Virucidal properties of new multifunctional fibrous N-halamine-immobilized styrene-divinylbenzene copolymers

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Abstract

Virucidal properties of N-chlorosulfonamides immobilized on fibrous styrene-divinylbenzene copolymers have been studied. Corresponding materials with different functional group structures and chlorine content have been synthesized on FIBAN polymer carriers in the form of staple fibers and non-woven fabrics. The study has been conducted in general accordance with EN 14476 standard on poliovirus type-1 and adenovirus type-5. It has been found that all tested samples exhibit pronounced virucidal activity: regardless of the carrier polymer form, sodium N-chlorosulfonamides inactivated both viruses in less than 30 s, and N,N-dichlorosulfonamides—in 30–60 s. The main mechanism of action of these materials, obviously, consists in the emission of active chlorine from the functional group into the treated medium under the action of the amino groups of virus fragments and cell culture. Considering the previously described antimicrobial and reparative properties of such materials, as well as their satisfactory physical and mechanical properties, the synthesized polymers are promising for the creation of medical devices with increased resistance to microbial contamination, such as protective masks, filter elements, long-acting wound dressings, and others.

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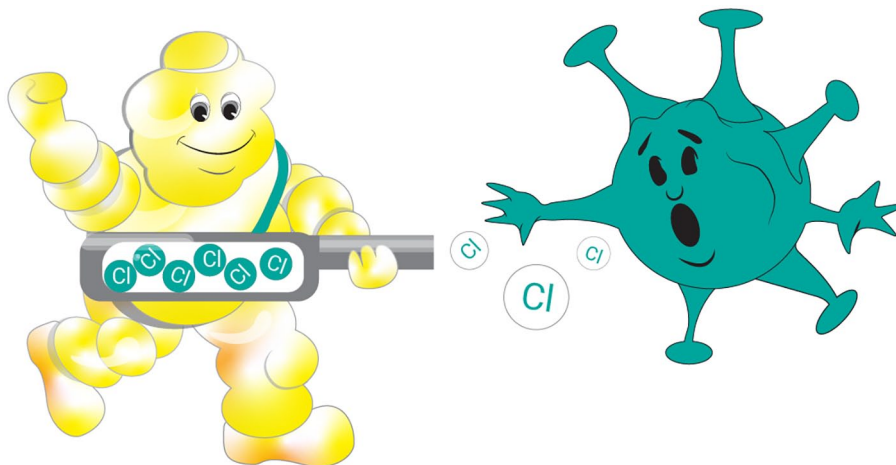
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Graphical Abstract

Introduction

Recent events related to the COVID-19 pandemic have once again confirmed the vital need for the widespread implementation of measures to prevent infectious diseases. Materials and technologies that provide protection against infections of various etiologies certainly include antiseptics and disinfectants of various compositions,[1–3] devices for treating premises with proper types of radiation of sufficient power (ozone generators, UV-recirculators, etc.),[4–7] as well as water and air treatment systems.[8–11] The other extremely important aspect is the use of personal protective equipment, primarily protective masks and respirators, because most epidemic diseases spread through an erogenic mechanism.[12,13] It should be noted that the massive application of the above procedures, as well as the tightening control over hygiene and sanitization of premises in accordance with quarantine protocols, led to an average 35% decrease in the incidence of multi-drug resistant hospital infections, which proves the high efficiency of such measures.[14] Therefore, the line of creating new compounds and materials that could be widely used for the prevention (and not for the treatment) of infections, must be boosted.

In the last decades, the synthesis of antimicrobial materials for medical applications is becoming increasingly important. Many functional polymers with microbiocidal activity have been developed, differing in the nature of the carrier and antimicrobial agent, manufacturing technology, physical form, etc.[15–18] Polymers impregnated with disinfectors (alcohols, surfactants, chlorhexidine, antibiotics, silver composites, and so on) are easy to manufacture and at the same time quite effective.[19–22] However, in most cases, they are actually disposable because of the very limited resource of work, moreover, they often require special packaging and storage conditions. Therefore, they are mainly used as sanitary napkins and less often as containers and dressings. Polymers with chemically grafted, or immobilized (covalently bonded), functional groups (quaternary ammonium, phosphonium groups, guanidine fragments, surfactants, enzymes, and others) are more technologically

complex.[23–27] Such materials, through various mechanisms, inactivate pathogens upon direct contact. In some cases, they are also capable of releasing a certain amount of an active micro-biocidal agent into the environment. Their distinctive features are prolonged action and high stability; therefore, they are actively used to create medical goods: catheters, implants, prostheses, protective clothing, etc.

