In vitro testing of Hydroxychloroquine and Azithromycin on SARS-CoV-2 shows synergistic effect

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Abstract

Human coronaviruses SARS-CoV-2 appeared at the end of 2019 and led to a pandemic with high morbidity and mortality. As there are currently no effective drugs targeting this virus, drug repurposing represents a short-term strategy to treat millions of infected patients at low costs. Hydroxychloroquine showed an antiviral effect *in vitro. In vivo* it also showed efficacy, especially when combined with azithromycin in a preliminary clinical trial. Here we demonstrate that the combination of hydroxychloroquine and azithromycin has a synergistic effect in vitro on SARS-CoV-2 at concentrations compatible with that obtained in human lung.

Background

Since the end of 2019, the world has encountered epidemic conditions attributable to a novel Coronavirus SARS-CoV 2 (*1-3*). This is the 7th Coronavirus identified to infect Human population (*1;4;5*) and the first one that had pandemic potential in non-immune populations in the 21st century (*6)*. Finding therapeutics is thus crucial, and it is proposed to do so by repurposing existing drugs (*7-9*). This strategy presents the advantages that safety profiles of such drugs are known and that they could be easily produced at relatively low cost, thus being quicker to deploy than new drugs or a vaccine. Chloroquine, a decades-old antimalarial agent, an analog of quinine, was known to inhibit the acidification of intracellular compartments (*10*) and has shown *in vitro* and *in vivo* (mice models) activity against different subtypes of Coronaviruses: SARS-CoV-1, MERS-CoV, HCoV-229E and HCoV-OC43 (*11-16*). In 2004 it was tested in vitro against SARS-CoV 1 (*17*) and caused a 99% reduction of viral replication after 3 days at 16 μM. Moreover, tests in vitro have shown inhibition of viral replication on SARS-CoV 2 detected by PCR and by CCK-8 assay (*18*). Hydroxychloroquine (hydroxychloroquine sulfate; 7-Chloro-4-[4-(N-ethyl-N-b-hydroxyethylamino)-1-methylbutylamino]quinoline sulfate) has shown activity against SARS-CoV2 in vitro and exhibited a less toxic profile (*19*). This drug is well known and currently used mostly to treat autoimmune diseases and also by our team to treat Q fever disease (*20;21*) and Whipple's disease (*22;23*). In those clinical contexts, concentrations obtained in serum are close to 0.4-1 μg/mL at the dose of 600 mg per day over several months (*24*). Clinical tests of chloroquine and hydroxychloroquine to treat COVID-19 are underway in China (*25*), with such trials using hydroxychloroquine in progress in the US (ClinicalTrials.gov Identifier: NCT04307693) and in Europe with the Discovery Trial. In this drug repurposing effort, antibacterial components have also been tested. Teicoplanin, a glycopeptide, was demonstrated in vitro to inhibit cellular penetration of Ebola virus (26) and SARS-CoV 2

(*27*). Azithromycin (azithromycin dehydrate), a macrolide, N-Methyl-11-aza-10-deoxo-10-dihydroerythromycin A, has shown antiviral activity against Zika (*28-30*) . Azithromycin is a well-known and safe drug, widely prescribed in the US, for example, with 12 million treatment courses in children under 19 years of age alone. (*31*). A recent study has identified these two compounds (azithromycin and hydroxychloroquine) among 97 total potentially active agents as possible treatments for this disease (*32*).

In a preliminary clinical study, hydroxychloroquine and, with even greater potency, the combination of hydroxychloroquine and azithromycin were found effective in reducing the SARS-CoV-2 viral load in COVID-19 patients (*33*). Since the beginning of the epidemic in the Marseille region we isolated numerous strains and we tested one of them, the SARS-CoV-2 IHUMI-3, using different concentrations of hydroxychloroquine and azithromycin, alone and in combination, with Vero E6 cells.

