High-performance method for specific effect on nucleic acids in cells using TiO$_2$-DNA nanocomposites

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Nanoparticles are used to solve the current drug delivery problem. We present a high-performance method for efficient and selective action on nucleic acid target in cells using unique TiO$_2$-PL-DNA nanocomposites (polylysine-containing DNA fragments noncovalently immobilized onto TiO$_2$ nanoparticles capable of transferring DNA). These nanocomposites were used for inhibition of human influenza A (H3N2) virus replication in infected MDCK cells. They showed a low toxicity (TC$_{50}$ < 1800 mg/ml) and a high antiviral activity (>99.9% inhibition of the virus replication). The specificity factor (antisense effect) appeared to depend on the delivery system of DNA fragments. This factor for nanocomposites is ten-times higher than for DNA in the presence of lipofectamine. IC$_{50}$ for nanocomposites was estimated to be 1.5 µg/ml (30 nM for DNA), so its selectivity index was calculated as ~1200. Thus, the proposed nanocomposites are prospective for therapeutic application.

Fragments of nucleic acids (NA) are widely used in life sciences including research methods and medical practice. NAs are among the most important sources for the development of a novel group of pharmaceuticals. NA-based drugs for antisense and antigen application include oligonucleotides, their analogues, ribozymes, DNAzymes, aptamers, small interfering RNAs (siRNAs), and plasmids containing transgenes. This class of compounds is extremely promising for drug therapy aimed to a wide range of diseases including infectious, cancer, neurological disorders such as Parkinson’s and Alzheimer’s diseases, cardiovascular disorders, etc. [e.g.,2,3]. NA-based drugs can be developed for individualized medicine. NA-based drugs can selectively suppress gene expression, inhibit activity of certain enzymes, or implement other special functions. The significant advantage of this type of drugs over currently available low molecular weight pharmaceuticals is their selective recognition of molecular targets. The effect of antisense oligonucleotides is known to be in their binding to complementary regions of a target RNA to form DNA/RNA hybrid duplexes, which leads to blocking the function of the target RNA or its cleavage by cellular RNase H. The important advantages of the antisense approach is that NA-drugs can be easily redirected to any target nucleic acids, while the search for new low-molecular drugs usually takes years.

However, because of the low ability to penetrate into cells, these compounds still have not found wide application in medicine. Poor cellular uptake and rapid in vivo degradation of NA-based drugs necessitate designing delivery systems to facilitate cellular internalization and preserve their activity. The transport of exogenous NA to cells can be achieved by using vehicles, which can be separated into two categories: viral and non-viral vectors. The former provides a high transfection rate and a rapid transcription of a foreign material incorporated in the viral genome. On the other hand, viral vectors present a variety of potential problems to the patients such as toxicity and immune and inflammatory responses. Insertional mutagenesis and oncogenic effects can occur when these vectors are used in vivo.

Cell-penetrating peptides as non-viral vectors are widely used for delivering various biomolecules into cells including plasmid DNAs, oligonucleotides, siRNAs, peptide-nucleic acids, proteins, etc. Cell-penetrating
A variety of supramolecular nanocarriers including various polymeric nanoparticles are used to deliver antisense oligonucleotides and siRNAs, as more fully described in recent reviews. Although cationic polymers, branched dendrimers, cationic liposomes, and cell-penetrating peptides are today under intensive studies, their efficiency as non-viral vectors for cell transfection is still low.

Current achievements of nanotechnology began to be used to solve the drug delivery problem, concerning particularly nucleic acid fragments. Recent advances in clinical trials concerning nanoparticle drug delivery systems are described in 14. Titanium dioxide is widely used in medicine as biocompatible and non-toxic material. TiO2 nanoparticles (≤5 nm) are known to penetrate through cell membranes. According to FDA (Management of the Food and Drug Administration, United States), TiO2 is recognized in 1966 as safe and harmless substance to humans. Compounds on the basis of TiO2 are widely used in cosmetics and as food supplements. Moreover, recent studies have shown that TiO2 nanoparticles at relatively low doses (up to 200 μg/ml) do not show any noticeable toxicity and no harmful effects on mammalian cells24, bacteria25, and animals26. Cytotoxicity of TiO2 nanoparticles used in this work did not exceed the level of natural death of MDCK cells27. TiO2 nanoparticles have been shown to be non-toxic in rats at low doses (5 mg/kg body weight)28. The above properties of titanium dioxide make it attractive to use as a vehicle of drugs, particularly, antisense oligonucleotides and their analogues into mammalian cells.

