Live attenuated influenza vaccine provides superior protection from heterologous infection in pigs with maternal antibodies without inducing vaccine associated enhanced respiratory disease

Amy L. Vincent, Wenjun Ma, Kelly M. Lager, Jürgen A. Richt, Bruce H. Janke, Matthew R. Sandbulte, Philip Gauger, Crystal L. Loving, Richard J. Webby, and Adolfo García-Sastre

Published Version Information

Citation: Vincent, A. L., Ma, W., Lager, K. M., Richt, J. A., Janke, B, H., Sandbulte, M. R., . . . García-Sastre, A. (2012). Live attenuated influenza vaccine provides superior protection from heterologous infection in pigs with maternal antibodies without inducing vaccine-associated enhanced respiratory disease. Journal of Virology, 86(19), 10597-10605.

Digital Object Identifier (DOI): doi:10.1128/JVI.01439-12

Publisher's Link: http://jvi.asm.org/content/86/19/10597.abstract

Live attenuated influenza vaccine provides superior protection from heterologous infection in pigs with maternal antibodies without inducing vaccine associated enhanced respiratory disease

Running title: Vaccine efficacy in pigs with maternal immunity

Amy L. Vincent,[1,*] Wenjun Ma,[1,2,#] Kelly M. Lager,[1] Jürgen A. Richt,[1,#] Bruce H. Janke,[2] Matthew R. Sandbulte,[3] Philip Gauger,[1,2] Crystal L. Loving,[1] Richard J. Webby,[4] and Adolfo García-Sastre[5,6,7]

[1]Virus and Prion Diseases of Livestock Research Unit, National Animal Disease Center, USDA, Agricultural Research Service, Ames, Iowa 50010; [2]Department of Veterinary Diagnostic and Production Animal Medicine and [3]Department of Veterinary Microbiology and Preventive Medicine, Iowa State University, Ames, Iowa 50011; [4]Division of Virology, St. Jude Children's Research Hospital, Memphis, Tennessee 38105; [5]Department of Microbiology, [6]Department of Medicine, Division of Infectious Diseases, and [7]Global Health and Emerging Pathogens Institute, Mount Sinai School of Medicine, New York, New York 10029

*Corresponding author. Mailing address: National Animal Disease Center, PO Box 70, Ames, IA 50010, USA. Phone: (515) 663-7371. Fax: (515) 663-7458. E-mail: amy.vincent@ars.usda.gov

[#]Current address: Department of Diagnostic Medicine/Pathobiology, Kansas State University, Manhattan, KS, USA

Abstract

Control of swine influenza A virus (IAV) in the US is hindered since inactivated vaccines do not provide robust cross-protection against the multiple antigenic variants co-circulating in the field. Vaccine efficacy can be further limited when administered to young pigs that possess maternally derived immunity. We previously demonstrated a recombinant A/sw/Texas/4199-2/1998 (TX98) (H3N2) expressing a truncated NS1 protein is attenuated in swine and has potential for use as an intranasal live attenuated influenza virus (LAIV) vaccine. In the present study, we compared 1 dose of intranasal LAIV with 2 intramuscular doses of TX98 whole inactivated virus (WIV) with adjuvant in weanling pigs with and without TX98-specific maternally-derived antibodies (MDA). Pigs were subsequently challenged with wild type homologous TX98 H3N2 virus or with an antigenic variant A/sw/Colorado/23619/1999 (CO99) (H3N2). In the absence of MDA, both vaccines protected against homologous TX98 and heterologous CO99 shedding, although the LAIV elicited lower hemagglutination inhibiting (HI) antibody titers in serum. The efficacy of both vaccines was reduced by the presence of MDA; however, WIV vaccination of MDA-positive pigs led to dramatically enhanced pneumonia following heterologous challenge, a phenomenon known as vaccine-associated enhanced respiratory disease (VAERD). A single-dose of LAIV to MDA-positive pigs still provided partial protection from CO99 and may be a safer vaccine for young pigs in field conditions where dams are routinely vaccinated and diverse IAV strains are in circulation. These results have implications not only to pigs but to other influenza virus host species.

Introduction

The speed and complexity of swine influenza A virus (IAV) evolution has sharply increased since 1998, when a new reassortant lineage with the "triple reassortant internal gene" (TRIG) constellation of internal genes began to circulate and eventually predominate in the North American pig population (29). As a result, many antigenic variants continue to emerge and diminish the field efficacy of IAV vaccines (11, 16, 27). Fully licensed influenza vaccines for use in swine in North America and Europe consist of whole inactivated virus, which may not be an optimal form of antigen for inducing cross-reactive cellular and mucosal immunity against antigenic variants (12). Live attenuated influenza virus (LAIV) vaccines represent an approach that could potentially prime pigs for broader cross-protective immunity. Rational design of attenuated IAV vaccine strains by molecular engineering has been explored in recent studies (14, 18, 23). One method is truncation of the NS1 gene, which encodes an immune modulating interferon antagonist (23, 24). It was previously shown that an H3N2 IAV with a truncated NS1 (NS1Δ126 TX98) replicated poorly in pigs after intranasal inoculation, but elicited neutralizing serum antibodies as well as mucosal antibodies and provided robust protection against homologous challenge in naïve pigs with a single intranasal application (26). There was a comparable level of cross-protection against a serologically distinct H3N2 strain in NS1Δ126 TX98-vaccinated pigs, which was likely mediated in part by cross-reactive mucosal IgA. The vaccine offered less but still substantial protection against challenge with an H1N1 virus, to which the antibodies failed to cross-react. T-cell priming was not analyzed, but may have contributed to heterologous and heterosubtypic protection. We hypothesize that replicating attenuated virus delivered intranasally (IN), such as NS1Δ126 TX98, primes a more robust

64 cellular and mucosal immunity than an inactivated virus vaccine delivered intramuscularly (IM),
65 therefore providing greater cross-protection against variant strains.

66 A concern with inactivated adjuvanted IAV vaccines is the phenomenon of vaccine-
67 associated enhanced respiratory disease (VAERD) (4, 5, 8, 25). This phenomenon is associated
68 with the use of vaccines containing a virus of the same HA subtype as the subsequent challenge
69 strain, but with substantial antigenic drift. Our group recently described VAERD in association
70 with the use of a vaccine containing a human-like delta cluster H1N2 antigen followed by
71 challenge with 2009 pandemic H1N1 (5). A consistent predisposing factor for VAERD is the
72 presence of IgG antibodies that cross-react to the heterologous virus but lack the ability to
73 neutralize infectivity. Distinguishing pathologic features of VAERD include severe
74 bronchointerstitial pneumonia with necrotizing bronchiolitis, interlobular and alveolar edema
75 and hemorrhage (4). These pulmonary changes were accompanied by significant elevation of
76 proinflammatory cytokines.