Materials and Methods

Viral isolation procedure and viral stock

The procedure of viral isolation of our SARS-Cov 2 strain IHUMI-3 was detailed elsewhere (33). The viral production was done in 75 cm^2 cell culture flask containing Vero E6 cells (American type culture collection ATCC® CRL-1586™) in MEM with 4% of fetal bovine serum and 1% glutamine. Cytopathic effect was monitored daily under an inverted microscope (Figure 1). After nearly complete cell lysis (approximately 96 hours), viral supernatant was used for inoculation on 96-wells plate.

Testing procedure for drugs

Briefly, we prepared 96-well plates with 5.10^5 cells/mL of Vero E6 (200µL per well), using Minimum Essential Media (Gibco, ThermoFischer) with 4% of fetal bovine serum and 1% glutamine. Plates were incubated overnight at 37°C in a CO_2 atmosphere. Drug concentrations tested were 1, 2 and 5 µM for hydroxychloroquine and 2, 5 and 10 µM for azithromycin. We

also tested combinations of these agents at these concentrations, each test done at least in triplicate. Four hours before infection, cell culture supernatant was removed and replaced by drugs diluted in the culture medium. At t=0, virus suspension in culture medium was added to all wells except in negative controls where 50µL of the medium was added. We tested different multiplicities of infection (MOI) at 2.5 and at 0.25. RT-PCR was done 30 minutes post-infection in one plate and again at 60 hours post-infection on a second plate. For this, 100 µL from each well was collected and added to 100 µL of the ready-use VXL buffer from QIAcube kit (Qiagen, Germany). The extraction was done using the manual High Pure RNA Isolation Kit (Roche Life Science), following the recommended procedures. The RT-PCR was done using the Roche RealTime PCR Ready RNA Virus Master Kit. The primers were designed against the E gene using the protocol of Amrane et al. (*34*) in the Roche LightCycler® 480 Instrument II.

Results

No cytotoxicity was associated with drugs alone or in combination in controls wells (without viruses). We detected RNA viral production from 24 to 16 cycle-thresholds (Ct, inversely correlated with RNA copy numbers) for the positive control that was associated with cell lysis. In all cases, cell lysis at 60 hours was correlated with viral production as compared to control (Figure 2). At low MOI, azithromycin or hydroxychloroquine alone had no or low impact on the viral production compared to the positive control. We observed only a moderate effect for hydroxychloroquine at 5 µM in 2 of the 3 replicates (Figure 2a). For the combination of azithromycin and hydroxychloroquine, we observed inhibition of viral replication for wells containing hydroxychloroquine at 5 µM in combination with azithromycin at 10 and 5 µM (Figure 2b). Moreover, no cytopathic effect was observed at 60 hours post infection in these wells (Figure 3). At high MOI, neither drug showed any effect.

The unique observed effect was with the combination of hydroxychloroquine at 2 μM and azithromycin at 10 μM, leading to total inhibition of viralreplication.

Discussion

In this present work, we could confirm a moderate effect of hydroxychloroquine alone on SARS-CoV2 at low MOI as previously observed with the lowest concentrations used in a prior study (*19*). The most striking observation was the synergistic effect of the combination of hydroxychloroquine and azithromycin. As compared to other studies testing hydroxychloroquine for which viral growth was evaluated at 48h, our conditions with prolonged incubation time of 60 hours showed that this effect remained observable. As for MOI, even at the higher MOI of 2.5, as compared to the data of Liu et al. where the highest MOI was of 0.8, the effect of the combination to inhibit viral growth was observable. Hydroxychloroquine has been demonstrated in vitro to inhibit replication of SARS-CoVs 1 and 2 (*17;19*). Concentrations of drugs for our study were based on the known cytotoxicity drugs (50% of cytotoxicity, EC 50) and their effect on microorganisms (50% inhibitory concentration, IC50). With Zika virus, azithromycin showed activity with an IC 50 range from 2.1 to 5.1 μM depending MOI (28) without notable effect on EC 50 at high concentration (*29)*. On Vero E6 it was shown that for hydroxychloroquine, EC 50 is close to 250 μM (249.50 μM), which is significantly above the concentrations we tested herein (*19*). Against SARS-CoV 2, the IC 50 of hydroxychloroquine was determined to be 4.51, 4.06, 17.31, and 12.96 μM with various MOI of 0.01, 0.02, 0.2, and 0.8, respectively.