In the previous paper, we described new nanocomposites consisting of DNA fragments noncovalently fixed on TiO2 nanoparticles through the polylisine linker (TiO2•PL-DNA)29. These nanocomposites were shown by confocal microscopy to penetrate into mammalian cells without any transfection agents and physical impact. Delivery of nucleic acid fragments into cells is just the first step of their use in living systems. However, the real value of the proposed nanocomposites can be revealed only when they are tested on cells and animals.

Here we present a high-performance method for the site specific effect on target nucleic acids in eukaryotic cells using unique TiO2•PL-DNA nanocomposites. These nanocomposites show a low toxicity, and after penetration into cells infected by influenza A virus, demonstrate a high specific antiviral activity.

**Results**

The synthesis of TiO2 nanoparticles in amorphous and crystal forms (anatase, brookite), the preparation of nanocomposites consisting of these nanoparticles and noncovalently immobilized polylysine (PL) or polylisine-containing DNA fragments (PL-DNA), and characteristics of the designed TiO2•PL and TiO2•PL-DNA nanocomposites were described in a recent paper30. It has been shown that the efficiency of immobilization of oligonucleotides onto TiO2 nanoparticles, the ability of designed TiO2•PL-DNA nanocomposites to form complementary complexes and penetrate into cells without any transfection agents or physical impact do not depend on the nanoparticles form. Here we used nanocomposites based on one form of nanoparticles (anatase). PL-DNA conjugates30 were immobilized on anatase to give TiO2•PL-DNA bearing 20 nmol of DNA per 1 mg of anatase.

The biological activity of the designed nanocomposites was demonstrated by an example of inhibition of influenza A virus replication in infected MDCK cells. The most widespread human influenza A virus (H3N2) was used in our experiments. Influenza A virus contains eight single-stranded RNA segments of negative polarity as the genome. After infection of cells with influenza virus, viral RNA (–strand) segments are transcribed into mRNAs (+strand) and replicated into complementary RNAs (+strand)31. RNA segment 5 encodes nucleoprotein (NP), which plays a key role in the incorporation of viral genome in cell nuclei of an infected body, thereby, in the following replication and assembly of the virus32. In addition to coding regions, all eight segments of viral (-)RNA are known to contain the conservative sequence CCUGCUUUUG-CU at the 3’-end33,34.

The noncoding 3’-terminal region of segment 5 was chosen as a target for the designed nanocomposite. It should be noted that the choice of this target is very reasonable because, according to literature data, morpholino oligomer and siRNA addressed to this conservative region of NP gene showed the highest antiviral activity among the other morpholino oligomers34 and 20 siRNA molecules35. Oligonucleotide 3’GAAAAAGCGGTTAGATATCTp (DNA1) complementary to the chosen region was used in our work to construct nanocomposites. As a control, we used oligonucleotide 3’GATCAACTCCCATATGGCATGp (DNA2) with a random sequence.

**Antiviral activity of TiO2•PL-DNA nanocomposites.** At first, we tested the effect of TiO2 nanoparticles and TiO2•PL-DNA nanocomposite on viability of MDCK cells in the absence of virus. The concentration of samples resulting in 50% cell death (TC50) for TiO2 and TiO2•PL-DNA1 was estimated to be ~1800 μg/ml (Fig. 1). It should be noted that just nanoparticles are responsible for the effect, and PL-DNA conjugates are hardly involved in this action.

The nontoxic concentration of nanocomposites 5 μg/ml corresponding to 0.1 μM for oligonucleotides was used to study the antiviral activity of the proposed TiO2•PL-DNA nanocomposite. Nanocomposite TiO2•PL-DNA1 containing oligonucleotide directed to the 3’-noncoding regions of initial viral (-)RNA and various controls including samples bearing a random DNA2 sequence were assayed for the antiviral activity against human influenza A virus H3N2. MDCK cells were infected at a moi of 0.05 TCID50/cell. Transfection of cells with nanocomposites was carried out in the absence of serum. The nanocomposites and controls were incubated

![Figure 1](image-url)
with cells for 4 h prior to infection. The results are presented as log TCID<sub>50</sub>/ml in Fig. 2 and as TCID<sub>50</sub>/ml in Table 1.

