RESEARCH ARTICLE

Novel multiplex assay for profiling influenza antibodies in breast milk and serum of mother-infant pairs [version 1; referees: 1 approved, 1 approved with reservations]

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Abstract

Background: During early life, systemic protection to influenza is passively provided by transplacental transfer of IgG antibodies and oral and gastrointestinal mucosal protection via breast milk (BM) containing predominantly IgA. Immune imprinting, influenced by initial exposure of the infant immune system to influenza, has recently been recognized as an important determinant of future influenza immune responses.

Methods: We utilized stored frozen BM from a prospective birth cohort to assess immune factors in human milk. The earliest available BM and a paired, timed serum sample was assessed from each of 7 mothers. Paired infant serum samples were assayed at up to three time points during the first 12 months of life, one prior to assumed disappearance of transplacentally transferred IgG, and one after. We utilized a novel multiplex assay to assess mothers’ and infants’ IgG and IgA antibodies in serum to a panel of 30 individual recombinant hemagglutinin (rHA) proteins of influenza virus strains and chimeric rHAs. We also characterized IgA and IgG antibody levels in breast milk providing mucosal protection.

Results: Our pilot results, analyzing a small number of samples demonstrate the feasibility of this method for studying paired maternal-infant IgG and IgA anti-influenza immunity patterns. Unlike IgG antibodies, breast milk influenza virus HA-specific IgA antibody levels and patterns were mostly discordant compared to serum. As expected, there was a steady decay of infant influenza specific IgG levels by 6 to 8 months of age, which was not, however, comparable in all infants. In contrast, most of the infants showed an increase in IgA responses throughout the first year of life

Conclusions: This new analytical method can be applied in a larger study to understand the impact of maternal imprinting on influenza immunity.

Keywords

breast milk, influenza, infants, protection, transplacental, antibody
Corresponding author: Kirsi M. Järvinen (kirsijarvinenseppo@URMC.Rochester.edu)

Author roles: Järvinen KM: Conceptualization, Data Curation, Investigation, Project Administration, Resources, Supervision, Writing – Original Draft Preparation, Writing – Review & Editing; Wang J: Investigation, Methodology, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; Seppo AE: Conceptualization, Investigation, Project Administration, Validation, Writing – Review & Editing; Zand M: Conceptualization, Formal Analysis, Methodology, Project Administration, Resources, Supervision, Validation, Visualization, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

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Introduction
The immune system in neonates and young infants is initially immature, without adequate protection against infections. The dogma is that during infancy, systemic protection is passively provided by transplacental transfer of IgG antibodies and oral and gastrointestinal mucosal protection via breast milk (BM) containing predominantly IgA and some IgG. However, the clinical protection provided by maternal influenza immunization or exposure varies by season and the corresponding match against circulating influenza strains. Therefore, maternal influenza exposure, whether through immunization or natural infection, provides maternal protection and has the potential to imprint the infant immune system and significantly impact infant morbidity and mortality, as recently comprehensively reviewed.

Maternal influenza immunization prior to or during pregnancy provides clinical protection with 70% efficiency in the infant. Only one study has described IgA antibody levels in human milk to influenza. Their results suggested that vaccination using a single strain of influenza A (A/New Caledonia/20/1999, H1N1) induced significantly higher IgA antibody levels than those seen in non-vaccinated, and those antibodies were positively correlated with viral neutralization. In addition, higher rates of exclusive breastfeeding in the first 6 months of life were associated with protection against febrile respiratory illness in the infants of vaccinated mothers, suggesting mucosal protection against influenza by BM antibodies. However, there is little data on how influenza antibody levels, or strain-specific antibody profiles, vary between mother’s serum, BM and infant serum. Data on the kinetic changes in anti-influenza IgG profiles between mother-infant pairs are also largely lacking.