77 Another obstacle for efficacious vaccination of pigs against IAV is interference from
78 maternally-derived immunity (MDI), particularly maternally-derived antibodies (MDA), acquired
79 through colostrum. Provided there are still sufficient antibody titers in the serum when pigs are
80 infected, MDA can reduce clinical disease (21), but the passive antibodies are less effective in
81 blocking viral shedding from the upper respiratory tract (2, 10), probably because the
82 predominant antibody isotype received in colostrum is IgG. Pigs with significant IAV-specific
83 MDA titers typically have suppressed adaptive antibody responses to homologous infection or
84 vaccination (21). This interference affects IgM, IgG, and hemagglutination inhibition (HI)
85 antibody titers in serum, as well as nasal IgA (10). T-cell proliferation assays have indicated that

the cellular immune response to IAV is less susceptible to MDA inhibition (8, 10). Analyses of pigs' immune responses to pseudorabies virus, an alpha herpesvirus, have shown a similar pattern, where MDA blocks the humoral but not the cellular immune response following piglet vaccination or infection (19, 28). One perceived advantage of vaccination with LAIV is that circulating MDA (mainly IgG) is less likely to interfere with intranasally-delivered antigen than with inactivated antigen delivered by a parenteral route. In the present study we tested the immunogenicity and protective efficacy of intranasal NS1Δ126 TX98 vaccine versus an inactivated, adjuvanted TX98 administered intramuscularly. These vaccine strategies were tested in naïve and MDA-positive weanling pigs subsequently challenged with homologous or heterologous strains of H3N2 IAV.

Methods

Viruses and vaccine preparation

Antigen for the whole inactivated virus (WIV) vaccine was A/sw/Texas/4199-2/1998 (wt TX98), grown in Madin-Darby canine kidney (MDCK) cells. Clarified virus from infected culture was inactivated by UV irradiation, using the sterilize setting in an ultraviolet cross-linking chamber (GS Gene Linker, Bio-Rad, Hercules, CA). Inactivation of the virus was confirmed by failure to replicate in 2 serial passages on MDCK cells. A commercial adjuvant was added at a 1:5 ratio (Emulsigen D, MVP Laboratories, Inc., Ralston, NE). Each dose of WIV contained approximately 128 HA units of virus. Attenuated virus for the LAIV was generated via reverse genetics as previously described (24). The attenuated vaccine virus contained an NS1 gene with a 3' premature termination plus the insertion of four stop codons in the three frames after, producing a protein 126 amino acids in length with a carboxy-terminal truncation (TX98-

NS1Δ126). The remaining seven gene segments were from wild type TX98. The challenge viruses included wild-type TX98 H3N2 and a heterologous A/SW/CO/23619/99 H3N2 (CO99). The TX98 and CO99 were shown previously to have limited serologic cross-reactivity (22). Vaccine and challenge viruses were grown in MDCK cells.

Experimental design

Eight sows obtained from a high-health herd free of IAV and porcine reproductive and respiratory syndrome virus (PRRSV) were vaccinated with the TX98 WIV. Each vaccinated sow received 3 doses at 2 week intervals beginning in mid-gestation. Six sows from the same high-health source were not vaccinated for IAV. All sows delivered their pigs without surgical intervention and pigs suckled their own dams. Pigs were bled for evaluation of transfer of MDA at 1 week of age and were weaned at 2 weeks of age. They were treated with ceftiofur crystalline free acid (Pfizer, New York, NY) at weaning to reduce respiratory bacterial contaminants. Pigs were demonstrated to be free of influenza virus by nasal swab sampling, and those born to non-vaccinated sows were shown by serum HI assay to be free of anti-influenza antibody prior to piglet vaccination.

To evaluate both vaccines when given in the presence or absence of H3N2 IAV-specific MDA, 51 pigs with MDA were divided into 7 groups and 52 pigs without MDA were divided into 7 groups (Table 1). Pigs in the LAIV groups were vaccinated with 2 mL of TX98-NS1Δ126 at 1 X 10^6 50% tissue culture infective doses ($TCID_{50}$) per ml by slowly dripping vaccine in the nose. LAIV was administered once at weaning, approximately 14 days of age. Pigs in the WIV groups were vaccinated intramuscularly with 1 ml of the formulation described above, at approximately 14 and 28 days of age. At 8 weeks of age non-vaccinated pigs with MDA were

130 determined to have HI titers below 1:40, indicating waning of MDA prior to challenge. Pigs in
131 each challenge group were inoculated with 2 ml (1 X 10^5 $TCID_{50}$/ml) of the indicated virus.
132 Challenge viruses were given intratracheally while the pigs were anesthetized following an
133 intramuscular injection of a cocktail of ketamine (8 mg/kg), xylazine (4 mg/kg), and Telazol (6
134 mg/kg, Fort Dodge Animal Health, Fort Dodge, IA). Challenge groups were housed in individual
135 isolation rooms and cared for in compliance with the Institutional Animal Care and Use
136 Committee of the National Animal Disease Center.

137 ***Clinical observation and sampling***

138 To compare the efficacies of WIV and LAIV against infection with homologous and heterologous
139 viruses, infected pigs were observed daily for clinical signs. Nasal swabs were taken on 0, 3, and
140 5 days post-infection (dpi), placed in 2 ml minimal essential media (MEM) and frozen at -80^{o}C
141 until study completion. All animals were humanely euthanized 5 dpi with a lethal dose of
142 pentobarbital (Sleepaway, Fort Dodge Animal Health, Fort Dodge, IA). After euthanasia, each
143 lung was lavaged with 50 ml MEM to obtain bronchoalveolar lavage fluid (BALF). Nasal swab
144 specimens were filtered (0.45 mm), and a 200 µl aliquot of each was plated onto confluent
145 phosphate buffered saline (PBS) washed MDCK cells in 24-well plates. After 1 hour incubation
146 at 37^{o}C, 200 µl serum-free MEM supplemented with 1 µg/ml TPCK trypsin and antibiotics was
147 added per well. All wells were evaluated for cytopathic effect (CPE) between 48-72 hours. Ten-
148 fold serial dilutions in serum-free MEM supplemented with TPCK trypsin and antibiotics were
149 made with each BALF sample and virus isolation positive nasal swab filtrate sample. Each
150 dilution was plated in triplicate in 100 µl volumes onto PBS-washed confluent MDCK cells in 96-
151 well plates. Plates were evaluated for CPE between 48-72 hours post infection. At 72 hours,

plates were fixed with 4% phosphate-buffered formalin and stained using immunocytochemistry with an anti-influenza A nucleoprotein monoclonal antibody as previously described (8). A $TCID_{50}$ titer was calculated for each sample using the standard method (20).

