior was observed: the CP module value of the gentamicin solution increased with the growing of the antibiotic concentration and was bigger than the CP value for the distilled water. This phenomenon is obviously related to the structural peculiarities of the gentamicin molecules and should be deeply studied further.

The mentioned antibiotics aqueous solutions were also probed by UV-Vis method and absorption bands for the aqueous solutions of the lincomycin hydrochloride (at 225 nm) and the levofloxacin hemihydrate (at 284 nm) were found. The concentration dependences of absorbance intensity for these two antibiotic solutions were measured.

We compared the absorbance measurement results two methods — the microwave dielectrometry and UV/Vis spectrophotometry — for the lincomycin hydrochloride and levofloxacin hemihydrate aqueous solutions. It was found a good correlation for the absorbance obtained by two used methods in determining of the levofloxacin and lincomycin concentrations in the water solutions.

Thus, we can conclude that the developed by us microwave dielectrometry approach and setup are prospective to be applied for antibiotics determination in aqueous solutions including environmental water samples, due to the technique demonstrates high sensitivity of CP to the changes of antibiotics concentration in the solution. In addition, the data of microwave dielectrometry are confirmed by the results of the UV-Vis spectrophotometry for levofloxacin and lincomycin solutions, as evidenced by the calculated Fisher's correlation coefficients close to unity.

1. J. Gallagher and C. MacDougall, *Antibiotics Simplified*, Jones & Bartlett Publishers (2011).
2. Alex Mason, *Real-time microwave*, *Hindawi J. Sensors* **2018**, 7976105 (2018).
3. F. Baquero, J.-L. Martinez, and R. Canton, *Current Opinion in Biotechnology* **19**, 260 (2008).
4. A. L. Batt, S. Kim, and D. S. Aga, *Chemosphere* **68**, 428 (2007).
5. O. Korostynska, A. Mason, A. Al-Shamma'a, W. Jansomboon, and S. Boontanon, *9th Intern. Conf. on Sensing Technology* (*ICST*), Auckland, New Zealand (2015), p. 492.
6. M. Soprani, O. Korostynska, A. Mason et al., *9th Intern. Conf. on Developments in eSystems Engineering* (*DeSE*), UK (2016), p. 317.
7. K. G. Karthikeyan and M. T. Meyer, *Sci. Tot. Environ.* **361**, 196 (2006).
8. *Pharmaceuticals in Drinking-Water*, World Health Organization (2012).
9. A. R. Mahmood, H. H. Al-Haideri, and F. M. Hassan, *Adv. Public Health* **2019**, 7851354 (2019).
10. M. Heidari, M. Kazemipour, B. Bina, A. Ebrahimi, M. Ansari, M. Ghasemian, and M. Mehdi Amin, *J. Environ. Public Health* **2013**, 351528 (2013).
11. Z. E. Eremenko, V.A. Pashynska, K. S. Kuznetsova, O. I. Shubnyi, N. I. Sklyar, and A. V. Martynov, Accepted for publication in *Radiofizika i Elektronika* (2021).
12. K. S. Kuznetsova, V. A. Pashynska, Z. E. Eremenko, O. I. Shubniy, and A. V. Martunov, *II Intern. Advanced Study Conf. Condensed Matter & Low Temperature Physics*, Kharkiv, Ukraine (2021).
13. Z. E. Eremenko, V. N. Skresanov, E. S. Kuznetsova, Yun Wu, and Yusheng He, *IEEE Trans. Instrum. Meas.* **63**, 694 (2014).
14. Z. E. Eremenko and E. S. Kuznetsova, *16th IEEE Intern. Conf. on Mathematical Methods in Electromagnetic Theory*, MMET, Lviv (2016).