In this pilot study utilizing a novel multiplex assay, we assessed infant immunity to various influenza strains reflecting maternal anti-influenza IgG levels and profiles in serum, as well as characterized IgA antibody responses in breast milk, which are distinct and reflect mucosal immunity. This new analytical method was applied to a small number of samples showing feasibility and patterns suggestive that a larger study needs to be done to understand the impact of maternal imprinting on influenza immunity.

Methods
We utilized stored frozen human foremilk collected in the morning, from a prospective birth cohort recruited in 1997–2001 in Finland to assess immune factors in human milk. The earliest available BM and a paired, timed serum sample was assessed from each of 7 mothers; ranging from 3 days to 2 months post-partum. Paired infant serum samples were assayed at up to three time points during the first 12 months of life, one prior to assumed disappearance of transplacentally transferred IgG, and one after. The samples collected in this cohort have been stored at -80°F with no recurrent freeze-thaw cycles. Aliquots have successfully been used in the past for measurement of serum and BM antibody levels with good antibody levels detected both for IgG and IgA. These mothers were unvaccinated, as guidelines for maternal influenza immunization were not in place at the time samples were collected. None of the infants had been vaccinated to influenza. Clinical characteristics and timing of samples available are shown in Table 1. The study was approved by the institutional review boards of the Helsinki University Central Hospital, the City of Helsinki, and the University of Rochester Medical Center, Rochester, NY.

<table>
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<tr>
<th>Dyad</th>
<th>Maternal age (years)</th>
<th>Breast milk sample</th>
<th>Infant age at serum sample (month of collection)</th>
<th>Exclusive BF length</th>
<th>Total BF length</th>
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<tr>
<td>1</td>
<td>32</td>
<td>3 weeks</td>
<td>2 month (Nov) 8 month (May) 12 month (Aug)</td>
<td>4 months</td>
<td>nk</td>
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<td>2</td>
<td>31</td>
<td>3 days</td>
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<td>3</td>
<td>32</td>
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<td>4</td>
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<td>5</td>
<td>26</td>
<td>1 month</td>
<td>5 month (Sep) 7 month (Nov)</td>
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<td>6</td>
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<td>30</td>
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<td>2 month (July) 4 month (Sep) 6 month (Nov)</td>
<td>0 months</td>
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nk, not known; BF, breastfeeding.
We have developed a multiplex assay (mPlex-Flu) that simultaneously measures absolute antibody concentrations against up to 50 influenza strains. The mPlex-Flu assay has several advantages over the traditional hemagglutinin inhibition (HAI) titer assay: a linear readout over 4 logs, and high sensitivity. Our previous studies also showed that mPlex-Flu assay results highly consistent with the results from HAI and ELISA assays in human pre-and post-influenza vaccine study. In the present study, a panel of 30 individual recombinant hemagglutinin (rHA) proteins of influenza virus strains and chimeric rHAs were used (see Table 2). This allowed us to estimate the specific anti-influenza IgG and IgA levels against H1, H2, H3 and Flu B seasonal influenza strains, as well as HA stalk specific antibodies using chimeric rHA (i.e. head from one influenza strain and stalk from

<table>
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<th>Table 2. The HA panel of the mPlex-Flu assay.</th>
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<td><strong>Influenza Virus Type</strong></td>
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<td><strong>Chimeric HA</strong></td>
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Seasonal Vaccine strains in Bold
another strain), cH5/1 and cH9/1 specific for group 1 (i.e. H1, H2, H5, H6) and cH4/7 and cH5/3 for group 2 (i.e. H3, H7) influenza strains, as previously described³.