The nanoparticles bearing no oligonucleotides were practically inactive independently on the presence or the absence of the PL residue (Fig. 2, columns 2 and 3). Unbound DNA<sub>1</sub> and DNA<sub>2</sub> fragments also showed very low antiviral activity (Fig. 2, columns 4 and 5; Table 1, row a). This is in agreement with literature data: phosphodiester oligodeoxynucleotides failed to inhibit replication of influenza A at concentration up to 80 μM<sup>36</sup>. The maximal antiviral efficacy (99.99% reduction of virus titer) demonstrated TiO<sub>2</sub>N PL-DNA<sub>1</sub> nanocomposite bearing complementary DNA<sub>1</sub> (Fig. 2, column 10; Table 1, row d): the virus titer was reduced by a factor of 8,000 (by about four orders of magnitude). PL-DNA<sub>1</sub> conjugate without nanoparticles showed significantly lower efficiency (by a factor of 740) than the same conjugate immobilized onto nanoparticles (compare columns 6 and 10 in Fig. 2 and rows b and d in Table 1). It should be noted that DNA<sub>1</sub> in TiO<sub>2</sub>N PL-DNA<sub>1</sub> nanocomposite demonstrated ~30-times higher antiviral activity than the same oligonucleotide in the presence of lipofectamine widely used as the transfection agent (compare columns 8 and 10 in Fig. 2 and rows c and d in Table 1). The antiviral activity of TiO<sub>2</sub>•PL-DNA nanocomposites bearing complementary and noncomplementary DNA fragments differed by a factor of about 3000 (compare columns 10 and 11 in Fig. 2 and cells 1d and 2d in Table 1).

All samples containing complementary fragment DNA<sub>1</sub> demonstrated the higher antiviral activity as compared to those bearing noncomplementary fragment DNA<sub>2</sub> (compare columns 6 and 7, 8 and 9, and 10 and 11 in Fig. 2 and columns 1 and 2, 3 and 4, and 5 and 6 in Table 1). We evaluated the ratio of the TCID<sub>50</sub>/ml values for these two types of nanocomposites (Table 1, column 7), which can be considered as a specificity factor indicating the antisense effect.

The results show that the specificity factor depends on the method of the delivery of the samples into cells. DNA<sub>1</sub> and DNA<sub>2</sub> without any transfection agent almost do not penetrate into the cells, and their antiviral activity is equally low. PL-DNA<sub>1</sub> and PL-DNA<sub>2</sub> penetrate into cells more efficiently, and the difference, although still low, is significantly higher than those observed for DNA<sub>1</sub>- and DNA<sub>2</sub>-containing samples.

Table 1 | Antiviral activity of studied DNA-containing samples

| row | Sample       | Virus titer, TCID<sub>50</sub>/ml | Reduction of virus titer, % | Reduction of virus titer, n-fold | Specificity factor<sup>a</sup> |
|-----|--------------|-----------------------------------|-----------------------------|----------------------------------|------------------------------|
|     |              | DNA<sub>1</sub> | DNA<sub>2</sub> | DNA<sub>1</sub> | DNA<sub>2</sub> | DNA<sub>1</sub> | DNA<sub>2</sub> |                                |
| a   | DNA          | 1,348,963 | 1,148,154 | 15 | 28 | 1 | 1.4 | 1 |
| b   | PL-DNA       | 147,911  | 794,328  | 90.7 | 50 | 11 | 2.0 | 5 |
| c   | DNA + lpf<sup>c</sup> | 6,310   | 793,349  | 99.6 | 50 | 251 | 2.0 | 130 |
| d   | TiO<sub>2</sub>•PL-DNA | 200     | 630,957  | 99.99 | 60 | 8,000 | 2.5 | 3,160 |
| e   | w/o sample   | 1,584,893 |              |                          |                              |                              |                            |

<sup>a</sup>Ratio of the TCID<sub>50</sub>/ml values for DNA<sub>2</sub>- and DNA<sub>1</sub>-containing samples.
<sup>b</sup>DNA<sub>1</sub> and DNA<sub>2</sub> are DNA fragments complementary and noncomplementary to viral RNA, respectively.
<sup>c</sup>Lipofectamine™ 2000.
between their antiviral actions is observed. When lipofectamine is used for transfection, complementary DNA becomes 130 times more efficient than noncomplementary DNA. The maximal difference (3160 times) was detected if DNA fragments were delivered into cells in TiO₂•PL-DNA₁ and TiO₂•PL-DNA₂ nanocomposites.