One of the main criticisms of previously published data was that drug concentrations for viral inhibitionused in vitro are difficult to translate clinically due to side effects that would occur at those concentrations. The synergy between azithromycin and hydroxychloroquine that we observed herein is at concentrations achieved in vivo and detected in pulmonary tissues (*35*-

37). Our data are thus in agreement with the clinical efficacy of the combination of hydroxychloroquineand azithromycin demonstrated by Gautret et al. (*33*). They support the clinical use of this drug combination, especially at the early stage of the COVID-19 infection before the patients have respiratory distress syndrome with associated cytokine storm and become less treatable by any antiviral treatment.

Figure 1: Observations of infected Vero E6 Monolayer.

Observation was done 48 hours post infection by the SARS-CoV 2 strain IHUMI-3. Magnitude X400. The picture was captured on ZEISS AxioCam ERC 5s.

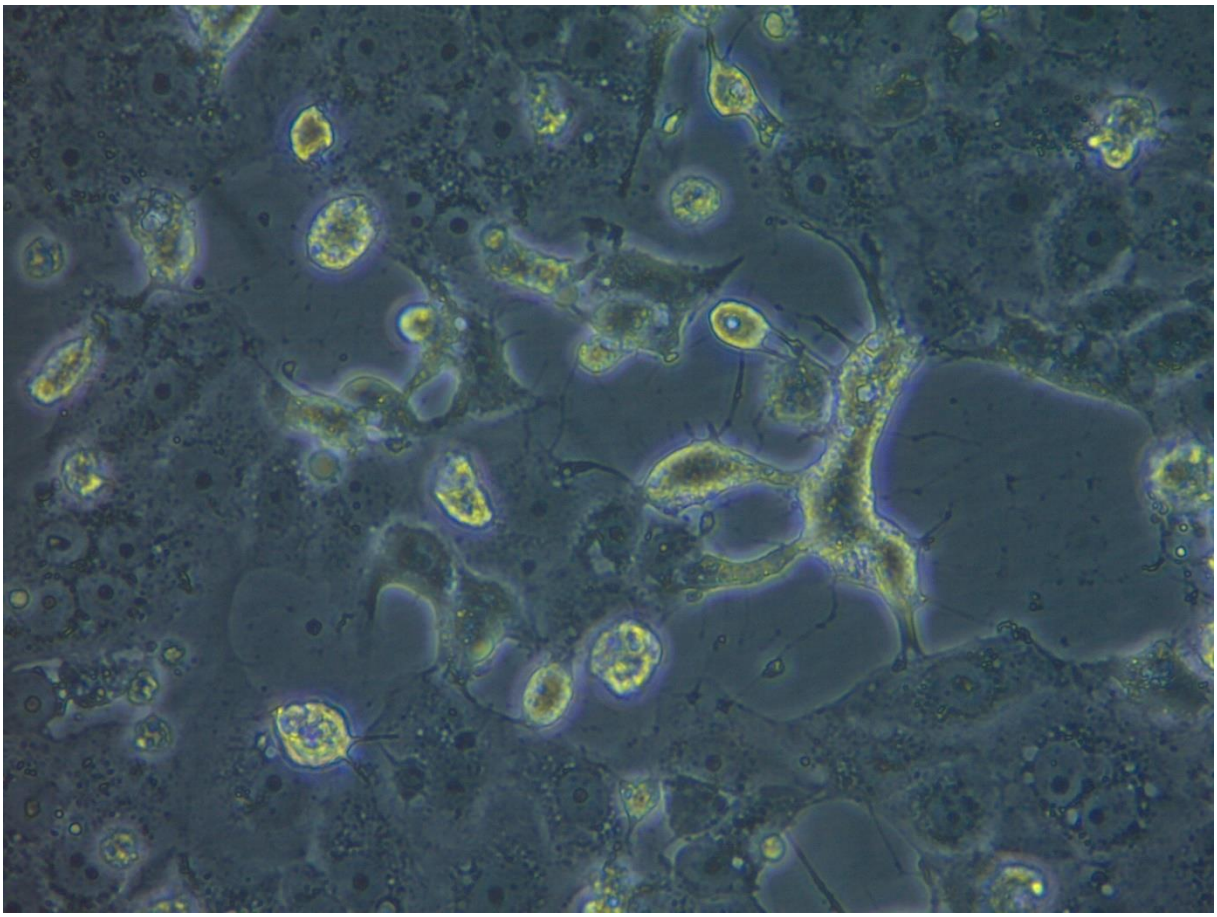


Figure 2: RNA viral quantification between 0 and 60 hours post infection.