Pathologic examination of lungs

At necropsy, lungs were removed and evaluated for the percentage of the lung affected with purple-red consolidation typical of IAV infection. The percentage of the surface affected with pneumonia was visually estimated for each lung lobe, and a total percentage for the entire lung was calculated based on weighted proportions of each lobe to the total lung volume (6). Tissue samples from the trachea and right middle or affected lung lobe were fixed in 10% buffered formalin for histopathologic examination. Tissues were processed by routine histopathologic procedures and slides stained with hematoxylin and eosin. Microscopic lesions were evaluated by a veterinary pathologist blinded to treatment groups. Individual scores were assigned to each of three parameters: percent of intrapulmonary airways demonstrating epithelial necrosis or proliferation, percent of bronchi and bronchioles demonstrating peribronchiolar lymphocytic cuffing (PBLC) and magnitude of neutrophil exudation in bronchioles and alveoli. The intrapulmonary airway epithelium was scored according to the following criteria: (0.0) no significant lesions; (1.0) a few airways affected with bronchiolar epithelial damage; (1.5) more than a few airways affected (up to 25%); (2.0) 50% airways affected often with interstitial pneumonia; (2.5) approximately 75% airways affected, usually with significant interstitial pneumonia; (3.0) greater than 75% airways affected, usually with significant interstitial pneumonia. Peribronchiolar lymphocytic cuffing was scored according to the following criteria:

(0.0) no significant lesions; (1.0) a few airways with light PBLC; (1.5) more than a few airways with PBLC (up to 25%); (2.0) 50% airways with PBLC; (2.5) approximately 75% airways with PBLC; (3.0) greater than 75% airways with PBLC. Neutrophil (PMN) exudation in bronchioles and alveoli were scored according to the following criteria: (0.0) none to minimal presence of neutrophils; (1.0) small clusters of PMNs present in occasional airways; (2.0) Prominent small to large aggregates of PMNs in bronchiolar lumens, minimally in alveoli. A composite score was computed using the sum of the three individual scores. The average group composite score was used for statistical analysis.

The trachea was evaluated with a single score based on the magnitude of epithelial attenuation or necrosis. Trachea scores were based on the following criteria: (0.0) normal epithelium the entire circumference; (1.0) focal epithelial attenuation; (2.0) Extensive epithelial attenuation or necrosis.

Serologic and mucosal antibody assays

Serum samples were collected by anterior vena cava or jugular venipuncture at the following points: pre-weaning (-7 dpv), primary vaccination (0 dpv), WIV secondary vaccination (14 dpv), 2 weeks post-secondary vaccination (28 dpv), challenge inoculation (49 dpv / 0 dpi), and necropsy (5 dpi). For use in the HI assay, sera were heat inactivated at 56^{o}C and treated to remove non-specific agglutinators with a 20% suspension of Kaolin (Sigma Aldrich, St. Louis, MO) followed by adsorption with 0.5% turkey red blood cells (RBC). HI assays were done using TX98 and CO99 viral antigens and turkey RBC using standard techniques and with a maximum titer of 1:640 (17).

Enzyme-linked immunosorbent assays (ELISA) to detect total IgG and IgA antibodies against whole virus preparations of TX98 and CO99 present in serum and BALF were performed as previously described (Gauger et al., 2011) with the following modifications. Serum samples were diluted to 1:2000 for the IgG ELISA. BALF samples were diluted to 1:4 for IgG and IgA ELISAs. Samples were diluted in bovine serum albumen (Fraction V BSA, Life Technologies) and PBS with a final concentration of 5% BSA to block non-specific antibodies. Independent assays were conducted using 50 µL of whole virus TX98 or CO99 at 100 HA units per well as ELISA antigen and coated plates were blocked with 150 µL of a commercial blocking buffer (Starting Block, Thermo Fisher). Anti-swine IgG (Kirkegaard and Perry) and anti-swine IgA (Bethyl Laboratories) were used at a 1:1500 dilutions in blocking buffer. Each sample was analyzed in duplicate. The optical density (O.D.) was measured at 405 nm wavelength with an automated ELISA reader. Antibody levels were reported as the mean O.D. for each sample and the means for each treatment group were compared.

Statistical analysis

Macroscopic and microscopic pneumonia scores, $\log_{10}$ transformed BALF and nasal swab virus titers, $\log_2$ transformations of HI reciprocal titers, and mean O.D. for ELISA assays were analyzed using analysis of variance (ANOVA) with a p-value ≤ 0.05 considered significant (GraphPad Prism software, La Jolla, CA). Data from treatment groups infected with different virus strains (TX98 versus CO99) were analyzed separately. Response variables shown to have a significant effect by treatment group were subjected to pair-wise mean comparisons using the Tukey-Kramer test.

Results

Serology

Serum antibody responses to the vaccines displayed different profiles compared between MDA-negative and MDA-positive pigs. In MDA-negative pigs, WIV induced high HI responses in sera against TX98 with a geometric mean reciprocal titer of 556 at 49 dpv, whereas LAIV induced TX98-specific HI titers only marginally above the limit of detection (Fig. 1A). Similarly, WIV induced greater levels of TX98-specific serum IgG in MDA-negative pigs (Fig. 1C). WIV vaccination induced a modest level of cross-reacting HI titers in sera against CO99 in MDA-negative pigs, with a geometric mean reciprocal titer of 61 at 0 dpi (Fig. 1B), and there was a corresponding increase in CO99 serum IgG (Fig. 1D). In contrast, LAIV induced no detectable HI or total IgG cross-reactivity against CO99, even in MDA-negative pigs (Fig. 1B and 1D, respectively).

Pigs that suckled immunized dams acquired MDA, as measured by serum HI titers against the vaccine strain TX98 at seven days before vaccination (-7 dpv) with a geometric mean reciprocal titer of 312 and a range between 40 and ≥640; however, pigs in the MDA-positive groups did not respond to LAIV or WIV vaccination with increases in HI antibody titers to TX98 (Fig. 1A). In these MDA-positive pigs, weakly cross-reactive HI titers against CO99 were detectable at -7 dpv (Fig. 1B). Homologous HI titers in the MDA-positive pigs declined by the day of challenge (49 dpv) to levels below or near the lower limit of detection (≤40). However, prior to challenge maternally-derived serum IgG specific to TX98 was still detectable by ELISA in non-vaccinated controls (Fig. 1C) but not against the heterologous CO99 (Fig. 1D). Although IgG levels in the WIV-vaccinated MDA-positive group were significantly higher than in the non-vaccinated MDA-positive group, WIV vaccination resulted in significantly higher IgG levels in the

MDA-negative pigs against both the TX98 and CO99 viruses (Fig. 1C and 1D, respectively). LAIV given to MDA positive pigs failed to induce an increase in the pre-existing total IgG in sera against TX98 or CO99 (Fig. 1C and 1D), similar to the HI response. Serum IgG responses after experimental challenge with TX98 or CO99 (5 dpi) displayed a similar pattern to the pre-challenge results (Fig. 1E and 1F), with the notable exception of a boost in IgG antibodies binding to CO99 in the pigs given LAIV in the absence of MDA and challenged with CO99 (Fig. 1F).