Special attention should be paid to polymeric materials containing functional groups-donors of active chlorine, which in most cases are N-halamine immobilized.[28–31] As carriers of active chlorine, polymers of various chemical structures and origin can be used, depending on the intended application; the chemical nature of chlorine-active groups is also very diverse.[32–36] Their main advantage is a wide range and rapidity of bactericidal and virucidal action, as well as the almost complete inability of developing resistance of microorganisms to them, which is especially important, given the rate of spread of antibiotic-resistant superbugs. In addition, such polymers can significantly increase the stability of active chlorine, the lack of which is the main problem of trivial chlorine-active drugs (hypochlorous acid, sodium hypochlorite, etc.).[37,38] Such polymers are used in water conditioning systems for disinfection and additional oxidation of some inorganic compounds, in healthcare equipment, in the textile industry, and even for the creation of protective clothing against chemical warfare agents.[39–42] Thus, the creation of such materials is extremely promising, especially in light of the more frequent epidemics of infectious diseases.

The synthesis of N-chlorosulfonamides immobilized on various forms of styrene-divinylbenzene copolymer carriers was previously described by our group.[42,43] The kinetics of the release of active chlorine from them into different media have been studied, and a number of studies of their antimicrobial properties *in vitro* and *in vivo* have been carried out.[44–47] This paper presents data on the virucidal activity of the synthesized materials.

Materials and methods

Synthesis of N-halamine-immobilized polymers

For the study, samples of N-chlorosulfonamides of various structures were synthesized and immobilized on polymer carriers which consists of sulfonated styrene copolymers with divinylbenzene on polypropylene filament. Such carriers are being industrially manufactured as ion exchangers of the FIBAN K-1 brand.[48,49] Unlike other known styrene-divinylbenzene polymers,[49–51] such materials can be obtained in the form of fibers insoluble in water and other ordinary solvents due to the presence of the polypropylene matrix and special technology of radiation-induced polymerization. This made it possible to synthesize target modified chlorine-active materials in the following forms: staple fiber ("cotton wool"), which, due to its developed surface, is promising for the creation of filter elements, and needle-punched nonwoven fabric ("cloth"), which is easier to standardize and thus is more convenient for use as a component of medical protective masks or antiseptic dressings (Figure 1).

The technique for immobilization of N-chlorosulfonamide groups on polymer carriers is the same for "cotton wool" and "cloth" and has been described in our work.[45] It includes successive stages of sulfochlorination of the corresponding carrier (I) with sulfurochloridic acid, amination of the formed sulfochloride (II) with ammonia, and chlorination of the synthesized amide (III) with sodium hypochlorite with the formation of Na-form of N-chlorosulfonamides (IV). To obtain dichloroderivatives (V), the amide (III) was chlorinated with the sodium hypochlorite acidified with acetic acid (Figure 2).

Confirmation of polymer structure

The chemical structure of the synthesized polymers was proven by IR spectroscopy, as demonstrated previously for granular forms.[52]
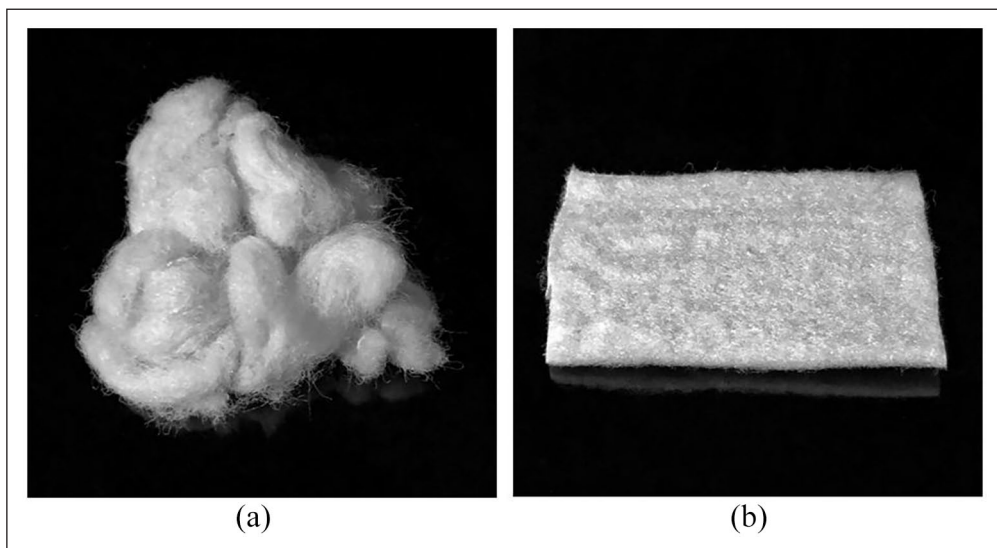
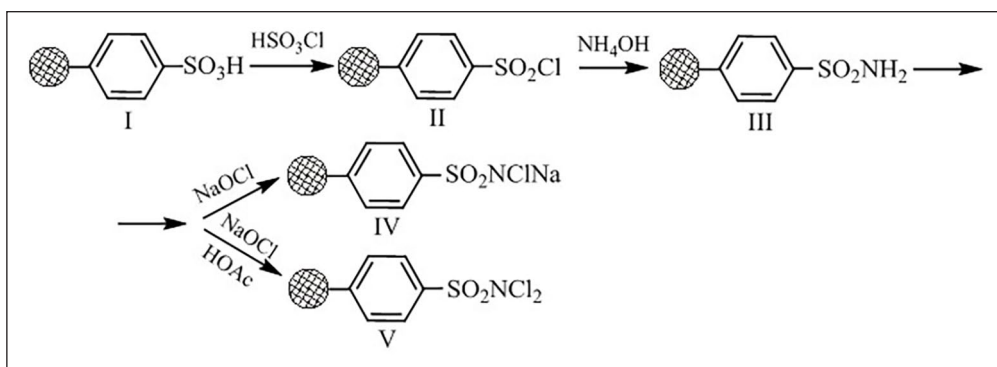**Figure 1.** The appearance of synthesized materials: (a) "cotton wool" sample and (b) "cloth" sample.