In the present study, samples of maternal serum (diluted 1:500 for IgA and 1:5000 for IgG), infant serum (1:10) and BM (1:10) were diluted using PBS and incubated with rHA coupled Luminex beads (Luminex Corp, Austin, TX). IgG or IgA binding was detected with anti-human IgG or IgA specific secondary antibodies (SouthernBiotech, AL, Cat No 2040-09, 2050-09, respectively). Median fluorescence intensities (MFI) were measured using a MAGPIX multiplex reader (Luminex Co.,TX) and converted into absolute IgG concentrations (ng/mL) using an IgG standard curve generated with a human standard serum, which is a mixture of sera from four subjects containing high levels of anti-influenza HA IgG and IgA against multiple influenza strains⁴. Since serum IgA is monomeric, while BM secreted IgA (SlgA) is dimeric⁵, the standard curves of BM SlgA against influenza viruses are very different from that of standard serum curves generated from human standard serum sample. We thus report the magnitude of BM IgA anti-influenza HA antibody levels in MFI units. For consistency, and to allow direct comparison, we also report IgG levels in MFI units. All data were analyzed by Prism 7, and heatmap figures were generated by Mathematic 11.2.

**Results**

This new analytical method was applied to a small number of samples showing feasibility and several interesting patterns. BM had a pattern of IgG reactivity very similar to maternal serum. Also, the levels and strain reactivity patterns of anti-influenza IgG in mother’s serum matched that of her infant, suggesting a robust transplacental transfer of antibodies. As expected, there was a steady decay of infant influenza specific IgG levels by 6 to 8 months of age (Figure 1A). This decay was, however, not comparable in all infants. Interestingly, mothers with highest anti-influenza HA IgG antibodies had infants with high initial anti-HA antibody maintained until 6 months of age (Pairs #3 and #7), compared to a mother with the lowest initial IgG (Pair #4), suggesting that initial levels attained transplacentally are directly associated with the rate of decline of passive systemic immunity. By the end of the first year, infant #1 maintained 6-month IgG antibody levels, which is likely due to new, natural exposure. Supplementary Figure 1 shows the heatmaps of IgG and IgA antibodies to influenza strains measured by multiplex array in paired mother’s serum (MS), breast milk (BM) and infant serum (IS) samples. Figure 2A shows the trajectory of IgG antibodies to selected individual strains.

Unlike with IgG antibodies, BM influenza virus HA-specific IgA antibody levels and patterns were mostly discordant compared to serum. Only some mother-infant pairs showed high a degree of concordance (Pairs #1 and #5). This may be due to the mucosal homing of IgA producing antibody-secreting cells to the mammary gland, resulting in a different antibody profile in breast milk from serum. Very low serum IgA antibodies in infants are consistent with the fact that IgA does not cross the placenta (Figure 1B). The pattern of IgA anti-HA antibody binding was largely similar to that of mother’s serum and milk IgG, and predominantly against H1, H3 and B influenza strains. As opposed to infant IgG responses, most of the infants (Pairs #1–4) showed an increase in IgA responses throughout the first year of life (Figure 1B), whereas no matching IgG antibody response was seen. This may be due to natural, mucosal exposure to influenza inducing local responses, possibly in the absence of a systemic infection inducing IgG antibodies. Figure 2B shows the trajectory of IgA antibodies to a few individual strains. Both anti-stalk group 1 (cH5/1, cH9/1) and group 2 (cH5/3 and cH4/7) IgG (Figure 1A) and IgA antibodies (Figure 1B), which can confer cross-strain immunity, were abundant in the early months in infant serum and BM, respectively.

**Discussion**

Our pilot data suggest feasibility for measuring antibody responses to influenza strains in maternal breast milk and paired infant serum utilizing a novel multiplex assay to assess changes over time. We show an anticipated decline in IgG responses to influenza HA in the first 5 months of life reflecting waning passive transplacentally acquired immunity, whereas the systemic IgA response in infants appears to be relatively poor, consistent with no vertical transfer. This does not exclude the possibility that such young infants might have a response at mucosal surfaces, such as in saliva upon exposure. Throughout the first year, however, a small increase in IgA antibodies, but not IgG antibodies, is seen in these unvaccinated infants, possibly suggesting that the adaptive immune response to natural exposure, in the absence of systemic infection induces initially local IgA, but not IgG antibodies. We also show that while the IgG specificity patterns were rather similar between breast milk and maternal serum, the patterns for IgA specificity were distinct and more pronounced in BM than those seen in serum. These data suggest that during this time, breast milk IgA may indeed be an important means of providing mucosal protection, which closely reflects maternal mucosal exposure to a variety of influenza strains to benefit the infant. Our previous results comparing food-specific IgA in human milk and maternal serum have shown similarly marked differences between human milk and serum IgA antibody profiles⁶. This is likely reflecting the fact that IgA-producing cells in mammary gland originate in the gut- and bronchus-associated lymphoid tissue, which constitute an important defense mechanism of the newborn⁷.