Mucosal Antibody Responses

After TX98 challenge (5 dpi), there were significant levels of TX98-specific IgG in lungs of WIV vaccinates, whether vaccinated in the presence or absence of MDA (Fig. 2A). LAIV vaccinates had significant levels of TX98-specific IgG in lungs only if the vaccine was administered in the absence of MDA (Fig. 2A). This was consistent in pigs challenged with CO99 as well (Fig. 2B). In sharp contrast, statistically significant IgA levels were only detected in the lungs of pigs vaccinated with LAIV in the absence of MDA. Results were similar in pigs challenged with either virus and in both the TX98 and CO99 ELISA assays (Fig. 2C and 2D, respectively). Thus, similar to the serum antibody profiles, mucosal antibody responses also differed between vaccine types and were impacted by the presence of MDA at the time of vaccination.

Replication of challenge viruses

Distinct differences were detected in replication of challenge virus based on MDA and vaccine status. Nasal replication of TX98 and CO99 challenge viruses was monitored by virus isolation and titration of virus in nasal swabs. As expected, no virus was detected in any of the pigs on the day of challenge (data not shown). In MDA-negative, non-vaccinated (NV) animals the two

viruses reached similar nasal titers at 3 and 5 dpi, between 10^4 and 10^5 $TCID_{50}$/ml (Fig 3). Non-vaccinated pigs that received TX98-specific MDA shed 10- to 100-fold less TX98 virus 3 and 5 dpi (Fig 3), even though their passive serum HI titers were near the lower limit of detection at the time of challenge (Fig 1A). In contrast, nasal shedding of CO99 was not significantly inhibited by the presence of residual TX98-specific MDA (Fig 3B). In MDA-negative pigs vaccinated with WIV or LAIV, both vaccines provided effective protection against the nasal shedding of TX98 and CO99, as almost no virus was detected 3 or 5 dpi in these treatment groups. Pigs that had been vaccinated with WIV in the face of MDA demonstrated reduced TX98 virus shedding at both samplings, but not complete prevention as in the MDA-negative, WIV-vaccinated pigs. The single dose of LAIV vaccine in the face of MDA also did not prevent shedding of TX98 at 3 dpi, but it led to a statistically significant reduction in nasal titers by 5 dpi, when compared with NV pigs with MDA. Finally, when administered in the face of MDA, both vaccines failed to protect against nasal replication of heterologous CO99, although statistically significant reductions in group mean titers were detected at both time points in the LAIV-vaccinated MDA pigs.

Virus titers were also measured in BALF specimens collected at necropsy, 5 dpi (Fig 4A). BALF collected from NV pigs had mean titers of 10^5-10^6 $TCID_{50}$/ml. Residual MDA appeared to provide a very limited amount of protection against TX98 replication in the lung – approximately a 10-fold reduction in titer – but not against CO99 (Fig 4A). These results are similar to what was observed for nasal titers at 5 dpi, though reductions due to MDA were greater in the nose compared to the lung. BALF samples from MDA-negative WIV and LAIV vaccinees contained no detectable TX98 or CO99, which closely followed the prevention of nasal shedding in these vaccinated groups. Even in the face of MDA, both vaccines significantly

283 reduced the TX98 virus loads in BALF (Fig. 3A). However, CO99 BALF viral loads were not
284 reduced in WIV vaccinates when the vaccine was administered in the face of MDA. MDA also
285 interfered with the efficacy of LAIV against CO99 although less dramatically than for WIV, as
286 LAIV provided for a significant reduction in BALF CO99 titers.

287 ***Lung pathology***

288 Challenge with either H3N2 strain caused mild lung pathology in pigs lacking maternal or
289 vaccine-induced immunity, consistent with previous reports (22, 26). MDA-positive pigs
290 vaccinated with WIV subsequently developed enhanced macroscopic pneumonia when
291 challenged with either homologous TX98 or heterologous CO99 (Fig 4B and 5C) as compared to
292 their respective MDA-negative counterparts. This WIV-associated enhancement was
293 particularly evident after CO99 challenge, with a group mean of 35% of the lung area affected
294 with pneumonia. Importantly, no enhancement in macroscopic pneumonia was seen with LAIV
295 under either MDA condition with either challenge virus and there was a general trend for
296 reduction in pneumonia. Non-vaccinated and LAIV groups challenged with CO99 had average
297 pneumonia percentages of 4.2% and 2.2%, respectively. Likewise the LAIV vaccine significantly
298 reduced the percentage of macroscopic lung pathology in MDA-negative animals challenged
299 with TX98. In pigs lacking MDA, both of the vaccines were associated with significantly reduced
300 macroscopic lung pathology following heterologous CO99 challenge. Although TX98-specific
301 serum HI titers from MDA had largely waned in non-vaccinated pigs by the time of challenge,
302 macroscopic pneumonia was less extensive in non-vaccinated pigs that had received MDA than
303 in those without MDA (Fig 3B). This difference in severity of macroscopic lesions corresponded
304 with a similar trend in BALF viral titer 5 dpi (Fig. 4A).

When administered to MDA-negative animals, both vaccines showed protective effects against both challenge viruses with respect to microscopic lung lesion scores (Fig 4C). The protective effects of LAIV against both challenge viruses, which did not reach statistical significance, appeared to be maintained when the vaccine was given to MDA-positive animals. However, as with macroscopic pneumonia, there were distinctly different outcomes when MDA-positive, WIV-vaccinated pigs were challenged with homologous TX98 versus heterologous CO99. Those vaccinated with WIV in the face of MDA, then challenged with TX98, had microscopic lesion scores not different from the non-vaccinated MDA-positive group. In contrast, WIV vaccination of MDA-positive pigs not only failed to provide protection against heterologous CO99, but a significant enhancement in lesion severity was demonstrated microscopically, paralleling the dramatic difference that was seen macroscopically. Importantly, LAIV did not contribute to enhanced microscopic lesion severity with either challenge virus.

Tracheal pathology

Regardless of MDA status, TX98 tended to induce more tracheal lesions than CO99 (Fig. 4D). In MDA negative pigs, both vaccines provided statistically significant reduction of these TX98 lesions, and in MDA positive pigs, LAIV still significantly reduced TX98-induced tracheal damage. However, tracheal damage was sharply higher in pigs that received WIV vaccine in the face of MDA and then were challenged with CO99. Thus, the overall enhanced respiratory disease from heterologous infection of the MDA-positive WIV vaccinates was clearly evident in the trachea as well as in the lung.