Figure 2. Scheme of synthesis of investigated polymers with immobilized N-chlorosulfonamide groups.

The corresponding spectra were recorded on a Spectrum BX II FT-IR spectrometer Perkin Elmer (USA). Polymer samples were dried in a vacuum desiccator, ground in an agate mortar with potassium bromide, and then pressed into tablets, which were further analyzed.

The content of residual free sulfonamide groups in the synthesized materials was determined similarly to the exchange capacity of strongly acidic cation exchangers. For immobilized N, N-dichlorosulfonamides, a weight sample of polymer about 1.5 g was added to 100 ml of 0.1 N calcium chloride solution and kept for 24 h with periodic stirring. Part of the solution (25 ml) was titrated with 0.1 N sodium hydroxide solution in the presence of methyl red as indicator. Following, the amount of acid formed in solution due to ion exchange adsorption of calcium cation was calculated using the corresponding formula.[53] The acid content in the solution is equivalent to the content of immobilized free -SO$_3$H groups. For the immobilized sodium N-chlorosulfonamides, the potentiometric method was used,[54] in which the corresponding polymer was treated with 1 N HCl solution for 2 h to convert it to

H-form. The product was washed with water until the filtrate was neutral and dried in a desiccator over sulfuric acid to constant weight. A weight sample of immobilized N-chlorosulfonamide in H-form (about 0.3–0.5 g) was placed into 50 ml of distilled water and kept for 24 h, shaking periodically. Then it was potentiometrically titrated with 0.1 N NaOH solution with a glass electrode to pH 7.0. The content of free SO_3H-groups in mg-eq/g was determined using the titration curve.

Determination of immobilized chlorine concentration

The concentration of immobilized chlorine was determined by special iodometric titration method according to the procedure described in our papers.[45,46] About 1.0 g of polymer was placed in a 250 ml flask with 100 ml of distilled water, then 10 ml of 10% KI solution and 10 ml of 10% H_2SO_4 were added mixing thoroughly after each step. The mixture was slowly heated in the closed flask on a water bath until the release of iodine starts. The released iodine was being titrated with 0.1 N sodium thiosulfate solution. The heating and titration of the analyzed sample were periodically repeated until the release of iodine into the solution ceases. The concentration of released active chlorine (Y) in mg-eq/dm³ has been calculated by the formula below:

$$Y = \frac{V \times 0.003545 \times 1000 \times 1000}{V_1},$$

in which V—the volume of the 0.1 N solution of sodium thiosulfate, which was used for titration of the analyzed sample, cm³;

0.003545—the mass of active chlorine, which corresponds to 1 cm³ of 0.1 N solution of sodium thiosulfate, g;

1000—conversion factor g/cm³ to g/dm³;

1000—conversion factor g/dm³ to mg/dm³

V_1—the volume of the solution taken for analysis, cm³.

The determination of chlorine concentration in the sample of investigated chlorine-active polymers was carried out immediately before each virological experiment.

Assessment of virucidal activity of synthesized polymers

The investigation of virucidal activity of materials has been performed in general accordance with EN 14476[55] on models of the vaccine strain of poliovirus type-1 and adenovirus type-5, which are highly resistant to physico-chemical environmental factors.[56,57]

Cell culture studies

HEp-2 was the transplantable cell culture, which has been used for the cultivation of both viruses. For cell culture growth, medium 199, Eagle's medium (Sigma Aldrich) with a double set of amino acids, and with the addition of 10% fetal bovine serum and antibiotics were used. For support medium, medium 199 (Sigma Aldrich), Eagle's medium with a double set of amino acids and with the addition of 2% fetal bovine serum were used.