Although our study does not address the antibody profiles in vaccinated dyads, maternal influenza vaccination is recommended during pregnancy to induce infant post-partum passive immunity, and for infants after 6 months of age, although many choose to defer vaccination. As indicated by our pilot study, responses in mothers and infants are heterogeneous. At present, there is no robust literature or clinical method to optimize the vertical transfer of protective antibodies. Furthermore, the mechanisms
Figure 1. The influenza virus hemagglutinin (HA)-specific antibody IgG and IgA levels in paired mother-infant samples. The antibody levels against homologue and cross-reactive HA proteins from different influenza virus strains were evaluated by the mPlex-Flu assay using paired mother’s serum, breast milk (BM) and infant’s serum at different ages expressed as months. **A.** The IgG antibodies against individual HA of influenza virus strains. Maternal serum was diluted 1:5000, infant serum 1:10 and breast milk 1:10. The IgG antibodies against influenza virus HA were estimated using Phycoerythrin (PE)-conjugated anti-human IgG (γ chain specific) secondary antibodies (SouthernBiotech, AL) and shown as means of median fluorescence intensity (MFI) (n=3). The antibody titers (Log$_2$(MFI+1)) against individual rHA of influenza virus strains were plotted and connected by LOWESS curves. In the panel of IgG MFI units of infant serum samples, the gray is the area under the HA antibody curve of the oldest sampling time point in the same subject. **B.** The IgA antibodies against individual HA of influenza virus strains. Maternal serum was diluted 1:500, infant serum 1:10 and breast milk 1:10. Then IgA antibodies were detected using PE-conjugated anti-human IgA (α chain specific) secondary antibodies (SouthernBiotech, AL) and shown as the mean of median fluorescence intensity (MFI) (n=3). The antibody titers (Log$_2$(MFI+1)) against individual rHA of influenza virus strains were plotted and connected by LOWESS curves. In the panel of Ig MFI units of infant serum samples, the gray is the area under the HA antibody curve of the youngest time point in the same subject.
of imprinting or maternal imprinting of the infant immune system are incompletely understood. Thus, there is a critical need for empirical data regarding maternal (serum, BM) and infant (serum) influenza-specific antibody levels over time to inform about maternal impact of influenza immunity, and to predict the individual window of infant susceptibility to influenza. Larger studies are required to further elucidate the interesting findings of this pilot study to aid in assessment of (maternal) imprinting of influenza immunity. Knowing the scope of passive immunity, both transplacental and that provided by BM, and when it vanishes, would allow for precision maternal-fetal and infant vaccination schedule design, also accounting for circulating influenza strains, seasonality, and vaccination status.

Data availability
F1000Research: Dataset 1. Raw data for the present study, https://doi.org/10.5256/f1000research.16717.d2241371, including the following files:

- **Influenza-specific IgA antibody data as MFI.** The file contains the IgA antibody data expressed as MFI for a panel influenza strains generated by mPlex-Flu assay utilizing all breast milk and serum samples. (IgA_20160908_MFI.xlsx)

- **Comparison of influenza-specific IgA antibodies between paired samples.** The MFI titer comparison of IgA antibody of maternal serum (MS) vs breast milk (BM) and infant’s serum (IS) over time using the Prism 7 software. (IgA version2018.pfx)