**Dose-response studies.** The dose-response effect of the TiO₂•PL-DNA₁ nanocomposite was studied in the pre-infection and post-infection assays. In the pre-infection treatment, MDCK cells were pretreated with the TiO₂•PL-DNA₁ sample for 4 h followed by infection with A/Aichi/2/68 virus at a multiplicity of infection (moi) of 0.1 TCID₅₀/cell for 1 h. After washing cells from the virus-containing medium and the subsequent incubation for 48 h, the virus titer was measured by the hemagglutination (HA) technique. In the post-infection treatment, MDCK cells were initially infected with influenza A virus for 1 h as above and washed, followed by incubation with TiO₂•PL-DNA₁ nanocomposite for 4 h. After 48 h incubation, the evaluation of virus titer was performed as in the previous case.

Concentrations of the nanocomposite causing 50% inhibition of viral production (IC₅₀) were evaluated to be ~1.5 μg/ml for the nanocomposite (~0.03 μM for DNA₁) in the pre-treatment or post-treatment assays (Fig. 3).

The data on cell viability and dose-response study allowed us to derive the selectivity index value, i.e. the ratio of TC₅₀ to IC₅₀ (SI ≈ 1200).

**Discussion**

The nucleic acids-based drugs are the foundation of a new medicine because they selectively recognize the complementary regions of nucleic acid targets and affect their functions in cells that allows for the inhibition of the expression of certain genes responsible for ailments without affecting host genes. As compared to low molecular weight pharmatheuticals, NA-based drugs have also other advantages such as simple design, easy preparation, high specificity, and low side effects.

However, NA-based drugs still have not found wide application in medical practice because of the low ability to penetrate into cells.

In the previous paper, we described new nanocomposites consisting of DNA-based drugs noncovalently fixed on inorganic nanoparticles used as transporters. Polylysine-containing DNA fragments were immobilized with a high efficiency onto titanium dioxide nanoparticle to give TiO₂•PL-DNA nanocomposites. We assumed that PL-DNA are immobilized onto TiO₂ nanoparticles due mainly to electrostatic interactions between negatively charged TiO₂ surface and positively charged amino groups of polylysine at physiological pH values (pH ≈ 7) (Fig. 4). The important role of electrostatic interactions in the binding of PL-DNA conjugates to titanium dioxide is confirmed by the fact that oligonucleotides without the PL linker are hardly immobilized onto TiO₂ nanoparticles, while the attachment significantly increases in the presence of cetyltrimethylammonium bromide, which masks the negative charge of the phosphate groups of oligomers (data not shown). The formed TiO₂•PL-DNA nanocomposites were shown by confocal microscopy to penetrate into mammalian cells without any transfection agents and physical impact.

Here we studied the next key stage of using NA-based drugs, namely, the interaction with target nucleic acids inside cells.

We examined TiO₂•PL-DNA nanocomposites bearing DNA fragment complementary to 3’-uncoding region of segment 5 of (-)RNA of influenza A virus (H3N2) for their antiviral activity (Fig. 2). This nanocomposite showed the high antiviral effect (99.99% inhibition of replication of virus) at a concentration of 0.1 μM for DNA₁ (Fig. 3).
comparison, the selectivity index for morpholino oligonucleotides by 1–1.2 log39. The same authors showed the similar antiviral effect of in the presence of lipofectamine led to the reduction of the virus titer infected with influenza A virus with phosphorothioate antisense nucleotides delivered into MDCK cells (TC50 to other DNA-containing samples.

The proposed nanocomposites appeared to be low toxic for MDCK cells (TC50 ≈ 1800 μg/ml), and at the working concentration of 5 μg/ml they were practically nontoxic (Fig. 1). It is important to note that it is the TiO2 nanoparticles that are responsible for the toxic action of nanocomposites, and DNA fragments do not contribute to this effect (Fig. 1). In opposite, the contribution of TiO2 nanoparticles in antiviral activity is very low, if at all. The IC50 Value (indicating 50% inhibition of viral replication) for the nanocomposite was evaluated from the data of dose-response study to be ~1.5 μg/ml (Fig. 3). These data allowed us to derive the selectivity index value, i.e. the ratio of TC50 to IC50 for the designed nanocomposite (SI ≈ 1200). In comparison, the selectivity index for morpholino oligonucleotides was estimated as ~409. High values of the selectivity index and the specificity factor indicate good prospects for using TiO2•PL-DNA nanocomposites in medical practice.