TCID$_{50/ml}$ determination

The TCID$_{50/ml}$ (tissue culture infectious dose, that causes 50% cell death) has been at first determined for each of the two tested viruses.[58] The tissue culture was examined on inverted microscope "Olympus Tokyo CK." Table 1 shows the results of these calculations for HEp-2 cells.

Preparation of virus-containing fluid

To prepare the virus-containing fluid, tissue culture cells with full cytopathic action caused by the studied viruses were transferred with the culture fluid into sterile tubes, frozen, then thawed, and centrifuged at 3000 rpm for 10 min. The supernatant was collected and used in the

Table 1. Calculation of $TCID_{50/ml}$ of poliovirus type-1and adenovirus type-5.

Virus dilution	Virus type	Number of virus-treated objects	Died	Survived	% Death
10^{-3}	poliovirus type-1	-	-	-	-
	adenovirus type-5	4	4	0	100
10^{-4}	poliovirus type-1	4	4	0	100
	adenovirus type-5	4	4	0	100
10^{-5}	poliovirus type-1	4	4	0	100
	adenovirus type-5	4	2	2	50
10^{-6}	poliovirus type-1	4	2	2	50
	adenovirus type-5	4	0	100	0
10^{-7}	poliovirus type-1	4	0	100	0
	adenovirus type-5	-	-	-	-

As can be seen from the Table 1, dilution of poliovirus type-1 10^{-6} causes 50% HEp-2 cell death, which means that the $TCID_{50/ml}$ of this virus is equal to its dilution of 10^{-6}, and, correspondingly, $TCID_{50/ml}$ of adenovirus type-5 is equal to its dilution of 10^{-5}. On this basis, for the main experiment the vaccine strain of poliovirus type-1 was used at a working concentration of $3lgTCID_{50/ml}$ (corresponding to a dilution of 10^{-3}), and adenovirus type-5 was used at a working concentration of $2.5lgTCID_{50/ml}$ (corresponding to a dilution of $10^{-2.5}$).

experiment. Before using the virus in the experiment, the titer of the virus-containing fluid was determined by the standard Reed and Muench-Mench method.[59]

Determination of virucidal activity

To determine the virucidal activity, the samples of "cloth" test materials with a size of 0.5×0.5 cm, and the samples of test "cotton wool" with the mass about 0.012 ± 0.0004 g (corresponds to the medium mass of the "cloth" samples of the given square), each in triplicate, were placed in sterile Petri dishes and filled with a cultural liquid containing viruses (separately) at the rate of 0.1 mL per one test object. The amount of viruses used was the concentration previously established. Test samples were kept in virus-containing fluid for a pre-determined time—30 s, 1, 5, 10, and 20 min. Then they were transferred into 1 mL of support medium and actively mixed; fluid was filtered with syringe filters to separate polymer fibers that could continue to emit active chlorine, and then were kept for another day for complete destruction of active chlorine to avoid its toxic effects on cell cultures. After that, the working virus-containing liquid was transferred to cell cultures. It has been found that when transferring fluid without

filtration and preliminary storage, the carrier cells died almost instantly, apparently under the influence of residual concentrations of active chlorine. In parallel, the same experiment has been performed with the initial FIBAN K-1 polymer carrier, which did not contain N-halamine functional groups. Each experiment included the following controls: control of infection of test objects (the same polymer samples that were not treated with virus-containing liquid), control of virus viability (the same experiment but without using polymer samples), and control of tissue culture cells. Each experiment was performed in triplicate. Before the main experiment, three passages on fresh tissue was made to increase the titer of the viruses.

Analysis of the viral pathogenic action on cell cultures

When HEp-2 tissue cells are infected with the vaccine poliovirus type-1, uniform fine-grained destruction of the cells occurs, followed by their exfoliation. In the absence of specific changes in cell culture, the virus is considered inactivated.[60]

When HEp-2 tissue cells are infected with adenovirus type-5, a characteristic aggregation of cells having the appearance of a "grape" on

Table 2. Polymer test samples synthesized for virucidal activity determination.

Sample №	Physical form of the carrier	Functional group	Immobilized chlorine content, %
1	"cotton wool"	$-SO_2-NClNa$	6.0
2	"cloth"	$-SO_2-NClNa$	3.7
3	"cotton wool"	$-SO_2-NCl_2$	12.0
4	"cloth"	$-SO_2-NCl_2$	6.0
5	"cotton wool"	$-SO_2-NH_2$	-
6	"cloth"	$-SO_2-NH_2$	-

the background of a partially destroyed monolayer of cells occurs. In the absence of specific changes in cell culture, the virus is considered inactivated.[61]

Results

To determine the virucidal activity, four samples containing immobilized N-chlorosulfonamide groups of different structures and 2 samples of polymer carrier FIBAN K-4 immobilized with free sulfonamide groups (to use as a control in virological experiment) were synthesized. Their appearance and physicochemical properties (density, humidity, fiber thickness, water absorption capacity, etc.) corresponded to previously described.[43–45]

The main characteristics of the samples are shown in Table 2.