- **Influenza-specific IgG antibody data as MFI.** The file contains the IgG antibody data expressed as MFI for a panel influenza strains generated by mPlex-Flu assay utilizing all breast milk and serum samples. (IgG_20160908_MFI.xlsx)

- **Comparison of influenza-specific IgG antibodies between paired samples.** The file contains MFI unit comparison of influenza-specific IgG antibodies of maternal serum (MS) vs breast milk (BM) and infant's serum (IS) over time using the Prism 7 software. (IgG version2018.pfx)

- **Program code for IgA heatmap.** The Mathematica 2 program code for generation of the heatmap figure of IgA data of maternal serum (MS), breast milk (BM) and infant’s serum (IS) from mPlex-Flu assay. (IgA MFI Revised.nb)

- **Program code for IgG heatmap.** The Mathematica 2 program code for generation of the heatmap figure of IgG data of maternal serum (MS), breast milk (BM) and infant’s serum (IS) from mPlex-Flu assay. (IgG MFI Revised.nb)
Grant information

The project described was supported by Grant Number K08 AI091655 (K MJ), R21 AI138500 (MZ, JW) and R01AI129518 (MZ) from the National Institute of Allergy and Infectious Diseases, and ULI TR002001 (MZ, JW) from the National Institute for Advancing Translational Sciences. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institute of Allergy and Infectious Diseases, the National Institute for Advancing Translational Sciences, or the National Institutes of Health.

The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Supplementary material

Supplementary Figure 1. Heatmaps of IgG and IgA antibodies to influenza strains measure by multiplex array in paired mother’s serum (MS), breast milk, (BM) and infant serum (IS) samples. The antibody levels against homologue and cross-reactive HA proteins from different influenza virus strains were evaluated by the mPlex-Flu assay using paired mother’s serum, breast milk (BM) and infant’s serum at different ages expressed as months. A. The IgG antibodies against individual HA of influenza virus strains. MS samples were diluted 1:5000, BM samples were diluted 1:10, and IS samples were diluted 1:10. The IgG antibodies against influenza virus HA were estimated using Phycoerythrin (PE)-conjugated anti-human IgG (γ chain specific) secondary antibodies (SouthernBiotech, AL) and shown as mean median fluorescence intensity (MFI) (n=3). B. The IgA antibodies against individual HA of influenza virus strains. MS samples were diluted 1:500, BM samples were diluted 1:10 and IS samples were 1:10 diluted. Then IgA antibodies were detected using PE-conjugated anti-human IgA (α chain specific) secondary antibodies (SouthernBiotech, AL) and shown as MFI unit also (n=3).

Click here to access the data

References

Open Peer Review

Current Referee Status: ? ✓

Version 1

Referee Report 04 February 2019

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David C. Dallas ¹, Jiraporn Lueangsakulthai ²

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Overall, this is a very interesting method and an interesting application. I have a few comments.

Page 1, Methods: This should be “which can provide mucosal protection”.

Page 3, Methods: Shouldn’t it be -80 Celsius? Not Fahrenheit.
Page 3, Methods: Please specify how the dilutions used for each sample type were determined.

Page 4, Table 2: Need to specify the meaning of the coloring of the text. It is not clear why some are colored and some are not. The table only says that “seasonal vaccine strains are in bold” but does not mention the colors.

Page 5, Results, paragraph 2: How do you defined “concordance”? What are your thresholds for how similar it needs to be? Pair 4 (IgA titers) could also be argued to be concordant.

Page 6, Figure 1 legend: curvel -> curve? Curvel is written twice—not sure if this is a word I’m not familiar with or a misspelling of “curve”.
Page 6, Figure 1: The text is very small. Can you figure out how to enlarge please?
Page 6, Figure 1 legend: MS abbreviation needs to be defined in the legend.
Page 6, Figure 1 legend: “IS”, infant serum needs to be defined in legend.
Page 6, Figure 1 legend: Need to explain why Log2 was selected for this display.
Page 6, Figure 1 legend: Need to explain what “net” MFI refers to. What is the “net” part?
Page 6, Figure 1 legend: Unclear why Log2(MFI + 1) is used. What is the + 1 for?