15. Z. E. Eremenko and E.S. Kuznetsova, *9th Intern. Kharkiv Symposium on Physics and Engineering of Microwaves, Millimeter and Submillimeter Waves, G-51, MSMW-2016.*
16. Z. E. Eremenko, E. S. Kuznetsova, A. I. Shubnyi, V. V. Glamazdin, and M. P. Natarov, *Proceedings of the 47th European Microwave Conference*, Nuremberg, Germany (2017), p. 707.
17. Z. E. Eremenko and E. M. Ganapolskii, *Telecommunications and Radio Engineering* **60**, 61 (2003).
18. Z. E. Eremenko, E. M. Ganapolskii, and V. V. Vasilchenko, *Meas. Sci. Technol.* **16**, 1619 (2005).
19. Z. E. Eremenko, E. M. Ganapolskii, and V. V. Vasilchenko, *Proc*. of *35th European Microwave Conference, Paris, France* (2005), p. 1007.
20. Z. E. Eremenko, V. N. Skresanov, A. I. Shubnyi, N. S. Anikina, V. G. Gerzhikova, and T. A. Zhilyakova, *Complex Permittivity Measurement of High-Loss Liquids and its Application to Wine Analysis*. *Electromagnetic Waves,* V. Zhurbenko Technical University of Denmark (2011), Ch. 19.
21. Z. E. Eremenko, K. S. Kuznetsova, N. I. Sklyar, and A. V. Martynov, *Measuring Complex Permittivity of High-Loss Liquids. Dielectric Materials and Applications*, P. K. Choudhury (ed.), Nova Science Publisher (2019), Chapt. 2.
22. V. N. Skresanov, Z. E. Eremenko, V. V. Glamazdin, and A. I. Shubnyi, *Meas. Sci. Technol.* **22**, 065403(10) (2011).
23. W. J. Ellison, K. Lamkaourchi, and M. J. Moreau, *J. Mol. Liq*. **68**, 171 (1996).
24. Michael H. Penner, *Basic Principles of Spectroscopy*, Ch. 21, S. Suzanne (ed.), Nielsen Purdue University West Lafayette, IN, Springer Science+Business Media, USA, LLC (2010).
25. P. Li and J. Hur, *Crit. Rev. Environ. Sci. Technol.* **47**, 131 (2017).
26. https://pubchem.ncbi.nlm.nih.gov/compound/Gentamicin-sulphate#section=Structures
27. The State Pharmacopoeia of Ukraine, Vol. 2, Suppl. 4, Kharkiv: State Enterprise «Ukrainian Scientific Pharmacopoeial Centre for Quality of Medicines» (2020).
28. J.-W. C. Alffenaar, E. M. Jongedijk, C. A. J. van Winkel, M. Sariko, S. K. Heysell, S. Mpagama, and D. J. Touw, *J. Antimicrob. Chemother*. **76**, 423 (2021).
29. S. Plata, *Appl. Math. Lett*. **19**, 499 (2006).

Розробка експериментальних методів виявлення антибіотиків у водних розчинах: мікрохвильова діелектрометрія в реальному часі та спектрофотометрія в ультрафіолетовій та видимій областях довжин хвиль

Z. E. Eremenko, V. A. Pashynska, K. S. Kuznetsova, A. V. Martunov

Для вивчення водних розчинів вибраних антибіотиків різних класів — лінкоміцину гідрохлориду, левофлоксацину гемігідрату, амікацину сульфату, гентаміцину сульфату — використано мікрохвильову діелектрометрію та УФ/Вид спектрофотометрію. Техніка мікрохвильової діелектрометрії демонструє високу чутливість значень комплексної проникності водних розчинів антибіотиків від концентрації антибіотиків у таких розчинах. У нашому дослідженні дані мікрохвильової діелектрометрії підтверджуються результатами УФ/Вид спектрофотометрії для водних розчинів левофлоксацину та лінкоміцину. Коефіцієнти кореляції Фішера для значень поглинання електромагнітних хвиль, отримані різними методами, близькі до одиниці для згаданих антибіотиків. Отримані експериментальні результати підтверджують, що розроблений нами метод мікрохвильової діелектрометрії перспективний для застосування для визначення антибіотиків у водних розчинах, включаючи зразки води навколишнього середовища.

Ключові слова: УФ/Вид спектрофотометрія, водні розчини, антибіотики, електромагнітні хвилі, мікрохвилі, комплексна діелектрична проникність.