The IR spectra of the synthesized polymers and the initial polymer carrier (samples 1, 3, 5) are shown in Figures 3 to 5 respectively. The spectra of the corresponding samples of "cloth" are qualitatively similar to those for "cotton wool."

The results of the virological experiments are shown in Tables 3 and 4.

Discussion

The data of the IR spectra of the synthesized samples are generally similar to those published by us earlier for granular chlorine-active polymers and confirm the declared structure of their functional groups. It was found that the materials are in hydrated form, because even after drying in a vacuum desiccator in the spectra there

are strong signals in the range of 3400 and $1640\,cm^{-1}$, which correspond to the valence and scissoring vibrations of hydroxyl groups of water molecules. It is known[62] that sodium forms of N-chlorosulfonamides can exist in the form of salts of N-chlorosulfoximidic acid. The spectrum of sample No. 1 contains the characteristic absorption band of sulfoximidic groups of 1220 and $1129\,cm^{-1}$, and the manifestation of the sulfoxide fragment is proved with band of $1040\,cm^{-1}$, thus, the spectrum agrees with the previously obtained data. For immobilized N,N-dichlorosulfonamide (sample No. 3) vibrations in the -S=O group region of $1340\,cm^{-1}$ (antisymmetric stretching vibrations) and of 1214, 1184, and $1128\,cm^{-1}$ (symmetric stretching vibrations) are characteristic. The IR spectrum of the unmodified carrier polymer (sample No. 5) contains absorption bands of sulfoxide groups in the region of $1350\,cm^{-1}$ (antisymmetric stretching vibrations), 1220, 1169, and $1127\,cm^{-1}$ (symmetric stretching vibrations). Unfortunately, determination of the presence of chlorine atoms from IR spectra is impossible, firstly, because of the weak signal intensity due to the relatively low content of N-Cl bonds in comparison with other types of bonds in the polymer, and secondly, because of the presence of many other signals in this region (about 750–$850\,cm^{-1}$). Therefore, the presence of chlorine can be determined only via titration.

The high degree of conversion of sulfo groups in the starting polymer into the target N-chlorosulfonamide groups, which are not capable of proton exchange, is confirmed by the low exchange capacity of the synthesized polymers. The exchange capacity of the carrier
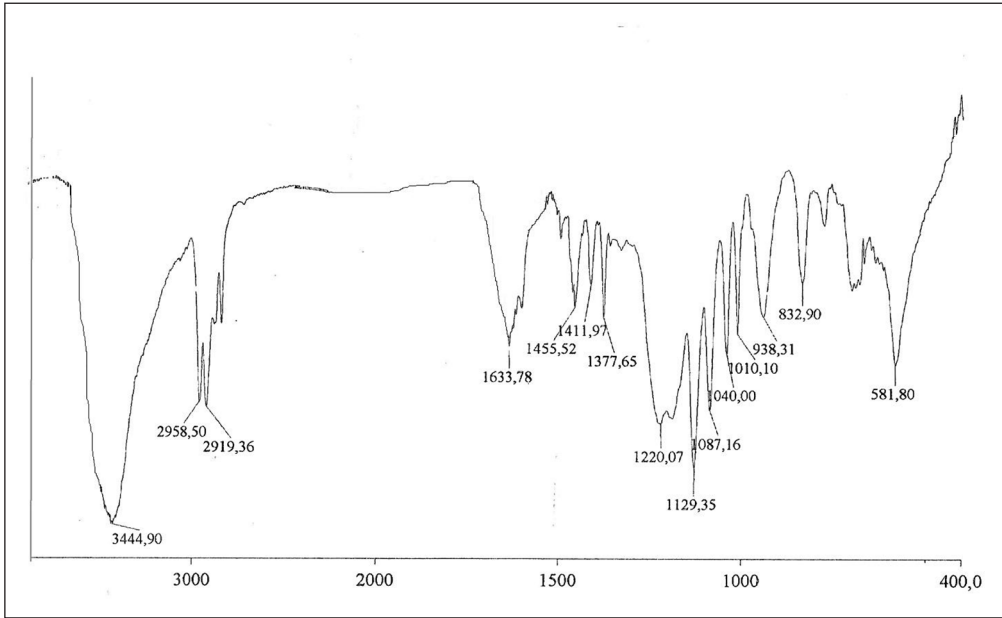
Figure 3. The IR spectrum of immobilized sodium N-chlorosulfonamide (sample №1).
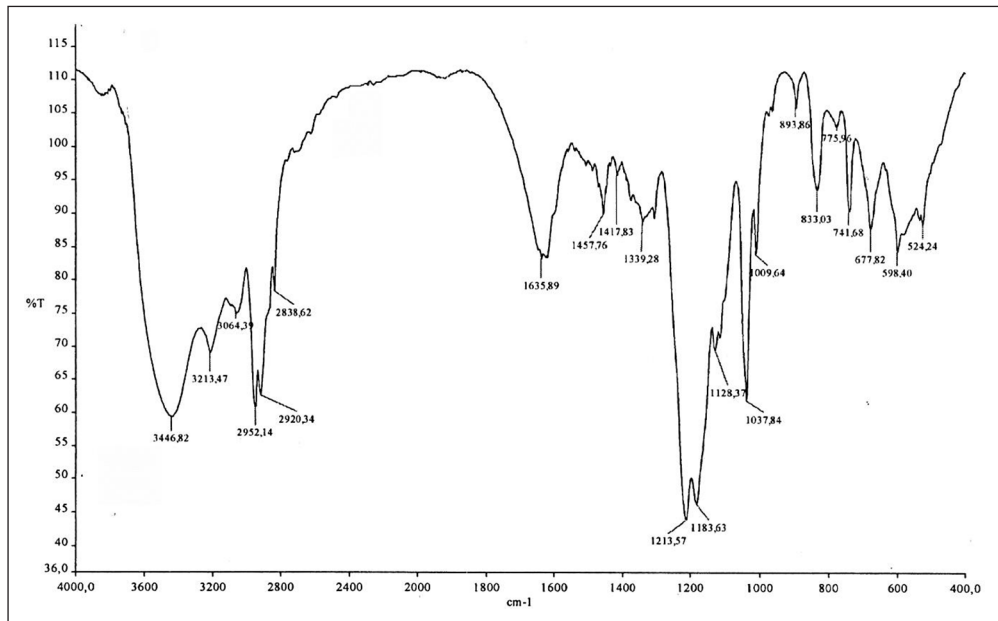