Discussion

The antigenic diversity of contemporary and emerging IAV strains is a major obstacle to effective and reliable vaccines for swine (16). IAV vaccines currently licensed around the world contain inactivated viral antigens representing H1N1, H3N2, H1N2, and 2009 pandemic H1N1 strains (12). Inactivated IAV vaccines elicit systemic neutralizing antibodies and protection against homologous challenge, but their efficacy against antigenically distinct strains is often diminished (1, 9). Intranasal vaccination with an attenuated virus is considered likely to elicit more cross-reactive T cells and mucosal antibodies against antigenically variant strains (12). Several attenuated viral constructs made by targeted genetic mutations have been tested in recent years (13, 18, 24). We previously reported the immunogenicity and protective efficacy of TX98 virus attenuated by truncation of the NS1 gene, which encodes a type I interferon antagonist protein (23, 26). This virus (identical to LAIV in the present report) was shown to have attenuated replication in the upper respiratory tract. When administered as an intranasal vaccine to young seronegative pigs, the TX98 LAIV elicited a mucosal IgA response, modest titers of serum HI antibodies, and antigen-specific T cells, while conferring protection against homologous challenge and a degree of cross-protection against variant strains with a single or two-dose regimen (7, 26). Our previous work indicated that two intranasal applications of the LAIV did not confer any benefit against homologous challenge compared to one dose (26) and one dose would be highly preferred for use in the swine population. Here we show that a single dose was highly efficacious against the homologous TX98 and heterologous CO99 in MDA-negative pigs. Although future studies are necessary to investigate whether two doses would

346 improve efficacy in the presence of MDA, the impact of the findings of this study come from the
347 differences between WIV and LAIV in the face of MDA with heterologous challenge.
348 One aim of the present study was to compare the efficacy of intranasal LAIV versus
349 intramuscular WIV vaccination in seronegative pigs. WIV vaccination induced high serum HI
350 titers to the homologous antigen, while HI responses following LAIV vaccination were weak or
351 below detection limits. Even before the WIV vaccinees were boosted with a second dose, they
352 achieved higher HI titers than LAIV vaccinees (Fig. 1A). Cross-reactive HI antibody titers against
353 heterologous CO99 tended to be 4- to 16-fold lower than homologous titers, and these were
354 only detectable in WIV vaccinees. Despite the marked differences in serological responses, both
355 vaccines supplied significant protection in the absence of MDA against the replication of not
356 only homologous TX98 but also heterologous CO99. Based on these data, protective immunity
357 induced by LAIV vaccination was likely mediated by T cells and/or mucosal antibodies, and here
358 we demonstrate a robust IgA response in the lower respiratory tract when the LAIV was
359 administered in the absence of MDA. Higher levels of IgG in the serum were also detected at 5
360 dpi, indicating a cross-reacting boost of antibody to the CO99 virus exposure. It is not clear if
361 the higher levels of serum (and mucosal) antibodies to CO99 at 5 dpi in the MDA-negative pigs
362 were specific only to the CO99 challenge virus or if the CO99 challenge boosted the TX98
363 primed response, particularly against epitopes that are shared between TX98 and CO99. While
364 there was no evidence of virus replication, the immune system had likely formed prior
365 immunity against common epitopes contained in the LAIV vaccine virus that may have been
366 boosted upon exposure to the CO99 virus. The protection provided by WIV vaccine against
367 CO99 in the non-MDA pigs was surprising, since previous studies reported limited HI cross-

368 reactivity between TX98 and CO99 (22) and the geometric mean cross-reactive HI titer at the
369 time of challenge in this study was 61, about ten-fold lower than the geometric mean
370 homologous HI titer to TX98. The cross-reacting HI antibodies and mucosal IgG antibodies
371 detected at 5 dpi are likely to have played a role in the heterologous protection, perhaps
372 enabled by the magnitude of the systemic antibody response to WIV. Cross-reactive T-cells
373 primed by the WIV may have also contributed to the protective effect against the heterologous
374 CO99 infection. Consistent with this, a similarly formulated H1N2 WIV vaccine was shown to
375 prime T cells in antibody-negative young pigs (7).
376 IAV vaccination of sows is a widespread practice in North American swine herds (3). This
377 presents a second practical problem concerning IAV vaccines in the swine industry: antibodies
378 transferred in colostrum from sows to their litters can interfere with subsequent vaccination of
379 the piglets (8) and are often poorly matched to viruses circulating on the sow farm or in down-
380 stream production stages. Colostrum-borne maternal antibodies, which are predominantly IgG,
381 are not expected to infiltrate the nasal mucosa of the upper respiratory tract, so we
382 hypothesized that the LAIV vaccine would be less sensitive to inhibition by MDA. Our serological
383 results demonstrated that MDA indeed prevented pigs from mounting active HI antibody
384 responses to WIV vaccine (Fig. 1A). Despite this, WIV vaccine administered in the face of MDA
385 still provided significant protection against homologous TX98 challenge, including decreased
386 nasal shedding (Fig. 3) and replication in the lung (Fig. 4A), but did not prevent damage to the
387 lower respiratory tract (Fig. 4B-D). This pointed again to the possibility that the adjuvanted WIV
388 in the face of MDA primed a cellular immune response that contributed to protection against

389 homologous virus. Moderate T-cell priming was demonstrated in pigs vaccinated with a similar
390 formulation of inactivated H1N2 IAV (7).
391 Critically, though, there was a pronounced failure of WIV vaccination in MDA-positive
392 pigs that were challenged with heterologous CO99. In this group, the vaccine failed to reduce
393 viral replication in nasal passages and the viral load in BALF (Fig. 3 and 4A). Strikingly,
394 macroscopic lung lesions were exacerbated (Fig. 4B and 5C) in a manner similar to another
395 VAERD model (4, 5, 25). Composite microscopic lung and tracheal lesions (Fig. 4 C-D) were
396 enhanced and similar in character to VAERD lesions previously reported (4). In sharp contrast,
397 there was no enhancement of pathologic lung changes in the MDA-positive group vaccinated
398 with LAIV; in fact, LAIV was partially protective against CO99 in terms of reducing lung damage
399 and viral load on 5 dpi (Fig. 4 and Fig. 5). Thus, although WIV and LAIV had similar efficacy in
400 naïve pigs, the presence of MDA titers at the time of vaccination followed with heterologous
401 viral challenge produced sharply different outcomes between the two vaccines. The abrogation
402 of the LAIV-induced IgA response in the lower respiratory tract (Fig. 2D) may explain the
403 reduction in efficacy in the MDA-positive pigs compared to LAIV given to MDA-negative pigs.
404 Evaluation of the antibody profile in the upper respiratory tract (nasal mucosa) was not
405 conducted in this study but should be considered in future studies to understand how MDA
406 interferes with the LAIV-induced mucosal antibody response and if the inhibition is limited to
407 the lower respiratory tract. We speculate that the cellular immune response to LAIV in MDA-
408 positive pigs was a key factor in cross-protection, since no lung IgA or cross-reacting serum HI
409 antibodies were evident above the limits of detection. It is also unclear if there was a role for
410 the presumably non-neutralizing IgG in the lungs of MDA-positive WIV vaccinates with VAERD

411 following heterologous challenge with CO99 in comparison to the absence of IgG in the lungs of
412 MDA-positive LAIV vaccinates without VAERD.

