Delivery of subunit influenza vaccine to skin with microneedles improves immunogenicity and long-lived protection

Dimitrios G. Koutsonanos, Emory University
Elena V. Vassilieva, Emory University
Anastasia Stavropoulou, Emory University
Vladimir G. Zarnitsyn, Georgia Institute of Technology
Edward Esser, Emory University
Misha T. Taherbhai, Emory University
Mark R. Prausnitz, Emory University
Richard W Compans, Emory University
Ioanna Skountzou, Emory University

Journal Title: Scientific Reports
Volume: Volume 2, Number 357
Publisher: Nature Publishing Group: Open Access Journals - Option B | 2012-04-12, Pages 1-10
Type of Work: Article | Final Publisher PDF
Publisher DOI: 10.1038/srep00357
Permanent URL: http://pid.emory.edu/ark:/25593/dvzdp

Final published version:
http://www.nature.com/srep/2012/120412/srep00357/pdf/srep00357.pdf

Copyright information:
© 2012 Koutsonanos et al.

This is an Open Access work distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 Unported License (http://creativecommons.org/licenses/by-nc-sa/3.0/).
Delivery of subunit influenza vaccine to skin with microneedles improves immunogenicity and long-lived protection

Dimitrios G. Koutsonanos¹, Elena V. Vassilieva¹, Anastasia Stavropoulou³, Vladimir G. Zarnitsyn², E. Stein Esser¹, Misha T. Taherbhai¹, Mark R. Prausnitz², Richard W. Compans¹ & Ioanna Skountzou¹

¹Department of Microbiology & Immunology and Emory Vaccine Center, Emory University School of Medicine, 1510 Clifton Road, Atlanta, GA 30322, ²School of Chemical and Biomolecular Engineering, Georgia Institute of Technology, 311 Ferst Drive, Atlanta, GA 30332-0100, ³Department of Microbiology & Immunology, Medical School, University of Athens, 75 Mikras Asias Street, 11527 Athens, Greece.

Influenza infection represents a major socio-economic burden worldwide. Novel delivery methods can render influenza vaccination easier and more acceptable by the public, and importantly confer protection equal or superior to that induced by conventional systemic administration. An attractive target for vaccine delivery is the skin. Recent studies have demonstrated improved immune responses after transdermal delivery of inactivated influenza virus with microneedle patches. Here we show that immunization with a licensed influenza subunit vaccine coated on metal microneedles can activate both humoral and cellular arms of the immune response and confer improved long-term protection in the mouse model when compared to the conventional systemic route of delivery. These results demonstrate the promising potential of microneedle delivery of licensed influenza subunit vaccines, that could be beneficial in increasing vaccine coverage and protection and reducing influenza-related mortality worldwide.
expressing cells leading to poor antigen-dependent T cell activation and reduced humoral and cellular immune responses\textsuperscript{25}. Other tissue targets for delivery of influenza vaccine have been proposed in recent years including the skin, which represents an ideal target for vaccine delivery. It contains a large network of immunologically active cells and APCs that take up the antigen and migrate to the proximal lymph nodes where naïve T and B cells will be activated to initiate the adaptive immune responses\textsuperscript{26}. We and others have previously reported that delivery of whole inactivated influenza virus via the skin using antigen-coated metal microneedle patches elicits strong humoral and cellular immune responses, serological memory and improved long term protection compared to the conventional routes of vaccine delivery\textsuperscript{20,27,28}.

In this study we investigate for the first time the efficacy of a single-dose skin vaccination with a licensed influenza subunit vaccine using antigen-coated metal microneedles and the longevity of immune responses induced upon skin delivery.

**Results**

Humoral immune responses after microneedle or IM delivery of influenza subunit vaccine. To compare the efficacy of immunization via the skin or intramuscularly, we first measured the levels of functional antibody titers against the hemagglutinin antigen (HA) of influenza virus induced after immunization. The Centers for Disease Control and Prevention (CDC) state that a titer of $\geq 1:40$ is indicative of protection in humans. In our experience titers of $\geq 1:40$ are also indicative or protection in mice. As shown in Fig. 1a, microneedle delivery of the subunit vaccine elicited levels of functional antibody titers indicative of protection (HAI>40) as early as week 4. By week 8 the IM immunized group exhibited the peak of protective HAI titers whereas the microneedle group reached the highest levels by week 12. Thirty six weeks post-immunization, we observed that 62% of the IM vaccinated animals exhibited protective levels (HAI>40) while 100% of the microneedle group maintained protective levels of functional antibody titers and two-fold higher titers when compared to the IM immunized group (p<0.0262). These results demonstrate that delivery of subunit influenza vaccine through the skin using microneedles elicits and sustains higher functional antibody titers, indicative of better duration of protection when compared to IM immunization.