For each condition, the first histogram represents average RNA cycle-thresholds quantification at H0, and the second histogram represents average RNA viral quantification 60 hours post-infection. Standard deviation scales are present for each condition (n=3 for all conditions and n=4 for the positive control).

2A. represents molecules tested alone, A10 is for azithromycin at 10 µM, A5 at 5 µM, A2 is at 2 µM, H5 is for hydroxychloroquine at 5 µM, H2 for 2 µM, H1 for 1 µM. **2B**. represents the combination of molecules tested.

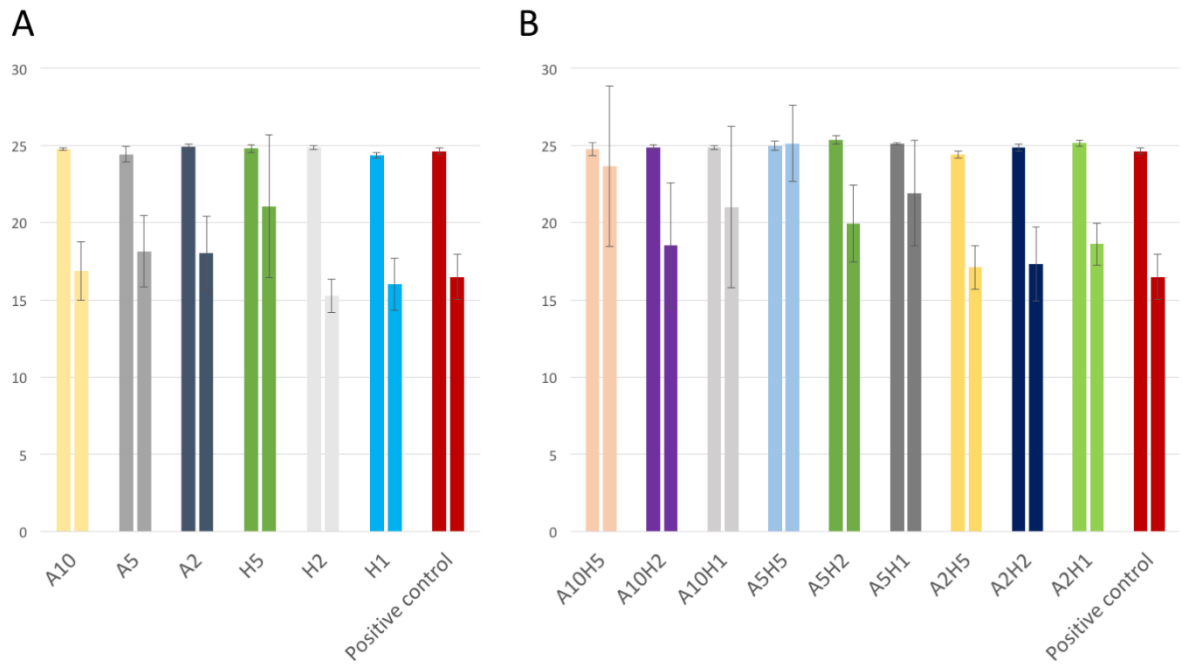
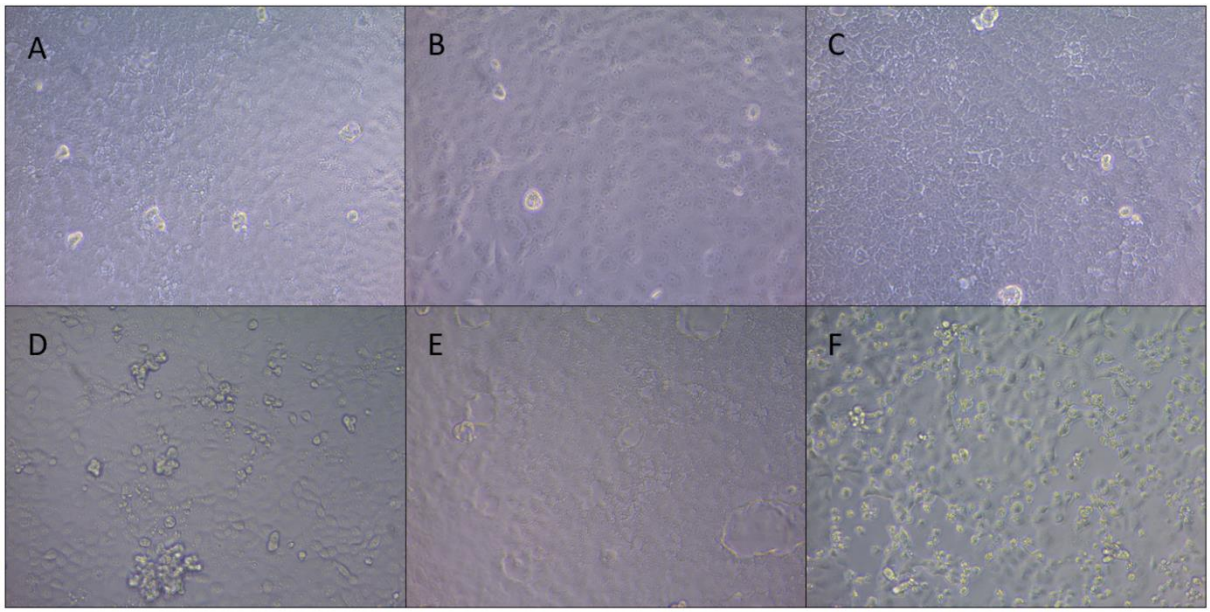