413 In a previous study, MDA-positive pigs that received a bivalent IAV vaccine containing
414 inactivated classical H1N1 were primed for enhanced pneumonia upon heterologous H1N1
415 challenge, whereas vaccination of MDA-negative pigs provided cross-protection (8). This
416 detrimental interaction between passive immunity and WIV vaccination parallels what we
417 observed in the present study with H3N2 viruses. Although the earlier study did not include an
418 LAIV treatment group for comparison, it did show evidence that intramuscular vaccination with
419 an inactivated virus administered in the face of MDA was ineffective at priming protective T-cell
420 memory. The mechanism(s) responsible for the enhancement of respiratory disease in our
421 model is not completely clear. It can be hypothesized that MDA's bind to vaccine antigen and
422 the method of antigen processing and presentation is different than when vaccine antigen is
423 not bound to antibody (seronegative pig). This change in antigen uptake and subsequent
424 presentation may alter the adaptive immune response (both humoral and cell-mediated) in the
425 piglet, possibly directing it away from neutralizing epitopes to conserved, albeit non-
426 neutralizing epitopes shared between the vaccine virus and challenge virus. After 2 doses of
427 WIV, HI antibodies against neither TX98 nor CO99 were detected in MDA-positive pigs, whereas
428 HI antibodies against both were detected in MDA-negative pigs. Although there was no HI
429 antibody response in MDA-positive pigs receiving WIV, there appeared to be a modest increase
430 in total IgG specific to TX98 in the serum prior to challenge (Fig. 1C). Total IgG was also present
431 in the lung at 5 dpi (Fig. 2 A and B) when there was still no detectable HI response in the serum
432 in this group (data not shown). This indicates that MDA interfered with the induction of

433 neutralizing HI antibodies by WIV. Upon challenge with the heterologous virus, immune
434 complexes may form between non-neutralizing antibodies and challenge virus that trigger
435 inflammatory responses such as those implicated in vaccine-enhanced respiratory syncytial
436 virus (RSV) infection of infants (3). The involvement of antibody in generating immune
437 complexes associated with severe respiratory disease and pulmonary damage has also been
438 described for 2009 pandemic H1N1 influenza disease (15). Roles for specific IgG subclasses have
439 not been clearly defined in the pig; thus, this type of analysis is not available for further
440 interrogation of within type differences in antibody responses induced by WIV vaccination in
441 the face of MDA. However, functional or qualitative differences in the antibodies produced in
442 response to WIV and LAIV in the presence or absence of MDA appear likely to have a critical
443 role in the clinical outcome after infection.
444 Another hypothesis, though not mutually exclusive, is that differences in antigen
445 processing and presentation of WIV vaccine antigen in MDA-positive pigs may alter the kinetics
446 of the response or may prime a qualitatively different T cell response and these T cells play a
447 role in immunopathology. A different subset of memory T cells may develop in MDA-positive,
448 WIV vaccinated pigs that upon heterologous challenge, when cross-neutralizing antibody is not
449 present, are activated and contribute to pathology, possibly through granzyme release and
450 killing of infected cells. Additional studies are needed to further characterize differences in the
451 antibody and T cell responses that develop following WIV vaccination of MDA-positive and
452 MDA-negative pigs and elucidate the immunopathogenic mechanism of enhanced disease
453 following heterologous challenge.

Collectively, the results of this experiment demonstrate very distinct outcomes of IAV vaccination and infection with heterologous virus, with pivotal factors including the format and route of administration of vaccines, the presence or absence of MDA, and the antigenic similarity of challenge virus to the vaccine strain. The differences go beyond protection versus non-protection, and point to realistic scenarios in the field where vaccinating sows and their piglets could potentiate more severe respiratory disease. This underscores the need to re-evaluate the way in which efficacy studies are designed for swine influenza vaccine licensure for use in pigs in the United States. Methods of IAV vaccine evaluation that focus simply on protection against homologous challenge in seronegative pigs would be unlikely to identify this problem. Determining the immune correlates of protection versus disease exacerbation would significantly aid the improvement of vaccine safety and efficacy under field conditions.

Acknowledgements

Funding was provided by USDA-ARS to ALV, WM, KML, JAR, and CLL. This study was supported in part by NIAID grants R01AI046954 and U01AI070469, and by CRIP (Center for Research in Influenza Pathogenesis, NIAID CEIRS contract number HHSN266200700010C) to AG-S.

The authors thank Michelle Harland and Gwen Nordholm for technical assistance, Brian Pottebaum and Jason Huegel for assistance with animal studies. Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. USDA is an equal opportunity provider and employer.

References

1. **Bikour, M. H., E. Cornaglia, and Y. Elazhary.** 1996. Evaluation of a protective immunity induced by an inactivated influenza H3N2 vaccine after an intratracheal challenge of pigs. Can J Vet Res **60:**312-314.
2. **Choi, Y. K., S. M. Goyal, and H. S. Joo.** 2004. Evaluation of transmission of swine influenza type A subtype H1N2 virus in seropositive pigs. Am J Vet Res **65:**303-306.
3. **Delgado, M. F., S. Coviello, A. C. Monsalvo, G. A. Melendi, J. Z. Hernandez, J. P. Batalle, L. Diaz, A. Trento, H. Y. Chang, W. Mitzner, J. Ravetch, J. A. Melero, P. M. Irusta, and F. P. Polack.** 2009. Lack of antibody affinity maturation due to poor Toll-like receptor stimulation leads to enhanced respiratory syncytial virus disease. Nat Med **15:**34-41.
4. **Gauger, P. C., A. L. Vincent, C. L. Loving, J. N. Henningson, K. M. Lager, B. H. Janke, M. E. Kehrli, Jr., and J. A. Roth.** 2012. Kinetics of Lung Lesion Development and Pro-Inflammatory Cytokine Response in Pigs With Vaccine-Associated Enhanced Respiratory Disease Induced by Challenge With Pandemic (2009) A/H1N1 Influenza Virus. Vet Pathol.
5. **Gauger, P. C., A. L. Vincent, C. L. Loving, K. M. Lager, B. H. Janke, M. E. Kehrli, Jr., and J. A. Roth.** 2011. Enhanced pneumonia and disease in pigs vaccinated with an inactivated human-like (delta-cluster) H1N2 vaccine and challenged with pandemic 2009 H1N1 influenza virus. Vaccine **29:**2712-2719.
6. **Halbur, P. G., P. S. Paul, M. L. Frey, J. Landgraf, K. Eernisse, X. J. Meng, M. A. Lum, J. J. Andrews, and J. A. Rathje.** 1995. Comparison of the pathogenicity of two US porcine reproductive and respiratory syndrome virus isolates with that of the Lelystad virus. Vet Pathol **32:**648-660.