We additionally determined the levels of influenza-specific circulating IgG antibodies in sera of vaccinated mice. Up to 8 weeks post-immunization the IM group demonstrated significantly higher antibody titers than the microneedle group (p<0.0018). From week 12 until week 36 there were no significant differences between the immunized groups (Fig. 1b). In our previous studies we reported that the isotype profile of the immune responses is affected by the route of immunization\textsuperscript{25–27}. Mice that received the subunit vaccine through the IM route of delivery exhibited approximately two-fold greater levels of IgG1 circulating antibodies when compared to microneedle immunized mice (p<0.0001) (Fig. 1c). In contrast, microneedle immunization induced a more potent IgG2a response with a two-fold greater difference when compared to IM injection (p<0.0001) (Fig. 1d). We found a more balanced IgG1/IgG2a ratio in the microneedle group, which skewed towards IgG2a responses at later time points (Fig. 1e). In contrast the IM immunized group demonstrated a predominant IgG1 response. These results indicate that microneedle-based delivery of influenza subunit vaccine induces stronger, long-lasting IgG2a titers indicative of a Th1 response when compared to IM immunization.

Delivery of subunit influenza vaccine through the skin using microneedle or through IM injection induced high levels of neutralizing antibody titers in both vaccinated groups. These responses in the microneedle group were significantly higher than the IM group at 24 (p=0.0426) and 36 weeks post-vaccination (p<0.0002) (Fig. 1f). These results further demonstrate the stronger immune responses induced after microneedle delivery of influenza subunit vaccine in the skin.

Evaluation of systemic recall and mucosal immune responses and assessment of viral replication after challenge. Twelve weeks after delivery of a single dose of subunit influenza vaccine, mice from all groups were challenged with 5xLD\textsubscript{50} of mouse-adapted A/Brisbane/59/2007 virus and 4 days later sera were collected for the evaluation of recall responses. We observed that the HAI titers were two-fold higher in the microneedle immunized group than the IM group (p<0.0195) (Fig. 2a), although there were no significant differences in the levels of IgG1 and IgG1 influenza-specific antibody titers between the vaccinated groups (Fig. 2b, 2c). In contrast, the levels of influenza-specific IgG2a antibody titers were significantly higher in the microneedle group when compared to the IM group (p<0.0223) (Fig. 2d) further indicating a stronger Th1 response induced after skin vaccination. Evaluation of mucosal immune responses (IgG3, IgG1, IgG2a and IgA) in the lungs of microneedle and IM immunized animals 12 weeks post-vaccination and 4 days post-challenge did not reveal significant differences between the two immunized groups (Fig. 3a–d).

In order to evaluate the protective capacity of the immune response induced after microneedle or IM delivery of influenza subunit vaccine, we determined the lung virus titers after challenge at three months post-vaccination. We were able to detect a high replication rate of the virus in the IM immunized group with a 1.5-fold decrease when compared to unimmunized infected animals (Fig. 3e). In contrast, mice that received the subunit vaccine through the microneedle route of delivery exhibited 40-fold lower lung virus titers when compared to the IM group. These results demonstrate the induction of more effective immune responses after microneedle delivery of subunit influenza vaccine in the skin resulting in greater inhibition of virus replication and more rapid clearance from the lungs of infected animals when compared to IM delivery.

Cellular immune responses in the lungs of immunized animals after lethal challenge. The levels of TNF-\(\alpha\), IL-4, IFN-\(\gamma\), IL-5, IL-6 and IL-10 were measured as indicators of cellular immune responses in the lung suspensions of mice challenged 12 weeks after delivery of subunit influenza vaccine via microneedle administration or IM injection. We observed higher TNF-\(\alpha\) levels in the unimmunized infected mice (Fig. 4a) when compared to either group of vaccinated animals, representative of the inflammatory process and cell death in their lungs\textsuperscript{25}. We measured similar levels of IL-4 in both microneedle and IM vaccinated groups (Fig. 4b), but these were elevated when compared to the levels detected in the unimmunized infected mice. Interleukin-4 inhibits the production of different pro-inflammatory cytokines including TNF-\(\alpha\). Evaluation of IFN-\(\gamma\), IL-5 and IL-6 levels (Fig. 4c, 4d, 4e) did not reveal any significant differences between the microneedle and IM vaccinated groups. The most notable difference in cytokine production was observed in the levels of IL-10 in the microneedle vaccinated group (Fig. 4f). Interleukin-10 is an important anti-inflammatory molecule recognized for blocking pulmonary inflammation and lung injury\textsuperscript{25}. We observed a 2-fold higher level in IL-10 production levels in microneedle immunized animals when compared to the IM group (p<0.0026). These results demonstrate that delivery of subunit influenza vaccine through the skin using microneedles induces robust cellular immune responses and increased production of IL-10, correlating with reduced lung inflammation after lethal challenge.