Figure 3: Observations of infected cells resistant or not to viral replication.

Picture were captured on ZEISS AxioCam ERC 5s, 58 hours post infection by the SARS-CoV 2 strain IHUMI-3. Magnitude X200. **3A-B-C.** overview of the monolayer in each well for the condition of Azithromycin 5 µM associated with hydroxychloroquine at 5 µM, **3D.** shows a cytopathic effect observed in one well in the condition Azithromycin 10 µM combined with hydroxychloroquine at 2 µM **3E.** negative control well and **3F.** positive control well.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Conflicts of Interest:

The authors declare no conflict of interest.

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References

(1) Zhu N, Zhang D, Wang W, Li X, Yang B, Song J, et al. A Novel Coronavirus from Patients with Pneumonia in China, 2019. N Engl J Med. 2020 Feb 20;382(8):727-33.

(2) Guan WJ, Ni ZY, Hu Y, Liang WH, Ou CQ, He JX, et al. Clinical Characteristics of Coronavirus Disease 2019 in China. N Engl J Med. 2020 Feb 28.

(3) Rothe C, Schunk M, Sothmann P, Bretzel G, Froeschl G, Wallrauch C, et al. Transmission of 2019-nCoV Infection from an Asymptomatic Contact in Germany. N Engl J Med. 2020 Mar 5;382(10):970-1.

(4) Zaki AM, van BS, Bestebroer TM, Osterhaus AD, Fouchier RA. Isolation of a novel coronavirus from a man with pneumonia in Saudi Arabia. N Engl J Med. 2012 Nov 8;367(19):1814-20.

(5) Vabret A, Dina J, Gouarin S, Petitjean J, Tripey V, Brouard J, et al. Human (non-severe acute respiratory syndrome) coronavirus infections in hospitalised children in France. J Paediatr Child Health. 2008 Apr;44(4):176-81.

(6) Morens DM, Folkers GK, Fauci AS. What is a pandemic? J Infect Dis. 2009 Oct 1;200(7):1018-21.