Figure 4. The IR spectrum of immobilized N,N-dichlorosulfonamide (sample №3).

polymer, calculated according to the above method, is 2.7–3.5 mg-eq/g, and the content of sulfo groups in the modified polymers is only 0.05–0.08 mg-eq/g.

As seen, all synthesized polymer samples contain a fairly high amount of immobilized chlorine. The choice of these samples was based on the previously described features of
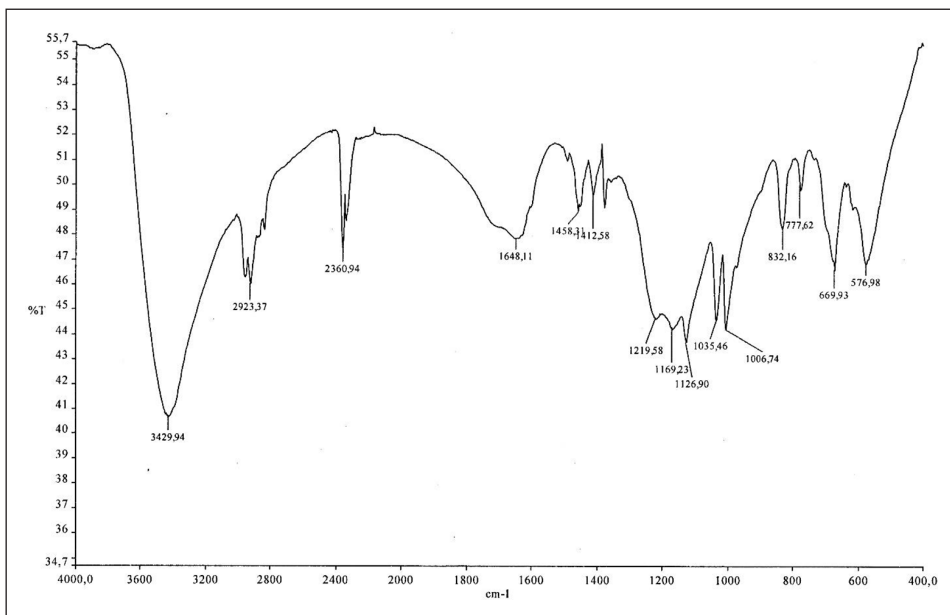
Figure 5. The IR spectrum of polymer carrier FIBAN-K1 (control sample №5).

Table 3. Virucidal activity (inactivation time) of synthesized polymers against poliovirus type-1[1].