Evaluation of long-lived bone marrow plasma cells. In order to further investigate the basis for high serum functional antibody titers and improved long-lived protective immune responses after microneedle delivery of influenza subunit vaccine when compared to
IM immunization, we determined the numbers of influenza virus-specific IgG long-lived plasma cells in the bone marrow 12 weeks after a single immunization, a sufficient period for the establishment of memory. We detected elevated numbers of influenza virus-specific long-lived plasma cells in the bone marrow of both immunized groups when compared to the naive group, and a significant increase in the numbers of long lived plasma cells in the microneedle group when compared to IM vaccinated animals.

Figure 1 | Evaluation of humoral immune responses and neutralizing antibody titers. Serum samples from mice were collected 2, 4, 8, 12, 24, and 36 weeks post immunization and analyzed for the levels of functional antibody titers against A/Brisbane/59/2007 by HAI (a), total serum IgG titers (b), and the IgG isotypes, IgG1 (c) and IgG2a (d) by quantitative ELISA, isotype profile ratio (e) and neutralizing antibody titers by microneutralization assay (f). MN: microneedle immunized group, IM: intramuscularly immunized group. ELISA antibody data represent the mean ± SEM. HAI data represent the geometric mean ± 95% CI. *: p<0.05, **: p<0.005, ***: p<0.0001. Statistics for the MN and IM group were performed with two-tailed unpaired Student’s t-test.
No significant difference was detected in the number of anti-influenza specific IgA antibody secreting cells in the bone marrow of microneedle or IM vaccinated groups (Fig. 5b). The higher numbers of influenza virus-specific long-lived plasma cells in the bone marrow of microneedle vaccinated animals may be responsible for the maintenance of high levels of influenza-specific functional antibody titers in the serum and improved protective humoral responses when compared to IM delivery of the vaccine.

Determination of IFN-γ and IL-4 secreting cells in the spleen. To compare the cellular immune responses induced after microneedle or IM delivery of subunit influenza vaccine, we determined the numbers of IFN-γ and IL-4 secreting cells in the spleens of mice 12 weeks after immunization. We detected significantly higher numbers of IFN-γ secreting cells in the microneedle immunized group when compared to IM vaccinated animals (p < 0.0105) (Fig. 6a). However we did not find any differences between the two immunized groups in the numbers of IL-4 secreting cells (Fig. 6b). These results indicate improved cellular immune responses after microneedle delivery of subunit influenza vaccine compared to IM delivery.

Duration of protective immunity. To evaluate the longevity and efficacy of subunit influenza vaccine in conferring protection after a single immunization through the skin or the muscle, cohorts of vaccinated mice were challenged with 5xLD₅₀ of mouse-adapted virus at 4, 12 and 36 weeks post-vaccination. Body weight changes and survival rates were registered daily as previously described. Four weeks post-immunization both vaccinated groups were fully protected against lethal challenge with an average body weight loss of 10–12% (Fig. 7a–a1). Twelve weeks post-immunization both groups again exhibited full protection against lethal challenge and an average body weight loss of 5–6% (Fig. 7b–b1). At week 36 post-immunization, the microneedle group was still fully protected against the virus challenge, exhibiting an average body weight loss of 5% and 100% survival. In contrast, the IM group was only partially protected with a mortality rate of 40% and an average body weight loss of 15% for the mice that survived the challenge (Fig. 7c–c1). These findings demonstrate that skin immunization with microneedles coated with an influenza subunit vaccine induces long-lived immunity capable of conferring full protection and survival against lethal challenge with the homologous virus at least up to thirty six weeks after a single immunization.