Some researchers studied the antiviral activity of oligonucleotides and their derivatives. Oligonucleotides with native phosphodiester bonds did not reveal antiviral activity at concentration, which were 270 times higher than we used30. Transfection of MDCK cells infected with influenza A virus with phosphorothioate antisense oligonucleotides aimed (4 μM) to different regions of the NP gene in the presence of lipofectamine led to the reduction of the virus titer by 1–1.2 log9. The same authors showed the similar antiviral effect of antisense oligonucleotides delivered into MDCK cells with the antibody delivery system29. In our case, the reduction of the virus titer achieves 3.9 log. A morpholino oligonucleotide with the same sequence as DNA, was also shown24 to be efficient against different strains of influenza A virus, although its efficiency was significantly lower than in our case (the inhibitory effect was 88–98% at 15 μM concentration). Moreover, morpholino oligonucleotides should be conjugated to an arginine-rich peptide to ensure the delivery into cells. The concentrations of morpholin or phosphorothioate oligonucleotides were higher by factors of 40–150, and their efficiency in the virus inhibition was significantly lower than in our case.

Short interference RNAs (siRNA) are under intense investigation as antiviral agents. After electroporation, NP-specific siRNA (5 μM) inhibited virus production by factors of 30,000 or 200 at a moi of 0.001 or 0.1, respectively22. Similar or even slight higher inhibitory effect showed siRNA directed to the M2 gene of influenza A virus15. The inhibitory effect of several NP-specific siRNAs on influenza A virus replication in MDCK cells transfected in the presence of lipofectamine was shown to be 0.8–1.6 log (6–43-fold reduction)12.

The antivirus efficiency of DNA fragments delivered into cells with the proposed TiO2•PL-DNA nanocomposites (~8,000-fold reduction of virus replication at 0.1 μM and 0.05 moi; 3.9 log of the inhibitory effect) is not inferior to (and even exceeds) that of siRNAs, which considered to be the most promising agents among nucleic acid drugs.

Thus, for the first time, we have shown the highly efficient and selective action on intracellular nucleic acid targets of antisense DNA fragments delivered into cells with TiO2 nanoparticles. The high inhibition of influenza A virus replication with the proposed nanocomposites shows their potency as antisense drugs. The proposed high-performance method for specific effect on nucleic acids in cells may find a wide application for the treatment of not only viral but also other nucleic acid-based diseases, when it is necessary to ensure effective and selective interaction of DNA with intracellular nucleic acid targets.

Methods

Chemicals were obtained from commercial suppliers. We used: PMI-1640 medium, antibiotics (Bio领取, Russia); trypsin (Sigma, USA); fetal calf serum (Gibco, USA); L-glutamate, PBS buffer, chicken erythrocytes, MDCK cells, and influenza A virus Aichi/2/68 (H3N2) (Vector, Russia); Lipofectamine™ 2000 (Invitrogen, USA). TiO2 nanoparticles in the crystal form (anatase, An) were synthesized as described in15. Oligonucleotides were synthesized by the phosphoroamidite method on AMO-800 DNA synthesizer (Bioset, Russia) using phosphoroamidite monomers (Glen Research, USA). Trypsin (1 μg/ml) and penicillin-streptomycin (100 U/ml) (SigmAldrich, USA) were stored at ~80°C.

The synthesis of polysilane-containing oligonucleotides (PL-DNA) and nanocomposites consisting of anatase nanoparticles and PL-DNA conjugates (AnPL-DNA) were fulfilled as described in13. The virus was grown in the allantoic cavity of 10-day-old embryonated chicken eggs (Vector, Russia) at 37°C. Allantoic fluid was harvested for 48 h after virus inoculation, aliquoted, and stored at ~80°C.

Cell viability assays. MDCK cells in logarithmic phase were seeded at 10000 cells/ml in RPMI-1640 nutrient medium in 96-well plates (100 μl/well) and incubated at 37°C and 5% CO2. Two days after the formation of a continuous monolayer, cells were treated with 3H-thymidine (200 μl/well) at the mentioned concentration. The samples of TiO2 nanoparticles or TiO2•PL-DNA nanocomposites were diluted with RPMI-1640 medium to the needed concentration (10–1000 μg/ml) and incubated with MDCK cells at 37°C and 5% CO2 for two days. Destructive changes in the cells were evaluated by an inverted microscope. MDCK cells without studied samples were used as a control. Cells were stained with trypan blue24, and the number of viable cells was counted in a Goryaev chamber. All experiments were performed in three independent series (Fig. 1).