7. **Kappes, M. A., M. R. Sandbulte, R. Platt, C. Wang, K. M. Lager, J. N. Henningson, A. Lorusso, A. L. Vincent, C. L. Loving, J. A. Roth, and M. E. Kehrli, Jr.** 2011. Vaccination with NS1-truncated H3N2 swine influenza virus primes T cells and confers cross-protection against an H1N1 heterosubtypic challenge in pigs. Vaccine.

8. **Kitikoon, P., D. Nilubol, B. J. Erickson, B. H. Janke, T. C. Hoover, S. A. Sornsen, and E. L. Thacker.** 2006. The immune response and maternal antibody interference to a heterologous H1N1 swine influenza virus infection following vaccination. Vet Immunol Immunopathol **112:**117-128.

9. **Lee, J. H., M. R. Gramer, and H. S. Joo.** 2007. Efficacy of swine influenza A virus vaccines against an H3N2 virus variant. Can J Vet Res **71:**207-212.

10. **Loeffen, W. L., P. P. Heinen, A. T. Bianchi, W. A. Hunneman, and J. H. Verheijden.** 2003. Effect of maternally derived antibodies on the clinical signs and immune response in pigs after primary and secondary infection with an influenza H1N1 virus. Vet Immunol Immunopathol **92:**23-35.

11. **Lorusso, A., A. L. Vincent, M. L. Harland, D. Alt, D. O. Bayles, S. L. Swenson, M. R. Gramer, C. A. Russell, D. J. Smith, K. M. Lager, and N. S. Lewis.** 2010. Genetic and antigenic characterization of H1 influenza viruses from United States swine from 2008. J Gen Virol.

12. **Ma, W., and J. A. Richt.** 2010. Swine influenza vaccines: current status and future perspectives. Anim Health Res Rev **11:**81-96.

13. **Masic, A., J. S. Booth, G. K. Mutwiri, L. A. Babiuk, and Y. Zhou.** 2009. Elastase-dependent live attenuated swine influenza A viruses are immunogenic and confer protection against swine influenza A virus infection in pigs. J Virol **83:**10198-10210.

14. **Masic, A., X. Lu, J. Li, G. K. Mutwiri, L. A. Babiuk, E. G. Brown, and Y. Zhou.** 2010. Immunogenicity and protective efficacy of an elastase-dependent live attenuated swine influenza virus vaccine administered intranasally in pigs. Vaccine **28:**7098-7108.

15. **Monsalvo, A. C., J. P. Batalle, M. F. Lopez, J. C. Krause, J. Klemenc, J. Z. Hernandez, B. Maskin, J. Bugna, C. Rubinstein, L. Aguilar, L. Dalurzo, R. Libster, V. Savy, E. Baumeister, G. Cabral, J. Font, L. Solari, K. P. Weller, J. Johnson, M. Echavarria, K. M. Edwards, J. D. Chappell, J. E. Crowe, Jr., J. V. Williams, G. A. Melendi, and F. P. Polack.** 2011. Severe pandemic 2009 H1N1 influenza disease due to pathogenic immune complexes. Nat Med **17:**195-199.

16. **Olsen, C. W.** 2002. The emergence of novel swine influenza viruses in North America. Virus Res **85:**199-210.

17. **Palmer, D. F., M. T. Coleman, W. D. Dowdle, and G. O. Schild.** 1975. Advanced laboratory techniques for influenza diagnosis. Immunology series no. 6. U.S. Dept. of Health, Education, and Welfare, Washington, D.C.

18. **Pena, L., A. L. Vincent, J. Ye, J. R. Ciacci-Zanella, M. Angel, A. Lorusso, P. C. Gauger, B. H. Janke, C. L. Loving, and D. R. Perez.** 2011. Modifications in the polymerase genes of a swine-like triple-reassortant influenza virus to generate live attenuated vaccines against 2009 pandemic H1N1 viruses. J Virol **85:**456-469.

19. **Pomorska-Mol, M., I. Markowska-Daniel, and Z. Pejsak.** 2010. Evaluation of humoral and antigen-specific T-cell responses after vaccination of pigs against pseudorabies in the presence of maternal antibodies. Vet Microbiol **144:**450-454.

20. **Reed, L. J., and H. Muench.** 1938. A simple method of estimating fifty percent end points. . American Journal of Hygiene **27:**5.

21. **Renshaw, H. W.** 1975. Influence of antibody-mediated immune suppression on clinical, viral, and immune responses to swine influenza infection. Am J Vet Res **36:**5-13.

22. **Richt, J. A., K. M. Lager, B. H. Janke, R. D. Woods, R. G. Webster, and R. J. Webby.** 2003. Pathogenic and antigenic properties of phylogenetically distinct reassortant H3N2 swine influenza viruses cocirculating in the United States. J Clin Microbiol **41:**3198-3205.

23. **Richt, J. A., P. Lekcharoensuk, K. M. Lager, A. L. Vincent, C. M. Loiacono, B. H. Janke, W. H. Wu, K. J. Yoon, R. J. Webby, A. Solorzano, and A. Garcia-Sastre.** 2006. Vaccination of pigs against swine influenza viruses by using an NS1-truncated modified live-virus vaccine. J Virol **80:**11009-11018.

24. **Solorzano, A., R. J. Webby, K. M. Lager, B. H. Janke, A. Garcia-Sastre, and J. A. Richt.** 2005. Mutations in the NS1 protein of swine influenza virus impair anti-interferon activity and confer attenuation in pigs. J Virol **79:**7535-7543.

25. **Vincent, A. L., K. M. Lager, B. H. Janke, M. R. Gramer, and J. A. Richt.** 2008. Failure of protection and enhanced pneumonia with a US H1N2 swine influenza virus in pigs vaccinated with an inactivated classical swine H1N1 vaccine. Vet Microbiol **126:**310-323.