Discussion

In the present study we report for the first time that microneedle delivery of a single dose of a licensed influenza subunit vaccine to
BALB/c mice confers complete protection 36 weeks post-vaccination whereas only partial protection was induced after the conventional IM route of delivery. At the same period microneedle immunization also induces higher functional antibody titers and higher influenza specific IgG2a antibodies than the IM immunized group, indicative of stronger cellular immune responses. In our experimental mouse model, both microneedle and IM immunized groups exhibited similar levels of hemagglutination inhibition titers (HAI) at early time points after immunization. Thirty six weeks later, though, we found that 38% of the IM immunized animals demonstrated a significant drop of HAI titers below protective levels (HAI<40), while the microneedle vaccinated group in its entity retained HAI titers above protective levels (HAI>40). The maintenance of these high levels of functional antibody titers throughout a period of nine months can be attributed to the higher number of influenza-specific antibody secreting cells (long-lived bone marrow plasma cells) detected in the microneedle immunized group when compared to the ASC numbers found in the IM cohort.

We have previously reported that skin immunization with whole inactivated virus-coated metal microneedles was equal or superior to systemic vaccination. In those studies we found a high anti-influenza virus IgG1/IgG2a antibody ratio in the microneedle group that received 10 μg of vaccine indicating a skewed Th2 response. This response resulted in a two-fold increase of IL-4 production when compared to the intramuscularly delivered vaccine whereas the IFN-γ production was higher in the IM group than the microneedle
The long-lived antibody secreting cells and the memory B cells were at similar levels in the bone marrow of both immunized cohorts. Those data could not clearly favor either route of vaccination because whole inactivated virus vaccine displays stronger immunogenicity which can activate both arms of immune responses, humoral and cellular. In the present study we tested a licensed influenza subunit vaccine as an antigen by metal microneedle delivery through the skin and compared it to IM delivery. Several studies have previously demonstrated that IM delivery of subunit influenza vaccines induces poor cellular immune responses in humans. Here we show that microneedle delivery of a subunit influenza vaccine elicits higher numbers of IFN-γ secreting cells in the spleen of immunized animals when compared to IM immunization. IFN-γ has been reported to play a major role in the control of viral infections leading to faster viral clearance and apoptosis of infected cells. Furthermore, while microneedle delivery of whole inactivated virus demonstrated a robust IgG1 response, and similar numbers of ASC in the bone marrow, delivery of the subunit vaccine induced a balanced IgG1 and IgG2a response (ratio = 1) and higher numbers of ASC in the bone marrow when compared to IM delivery. These data are

Figure 4 | Cellular immune responses in lung suspensions after virus challenge. The levels of TNF-α (a), IL-4 (b), IFN-γ (c), IL-5 (d), IL-6 (e) and IL-10 (f) cytokines were measured in lung suspensions of MN and IM immunized animals 12 weeks post vaccination and 4 days post-challenge with 5xLD<sub>50</sub> of live virus. INF: infected mice; N: naïve mice. Data represent the mean ± SEM. **: p<0.005. Statistics for the MN and IM group were performed with two-tailed unpaired Student’s t-test.
similar to those obtained with polymer microneedle delivery of whole inactivated virus\textsuperscript{27}.

Activation of both arms of the adaptive immune response contributes to enhanced protection and rapid virus clearance from the lungs after infection, as demonstrated by the 40-fold lower virus titers in the lungs of microneedle immunized mice after lethal challenge, compared to the titers measured in the IM immunized mice. This finding can also be significant for influenza transmission. Influenza vaccines in 90% of vaccinees are delivered by the intramuscular route. Although vaccinated individuals are protected from the disease, they are still able to transmit the virus for a 24–48 h window\textsuperscript{31–33}. The greater inhibition of viral replication and more rapid clearance of the virus observed in the microneedle immunized group could further reduce the infectious potential of vaccinated individuals minimizing transmission from direct contact.

Influenza represents a significant burden to public health\textsuperscript{34–37}. The World Health Organization estimates that there are more than 1.2 billion people at high risk for severe influenza outcomes worldwide: 385 million elderly, 140 million infants and 700 million adults and children with underlying health conditions including pregnant women\textsuperscript{39}. Additionally the WHO estimates that there are approximately 24 million health care workers at high risk for influenza infection who pose a risk for transmission of influenza virus to high risk populations\textsuperscript{39}. Besides increased health care costs, influenza infection poses a major socio-economic burden leading to high levels of worker absenteeism, disruption in work and productivity losses. It is estimated that in the United States, annual influenza epidemics result in an average of 3.1 million hospitalization days and 31.4 million outpatient visits with an average direct medical cost of 10.4 billion dollars annually\textsuperscript{40}. Projected lost earnings due to illness and loss of life averages to 16.3 billion dollars annually, while the total direct and indirect economic burden of annual influenza epidemics amount to 87.1 billion dollars in the US alone\textsuperscript{40}.