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

**Competing Interests:** No competing interests were disclosed.

**Reviewer Expertise:** milk protein digestion and peptidomics

We have read this submission. We believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

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**Kirsty Le Doare**
Department of Paediatrics, Imperial College London, London, UK

This interesting pilot study investigates the association between anti-influenza antibodies measured by Luminex in blood and breast milk.

Breast milk is a much understudied body fluid. However, the numbers in this study and the fact that the timing of breast milk collection varies so greatly means that the results are merely descriptive. Breast milk changes throughout feeding, by time of day and by time of collection relative to feeds. Thus the sampling, although I understand the rationale of convenience, means that the results are not interpretable as they currently are described.

It would be useful to add more detail from the original study on timing of sample collection etc. How do you account for different rates of decline? IgG rate of decline is uniform across many pathogens and I am unsure why this should be any different in your study. What was the half life and how does it compare to the other studies you cite?

Could the differences you see between pairs also be due to non-specific binding within your assay?

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Yes
If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Vaccine immunity

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 28 Jan 2019

Kirsi Jarvinen, University of Rochester Medical Center, USA

COMMENT: Breast milk is a much understudied body fluid. However, the numbers in this study and the fact that the timing of breast milk collection varies so greatly means that the results are merely descriptive. Breast milk changes throughout feeding, by time of day and by time of collection relative to feeds. Thus the sampling, although I understand the rationale of convenience, means that the results are not interpretable as they currently are described.

REPLY: As mentioned under methods, we utilized stored frozen foremilk collected in the morning. The sample was not a convenience sample but taken according to the study protocol using strict criteria in a prospective manner. Specifically samples were foremilk (not mixed sampling or hindmilk) taken always between hours 8 and 11, and 1-2 hours after the last feeding.

COMMENT: It would be useful to add more detail from the original study on timing of sample collection etc.

How do you account for different rates of decline? IgG rate of decline is uniform across many pathogens and I am unsure why this should be any different in your study. What was the half life and how does it compare to the other studies you cite?

REPLY: As part of the prospective study, breast milk and serum samples were collected during followup visits, and included colostrum and breast milk at 1 month, 3 months, 6 months, 9 months, and 12 months of duration of lactation. However, a few samples were never received due to missed visits or sample timing had to be moved due to illness or other difficulties in getting to the scheduled visits, and some samples have been used up in prior studies. Therefore, not all sample time points are available for all subjects. Regarding decline in IgG, we agree that the levels decline throughout the lactation, as seen in Fig 2a. Due to the small number of samples, no statistical modeling or halflife calculations have been done.

COMMENT: Could the differences you see between pairs also be due to non-specific binding within your assay?

REPLY: The mPlex-Flu assay is a novel assay to estimate the specific antibody binding to recombinant hemagglutinin (rHA) of multiple influenza virus strains. It has been shown to strongly...
correlate with all functional assays of influenza specific antibodies, such as hemagglutination inhibition (HAI) assay and influenza virus micro-neutralization assay (Wang J et al 2015 Ref 8, Wang J et al 2018 (new reference added #9)). In addition, in our previous study, mPlex-Flu assay had been shown to have excellent specificity for each influenza virus strains using the HA specific bind blocking in multiple plex assay (Ref 8), and we also used this method to confirmed the specificity of mPlex-Flu assay using human milk samples is similar to using human serum samples (New Supplementary Fig 1). These data suggest minimal non-specific binding between pair samples. As we have demonstrated before, there is cross-reactivity of anti-HA antibodies between antigenically similar influenza strains, which is directed against specific B cell epitopes with similar or homologous sequences and antigenic similarity. This type of cross reactivity, while it may be broad, is specific and based on shared epitopes.

**Competing Interests:** None

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