Experiment replicate	Test-sample	Exposure time				
		30 s	1 min	5 min	10 min	20 min
1	1	—	—	—	—	—
	2	—	—	—	—	—
	3	✓	—	—	—	—
	4	✓	—	—	—	—
	5	✓	✓	✓	✓	✓
	6	✓	✓	✓	✓	✓
2	1	—	—	—	—	—
	2	—	—	—	—	—
	3	✓	—	—	—	—
	4	✓	—	—	—	—
	5	✓	✓	✓	✓	✓
	6	✓	✓	✓	✓	✓
3	1	—	—	—	—	—
	2	—	—	—	—	—
	3	✓	—	—	—	—
	4	✓	—	—	—	—
	5	✓	✓	✓	✓	✓
	6	✓	✓	✓	✓	✓
CVV		✓	✓	✓	✓	✓
CCC		—	—	—	—	—

CVV: control of virus viability; CCC: control of cell culture.
(1)Note: the next symbols are used in Tables:
✓ presence of cytopathogenic effect of the virus.
— absence of cytopathogenic effect of the virus.

Table 4. Virucidal activity (inactivation time) of synthesized polymers against adenovirus type-5 [1].

Experiment replicate	Test-sample	Exposure time				
		30 s	1 min	5 min	10 min	20 min
1	1	—	—	—	—	—
	2	—	—	—	—	—
	3	✓	—	—	—	—
	4	✓	—	—	—	—
	5	✓	✓	✓	✓	✓
	6	✓	✓	✓	✓	✓
2	1	—	—	—	—	—
	2	—	—	—	—	—
	3	✓	—	—	—	—
	4	✓	—	—	—	—
	5	✓	✓	✓	✓	✓
	6	✓	✓	✓	✓	✓
3	1	—	—	—	—	—
	2	—	—	—	—	—
	3	✓	—	—	—	—
	4	✓	—	—	—	—
	5	✓	✓	✓	✓	✓
	6	✓	✓	✓	✓	✓
CVV		✓	✓	✓	✓	✓
CCC		—	—	—	—	—

CVV: control of virus viability; CCC: control of cell culture.
(1)Note: the next symbols are used in Tables:
✓ presence of cytopathogenic effect of the virus.
— absence of cytopathogenic effect of the virus.

the technology of obtaining such materials and the kinetics of active chlorine emission from them into aqueous solutions under the action of various activators.[46,63] We have shown that practically any compound with the amino function of chemical (ammonia, ammonium chloride, glycine, taurine, aminocaproic acid, etc.) or biological (bread mold, blood, etc.) origin in solutions lead to the transfer of active chlorine from the polymer to this solution, while the immersion of the same polymers into a medium that does not contain such impurities practically does not cause the release of chlorine. The release of chlorine mainly determines the antimicrobial properties of our materials. It was assumed that the presence of viral polyaminoacids and host cell proteins in the solution will activate this process, too.

The noticeably lower concentration of chlorine in "cloth" samples 2 is due to the peculiarities of the technology of their synthesis, specially the slower diffusion of reagents into the initial, much denser nonwoven fabric compared to staple fiber, as well as milder conditions (lower temperature and concentration of the sulfochlorinating agent) to avoid the destruction of the polymer carrier.[64] Our attempts to obtain "cloth" samples by pressing the already modified chlorine-active "cotton wool" showed that in this way it is possible to achieve a higher (up to 8%) content of active chlorine in them, but at the same time the yield of such a fabric is much less than when modifying the pressed fabric due to a decrease in physical-mechanical qualities of the fiber during its chemical functionalization. Dichlorosulfonamide fibers and fabrics obviously have a higher concentration

of immobilized chlorine, but the aspects described above also apply to them, and its value for "cotton wool" is about two times higher than that for "cloth" with the full chemical equivalence of functional groups. In addition, when previously studying the kinetics of active chlorine release into various solutions, we found that its maximum concentration in the case of dichloroderivatives is reached more slowly than for the sodium forms of monochlorosulfonamides.[63] This is probably caused by the dissociation of N-Na bonds in the case of monochloramides, which leads to the formation of an electric double layer around the functional group, and the resulting stabilized anion facilitates the detachment of the chlorine atom. For dichloramides, this process is impossible. Such kinetics also affects the antimicrobial properties of polymers: when testing bactericidal activity by the method of agar plates, after a 1 day of treating Petri dishes with a contaminated nutrient medium, the zones of suppression of the growth of microorganisms around the samples of monochloramides in Na-form are wider than those for dichloroderivatives. However, on the second day there were practically no changes in zones of inhibition around polymeric monochloramides, whereas a significant increase was observed around dichloramides.[65,66] Thus, NClNa-polymers provide a faster effect, while NCl_2-forms have a prolonged action, which may be true for virucidal properties as well.

Comparison with FIBAN K-4 polymers with immobilized sulfonamide groups $-SO_2NH_2$ has been carried out to determine the possible virucidal activity of the free sulfo-groups $-SO_3H$, which are present in small amounts (up to 0.3 mg/g) in the studied polymers, and of the sulfonamide group itself, which is a product of hydrolysis of N-chlorosulfonamides.