26. **Vincent, A. L., W. Ma, K. M. Lager, B. H. Janke, R. J. Webby, A. Garcia-Sastre, and J. A. Richt.** 2007. Efficacy of intranasal administration of a truncated NS1 modified live influenza virus vaccine in swine. Vaccine **25:**7999-8009.

27. **Webby, R. J., K. Rossow, G. Erickson, Y. Sims, and R. Webster.** 2004. Multiple lineages of antigenically and genetically diverse influenza A virus co-circulate in the United States swine population. Virus Res **103:**67-73.

28. **Wittmann, G., and V. Ohlinger.** 1987. Aujeszky's disease vaccination and infection of pigs with maternal immunity: effects on cell- and antibody-mediated immunity. Arch Virol **92:**87-101.

29. **Zhou, N. N., D. A. Senne, J. S. Landgraf, S. L. Swenson, G. Erickson, K. Rossow, L. Liu, K. Yoon, S. Krauss, and R. G. Webster.** 1999. Genetic reassortment of avian, swine, and human influenza A viruses in American pigs. J Virol **73:**8851-8856.

568 **Table 1.** Study design for comparison of LAIV and WIV vaccines

Treatment Group	MDA Status[1]	Piglet Vaccine	Piglet Challenge	N
MDA / NV / NC	+	None	Sham	4
MDA / NV / TX	+	None	wt TX98	8
MDA / NV / CO	+	None	wt CO99	8
MDA / WIV / TX	+	TX98 WIV	wt TX98	8
MDA / WIV / CO	+	TX98 WIV	wt CO99	8
MDA / LAIV / TX	+	TX98 LAIV	wt TX98	8
MDA / LAIV / CO	+	TX98 LAIV	wt CO99	7
no MDA / NV / NC	-	None	Sham	4
no MDA / NV / TX	-	None	wt TX98	8
no MDA / NV / CO	-	None	wt CO99	8
no MDA / WIV / TX	-	TX98 WIV	wt TX98	8
no MDA / WIV / CO	-	TX98 WIV	wt CO99	8
no MDA / LAIV / TX	-	TX98 LAIV	wt TX98	8
no MDA / LAIV / CO	-	TX98 LAIV	wt CO99	8

569 [1] MDA(+) pigs suckled sows which were previously vaccinated with three doses of TX98 WIV.

570 MDA(-) pigs suckled sows which were not vaccinated against IAV.

571 **Figure 1**. Serum antibody levels due to maternal derived antibody and/or response to vaccine.
572 Reciprocal geometric mean hemagglutination inhibition (HI) titers at multiple time points prior
573 to challenge against TX98 H3N2 antigen (A) and against CO99 antigen (B). MDA designates
574 groups with maternally-derived antibody induced by immunizing dams with TX98 vaccine.
575 Treatment groups were non-vaccinated (NV), vaccinated at 0 days post-vaccination (dpv) and
576 14 dpv with TX98 whole inactivated virus (WIV), or vaccinated intranasally with TX98 live-
577 attenuated influenza virus (LAIV) at 0 dpv only. Mean optical density (O.D.) of serum IgG in
578 whole virus ELISA assays against TX98 antigen (C) and against CO99 antigen (D) at 49 dpv (0
579 days post infection). Mean optical density (O.D.) of IgG in whole virus ELISA assays at 5 days
580 post challenge against TX98 antigen for groups challenged with TX98 (E) and against CO99
581 antigen for groups challenged with CO99 (F). Open bars designate groups without MDA and
582 solid bars designate groups with MDA. Statistically significant differences between MDA
583 statuses within a vaccine group are marked with asterisks and differences between vaccine
584 treatment groups with matched MDA status are identified by connecting lines ($P < 0.05$).
585 **Figure 2.** Antibody levels in broncho-alveolar lavage fluid at five days post infection. Mean
586 optical density (O.D.) of IgG in whole virus ELISA assays against TX98 antigen (A) and against
587 CO99 antigen (B) and of IgA against TX98 antigen (C) and against CO99 antigen (D). Groups
588 challenged with TX98 are represented in panels A and C whereas groups challenged with CO99
589 are represented in panels B and D. Open bars designate groups without MDA and solid bars
590 designate groups with MDA. Statistically significant differences between MDA statuses within a
591 vaccine group are marked with asterisks and differences between vaccine treatment groups

592 with matched MDA status and challenge virus strains are identified by connecting lines ($P <$
593 0.05).
594 **Figure 3.** A. Nasal shedding of challenge virus at 3 (A) and 5 (B) dpi in nasal swabs (NS). Piglets
595 were vaccinated in the presence or absence of circulating MDA against TX98. At vaccination,
596 piglets received no vaccine (NV), two intramuscular doses of TX98 WIV, or one intranasal dose
597 of TX98 LAIV. Forty-nine days after the initial vaccine dose, piglets were challenged by intra-
598 tracheal inoculation with TX98 or CO99. Nasal swab specimens were collected from 3 and 5
599 days post-infection (dpi), and titrated by $TCID_{50}$ assay on MDCK cells. Statistically significant
600 differences between MDA statuses within a vaccine group are marked with asterisks and
601 differences between vaccine treatment groups with matched MDA status and challenge virus
602 strains are indentified by connecting lines ($P < 0.05$).
603 **Figure 4**. Adjuvanted TX98 WIV administered to MDA-positive piglets enhances the severity of
604 subsequent infection with heterologous H3N2 strain CO99, whereas TX98 LAIV vaccine partially
605 cross-protects. MDA-positive pigs suckled colostrum from TX98-vaccinated sows and MDA-
606 negative pigs suckled from naïve sows. WIV was delivered intramuscularly at 2 and 4 weeks of
607 age, while LAIV was delivered intranasally only at 2 weeks of age. At 8 weeks of age (49 dpv)
608 pigs were challenged intratracheally with TX98 or CO99. At 5 days post-infection (dpi), pigs
609 were euthanized, BALF samples were collected, and necropsy was conducted. BALF samples
610 were titrated by $TCID_{50}$ assay on MDCK cells (A). Macroscopic lesions were scored as the
611 percentage of total lung surface area involved (B). Microscopic pneumonia (C) and tracheal
612 damage (D) were scored as described in Materials and Methods. Statistically significant
613 differences between MDA statuses within a vaccine group are marked with asterisks and

differences between vaccine treatment groups with matched MDA status and challenge virus strains are identified by connecting lines ($P < 0.05$).

Figure 5. Photographs of macroscopic lung pathology in pigs positive for MDA at the time of vaccination, shown 5 days after heterologous challenge with CO99. Photographs of ventral surfaces of lungs are representative of three vaccine treatment groups: non-vaccinated challenge controls (A); TX98 LAIV-vaccinated pigs (B); and TX98 WIV-vaccinated pigs (C).