(7) Kruse RL. Therapeutic strategies in an outbreak scenario to treat the novel coronavirus originating in Wuhan, China. F1000Res. 2020;9:72.

(8) Lai CC, Shih TP, Ko WC, Tang HJ, Hsueh PR. Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and coronavirus disease-2019 (COVID-19): The epidemic and the challenges. Int J Antimicrob Agents. 2020 Mar;55(3):105924.

(9) Colson P, Rolain JM, Lagier JC, Brouqui P, Raoult D. Chloroquine and hydroxychloroquine as available weapons to fight COVID-19. Int J Antimicrob Agents. 2020 Mar 4;105932.

(10) Ohkuma S, Poole B. Fluoresence probe measurement of the intralysosomal pH in living cells and the perturbation of pH various agents. Proc Natl Acad Sci USA. 1978;75:3327-31.

(11) Keyaerts E, Li S, Vijgen L, Rysman E, Verbeeck J, Van RM, et al. Antiviral activity of chloroquine against human coronavirus OC43 infection in newborn mice. Antimicrob Agents Chemother. 2009 Aug;53(8):3416-21.

(12) Vincent MJ, Bergeron E, Benjannet S, Erickson BR, Rollin PE, Ksiazek TG, et al. Chloroquine is a potent inhibitor of SARS coronavirus infection and spread. Virol J. 2005 Aug 22;2:69.

(13) Savarino A, Boelaert JR, Cassone A, Majori G, Cauda R. Effects of chloroquine on viral infections: an old drug against today's diseases? Lancet Infect Dis. 2003 Nov;3(11):722-7.

(14) de Wilde AH, Jochmans D, Posthuma CC, Zevenhoven-Dobbe JC, van NS, Bestebroer TM, et al. Screening of an FDA-approved compound library identifies four small-molecule inhibitors of Middle East respiratory syndrome coronavirus replication in cell culture. Antimicrob Agents Chemother. 2014 Aug;58(8):4875-84.

(15) Kono M, Tatsumi K, Imai AM, Saito K, Kuriyama T, Shirasawa H. Inhibition of human coronavirus 229E infection in human epithelial lung cells (L132) by chloroquine: involvement of p38 MAPK and ERK. Antiviral Res. 2008 Feb;77(2):150-2.

(16) Devaux CA, Rolain JM, Colson P, Raoult D. New insights on the antiviral effects of chloroquine against coronavirus: what to expect for COVID-19? Int J Antimicrob Agents. 2020 Mar 11;105938.

(17) Keyaerts E, Vijgen L, Maes P, Neyts J, Van RM. In vitro inhibition of severe acute respiratory syndrome coronavirus by chloroquine. Biochem Biophys Res Commun. 2004 Oct 8;323(1):264-8.

(18) Wang M, Cao R, Zhang L, Yang X, Liu J, Xu M, et al. Remdesivir and chloroquine effectively inhibit the recently emerged novel coronavirus (2019-nCoV) in vitro. Cell Res. 2020 Mar;30(3):269-71.

(19) Liu J, Cao R, Xu M, Wang X, Zhang H, Hu H, et al. Hydroxychloroquine, a less toxic derivative of chloroquine, is effective in inhibiting SARS-CoV-2 infection in vitro. Cell Discov. 2020;6:16.

(20) Raoult D, Houpikian P, Tissot-Dupont H, RISS JM, Arditi-Djiane J, Brouqui P. Treatment of Q fever endocarditis : comparison of two regimens containing doxycycline and ofloxacin or hydroxychloroquine. Arch Intern Med. 1999;159(2):167-73.

(21) Raoult D, Drancourt M, Vestris G. Bactericidal effect of Doxycycline associated with lysosomotropic agents on *Coxiella burnetii* in P388D1 cells. Antimicrob Agents Chemother. 1990;34:1512-4.

(22) Boulos A, Rolain JM, Raoult D. Antibiotic susceptibility of *Tropheryma whipplei* in MRC5 cells. Antimicrob Agent Chemother. 2004;48(3):747-52.