Comparison of antiviral activity of samples (Preinfection assays). MDCK cells were seeded as above and incubated with samples under investigation (DNA, PL-DNA, DNA + Lipofectamine™ 2000, TiO2, TiO2•PL, and TiO2•PL-DNA) added in RPMI-1640 (100 μl/well) without trypsin. The final concentration was 0.1 μM for oligonucleotide in all DNA-containing samples and 5 μg/ml for nanoparticles and nanocomposites. Transfection of DNA with lipofectamine was performed according to the manufacturer’s protocol. Transfection experiments were carried out in the absence of serum. Cells were incubated at room temperature and 5% CO2, and 100% humidity for 4 h, followed by rinsing with RPMI-1640. Virus A/Aichi/2/68 (H3N2) was then added in each well (100 μl/well) at a multiplicity of infection (moi) of 0.05 TCID50/cell in a medium containing trypsin. After 1 h adsorption at room temperature, virus-containing media were removed; cells were rinsed with RPMI-1640 medium without trypsin, and the same medium containing trypsin was applied to each well (100 μl). Cells were incubated at 37°C and 5% CO2 and 100% humidity for 48 h. Samples of virus culture were collected and their measurements were performed by hemagglutination (HA) assays using round-bottom 96-well plates. Serial ten-fold dilutions of virus samples with RPMI-1640 medium containing 2 μg/ml trypsin were applied to MDCK cells for 18 h. The presence of virus was visually determined in HGR with a 1% suspension of chicken erythrocyte. The titer was evaluated by noting the highest dilution of the virus, which caused the hemagglutination reaction. Wells containing an adherent, homogenous layer of erythrocytes were scored as positive. MDCK infected by A/Aichi/2/68 (H3N2) virus without the treatment with nanocomposites were used as controls. Virus titer in cells treated with nanocomposites was expressed as log TCID50/ml, n = 6 (Fig. 2) and TCID50/ml (Table 1).

Dose-response studies. Preinfection assays. MDCK cells at ~80% confluence were incubated with the TiO2•PL-DNA nanocomposite taken in RPMI-1640 medium without trypsin (100 μl/well) at various concentrations (1, 2.5, 5, 10, 20, and 50 μg/ml). After 4 h incubation at 37°C and 5% CO2, and 100% humidity, preparations were removed; cells were rinsed with RPMI-1640 medium without trypsin. Virus A/Aichi/2/68 was then added in each well in RPMI-1640 medium (100 μl) containing trypsin (2 μg/ml) at a moi of 0.1 TCID50/cell. After 1 h adsorption at room temperature, virus-containing media were removed; cells were rinsed with RPMI-1640 medium without trypsin, and the same medium containing trypsin was applied to each well (100 μl). Cells were incubated at 37°C and 5% CO2 and 100% humidity for 48 h. The virus titers were evaluated as above.

Postinfection assays. MDCK cells at ~80% confluence were initially infected with A/Aichi/2/68 (H3N2) virus as described above. After 1 h adsorption at room temperature, virus-containing medium was removed, and cells were rinsed with RPMI-1640 medium without trypsin. Nanocomposite TiO2•PL-DNA taken in RPMI-1640 medium without trypsin was added (100 μl) to each well (100 μl). Incubation was continued for 3 days at 37°C and 5% CO2 and 100% humidity. Medium containing virus was collected, and its concentrations were determined by the endpoint dilution method. Cells were stained with trypan blue, and the number of viable cells was counted in a Goryaev chamber. All experiments were performed in three independent series (Fig. 1).
medium without trypsin (100 µl/well) at various concentrations (1, 2.5, 5, 10, 20, and 50 µg/ml) was applied to the infected MDCK cells, followed by the incubation for 4 h at 37°C and 5% CO2 and 100% humidity. The cultural media were then removed, cells were rinsed with RPMI-1640 medium without trypsin, and the same medium containing liquid from each well were applied to MDCK cells for 48 h to evaluate the virus titer. Results are presented in Fig. 3.

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