As can be seen from Tables 3 and 4, all the studied chlorine-active polymers, as expected, have pronounced virucidal activity, while the FIBAN K-4 carrier polymers with a free sulfonamide group used as a control do not possess such properties. Polymers with immobilized N-chlorosulfonamide groups in Na-form kill both viruses in less than 30 s, and polymeric dichlorosulfonamides—in 30–60 s. This once again confirms our above theory about different kinetics of active chlorine emission from these materials. The rate of suppression of viruses for polymers with the same functional group does not depend on the concentration of immobilized chlorine and, apparently, is determined only by the rate of diffusion of the solvent containing protein amino compounds into the fiber, and by the diffusion of active chlorine in the opposite direction. However, the absence of a difference in the neutralization of pathogens between "cotton wool" and "cloth" samples indicates that, despite the higher density and less developed surface of the latter, the diffusion of active chlorine from it at the used concentrations of the virus-containing liquid is sufficient for effective virucidal effect.

The mechanism of the virucidal action of the investigated chlorine-active polymers is most likely complex. The main contribution, apparently, is made by the emission of active chlorine into the virus-containing fluid, namely chlorination of the amino groups of carrier cells fragments and components of the nutrition medium (since the concentration of these compounds in the fluid is the highest), with the formation of corresponding N-chloroamines and subsequent destruction of the virus due to oxidation, chlorination, and transchlorination.[67–69] This is proved by the fact that when the fluid was transferred to the cell culture immediately after treatment with the polymer, the death of the carrier cells was observed, which was caused not by the pathogenic action of the virus, but by the presence of excessive amounts of active chlorine in it. In addition, most likely, there is also a direct transfer of active chlorine to the viral particle upon contact with the fiber, as a result of which the virus is inactivated due to oxidation and chlorination directly on the polymer; however, such transfer is statistically less likely due to the low concentration of the viral particle in the fluid compared to other amine-containing compounds. These mechanisms are indirectly confirmed by the longer inactivation time in the case of dichloroderivatives compared to monochloro-ones: the more hydrophilic -N(Na)-Cl bond ensures more efficient interaction of the

corresponding fiber with the virus or other protein structure than the less hydrophilic -N(Cl)-Cl. Unfortunately, under the conditions of a virological experiment, it was not possible to measure the concentration of active chlorine in biological fluids due to the small amounts and rapid decay of active chlorine in such systems. The iodometric determination of the concentration of active chlorine in the samples after the experiment showed some decrease, on average by 4%–5%, in comparison with the initial one. In addition to the emission of chlorine, a change in the pH of the medium during the decomposition of active chlorine can also make a certain contribution to the virucidal activity, as well as the adsorptive properties of the polymer carrier itself.

Our research has once again confirmed the high efficiency of active chlorine against highly resistant viruses. Numerous literature data indicate that hypochlorous acid, its salts, as well as solutions of organic N-halamines are powerful virucidal agents, regardless of the type of virus.[70–72] The COVID-19 pandemic has vastly stimulated the development of this area of chemistry. It has been shown that chlorine-active drugs, in particular hypochlorites, are effective against the SARS-Cov-2 virus, and their cheapness, availability and relative safety are significant advantages over other types of disinfectants (alcohols, guanidines, quaternary ammonium compounds, etc.).[73–75] A very important aspect is their high efficiency against bacteria, fungi and prions, as well as the nonspecific nature of their action and, as a consequence, the impossibility of developing resistance to them. Accordingly, chlorine-active polymers are becoming more and more promising and popular.[76–78] The advantages of our polymers over analogs are the absence of complex organic chlorine carrier groups in them, which can cause allergies upon contact with the skin, the comparative simplicity of the technology for their production, the absence of transfer of any compounds into the treated environment, except for sodium and chlorine ions, as well as the possibility of regeneration.

But the disadvantages that narrow the scope of their application are the impossibility of obtaining threads from them and poor soldering ability. The next stage of our research will be the study of microbial and viral permeability of synthesized polymers to liquid and gaseous media, and their antimicrobial activity against multi-resistant microorganisms and biofilms.

Conclusion

All the studied samples of polymers with immobilized N-chlorosulfonamide groups exhibit pronounced virucidal activity against the vaccine strain of the poliomyelitis virus type-1 and adenovirus type-5. Therefore, it can be assumed that such materials will exhibit antiviral activity against enveloped and less resistant viruses. Considering the previously described powerful antimicrobial properties and the ability to emit active chlorine into the environment contaminated with amino compounds, these materials are promising for the manufacture of a wide range of medical products, primarily personal protective equipment, protective clothes, wound dressings, as well as active filters for water and air treatment, which could be beneficial specially for the combat of epidemics of infectious diseases.

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