(23) Fenollar F, Puechal X, Raoult D. Whipple's disease. N Engl J Med. 2007 Jan 4;356(1):55-66.

(24) Armstrong N, Richez M, Raoult D, Chabriere E. Simultaneous UHPLC-UV analysis of hydroxychloroquine, minocycline and doxycycline from serum samples for the therapeutic drug monitoring of Q fever and Whipple's disease. J Chromatogr B Analyt Technol Biomed Life Sci. 2017 Aug 15;1060:166-72.

(25) Gao J, Tian Z, Yang X. Breakthrough: Chloroquine phosphate has shown apparent efficacy in treatment of COVID-19 associated pneumonia in clinical studies. Biosci Trends. 2020 Feb 19.

(26) Wang Y, Cui R, Li G, Gao Q, Yuan S, Altmeyer R, et al. Teicoplanin inhibits Ebola pseudovirus infection in cell culture. Antiviral Res. 2016 Jan;125:1-7.

(27) Zhang J, Ma X, Yu F, Liu J, Zou F, Pan T, et al. Teicoplanin potently blocks the cell entry of 2019-nCoV. bioRxiv 2020;https://doi.org/10.1101/2020.02.05.935387.

(28) Retallack H, Di LE, Arias C, Knopp KA, Laurie MT, Sandoval-Espinosa C, et al. Zika virus cell tropism in the developing human brain and inhibition by azithromycin. Proc Natl Acad Sci U S A. 2016 Dec 13;113(50):14408-13.

(29) Bosseboeuf E, Aubry M, Nhan T, de Pina JJ, Rolain JM, Raoult D, et al. Azithromycin Inhibits the Replication of Zika Virus. J Antivir Antiretrovir. 2018;10(1):6-11.

(30) Li C, Zu S, Deng YQ, Li D, Parvatiyar K, Quanquin N, et al. Azithromycin Protects against Zika virus Infection by Upregulating virus-induced Type I and III Interferon Responses. Antimicrob Agents Chemother. 2019 Sep 16.

(31) Fleming-Dutra KE, Demirjian A, Bartoces M, Roberts RM, Taylor TH, Jr., Hicks LA. Variations in Antibiotic and Azithromycin Prescribing for Children by Geography and Specialty-United States, 2013. Pediatr Infect Dis. J 2018 Jan;37(1):52-8.

(32) Nabirothckin S, Peluffo AE, Bouaziz J, Cohen D. Focusing on the Unfolded Protein Response and Autophagy Related Pathways to Reposition Common Approved Drugs against COVID-19. Preprints 2020;doi: 10.20944/preprints202003.0302.v1.

(33) Gautret P, Lagier JC, Parola P, Hoang VT, Meddeb L, Mailhe M, et al. Hydroxychloroquine and azithromycin as a treatment of COVID-19: results of an open-label non-randomized clinical trial. Int J Antimicrob Agents. 2020 Mar 20;105949.

(34) Amrane S, Tissot-Dupont H, Doudier B, Eldin C, Hocquart M, Mailhe M, et al. Rapid viral diagnosis and ambulatory management of suspected COVID-19 cases presenting at the infections diseases referral hospital in Marseille, France, -January 31st to March 1st, 2020: A respiratory virus snapshot. Travel Med Infect Dis. 2020;in press.

(35) Laaksonen AL, Koskiahde V, Juva K. Dosage of antimalarial drugs for children with juvenile rheumatoid arthritis and systemic lupus erythematosus. A clinical study with determination of serum concentrations of chloroquine and hydroxychloroquine. Scand J Rheumatol. 1974;3(2):103-8.

(36) Olsen KM, San PG, Gann LP, Gubbins PO, Halinski DM, Campbell GD, Jr. Intrapulmonary pharmacokinetics of azithromycin in healthy volunteers given five oral doses. Antimicrob Agents Chemother. 1996 Nov;40(11):2582-5.

(37) Baldwin DR, Wise R, Andrews JM, Ashby JP, Honeybourne D. Azithromycin concentrations at the sites of pulmonary infection. Eur Respir J. 1990 Sep;3(8):886-90.

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