Furthermore, the CDC reports that in randomized control trials among different age groups and individuals with medical conditions, the inactivated influenza vaccine effectiveness was estimated to be between 48%–70% during seasons when the vaccine was well matched with the circulating influenza strains\textsuperscript{41}. These data indicate that better influenza vaccines and more effective vaccination methods are needed that will increase vaccine coverage and reduce morbidity and mortality rates.

The skin represents an attractive target for vaccine delivery. Skin-based vaccination has received more attention recently due to encouraging results demonstrating improved immune responses.
after antigen delivery. Additionally there is evidence for dose sparing using transdermal immunization. Several studies have demonstrated improved immune responses after intradermal delivery of influenza vaccines. We and others have previously demonstrated that administration of whole inactivated influenza virus through the skin using solid metal microneedles was capable of inducing improved immune responses, serological memory and long-term protection when compared to the conventional routes of influenza immunization. However the effectiveness of this route for immunization using a subunit vaccine has not been investigated previously and the longevity of the immune responses has received only limited attention.

Here, we used microneedles to simply and reliably deliver influenza subunit vaccine targeted to the skin and we demonstrated enhanced immune responses when compared to the conventional systemic route of delivery. Microneedles, therefore, have the potential to make skin-based vaccination a clinically viable alternative which, besides the immunologic advantages demonstrated in this study, offers several logistical advantages including inexpensive manufacturing, small size for easy storage and distribution, a simple
administration process that might enable self-vaccination to increase patient coverage, and overall better acceptance of this route of vaccination by the general public (Kim Y.C. et al Advanced Drug Delivery Reviews, 2012 in press). Overall, our study demonstrates that microneedle-based delivery has the potential to be used with currently approved vaccines and formulations, and for improving results when compared to the current conventional routes, especially to generate long-lived protective immunity.

**Methods**

Microneedle fabrication and coating. As previously described, metal microneedles were fabricated by etching stainless steel sheets (McMaster-Carr, Atlanta, GA). Each microneedle measured 700 μm tall, with a cross-sectional area of 170 μm by 55 μm at the base and tapering to a sharp tip, with five microneedles per row. Microneedles were dip-coated using a coating solution formulated with 1% w/v carboxymethylcellulose (Carbo-Mer, San Diego, CA), 0.5% w/v Lutrol F-68NF (BASF, Mt. Olive, NJ), 15% w/v D (+)-trehalose dihydrate (Sigma, St. Louis, MO) and HI-N1 A/Brisbane/5200/2007 subunit vaccine solution. The vaccine was kindly provided by Novartis Vaccines and Diagnostics (Cambridge, MA).

Cells and viruses. Madin-Darby canine kidney (MDCK) cells (ATCC CCL 34, American Type Culture Collection, Manassas, VA) were maintained in Dulbecco’s Modified Eagle’s Medium (DMEM) (Mediatech, Herndon, VA) containing 10% fetal bovine serum (HyClone, ThermoFisher Scientific, Rockford, IL). Influenza virus stocks (A/Brisbane/5200/2007) were prepared, purified and inactivated as previously described. Hemagglutination (HA) activity was determined using turkey red blood cells (LAMPIRE Biological Laboratories, Pipersville, PA) as previously described. For inactivation, the purified virus was treated with formalin at a final concentration of 0.1% w/v and then dialyzed against PBS buffer. The virus was confirmed by plaque assay in MDCK cells. The mouse-adapted virus was prepared by serial passage 8 times in lungs of BALB/c mice. The LD₅₀ was calculated by the method of Reed-Muench, and viral titers were determined by plaque assay.

Immunizations, lethal challenge and sample collection. Female BALB/c mice (Charles River Laboratory, Wilmington, MA) (50 mice per group, 6–8 weeks old) received one dose (3 μg) of the subunit A/Brisbane/5200/2007 vaccine through the skin using microneedle arrays coated with the antigen or by IM injection. For microneedle delivery the mice were vaccinated by manual insertion of the microneedles into the skin only once per dorsal surface for 5 min while the mice received an equal dose of the vaccine in both legs. Unimmunized mice were used as an additional negative control. Animals were bled retro-orbitally 2, 4, 8, 12, 24 and 36 weeks post-immunization under systemic anesthesia. Four, 12 and 36 weeks post-immunization under systemic anesthesia. Four, 12 and 36 weeks post-immunization and four days post-challenge of an independent cohort of Charles River Laboratory, Wilmington, MA (50 mice per group, 6–8 weeks old) were used to immunize and four days post-challenge of an independent cohort of Charles River Laboratory, Wilmington, MA (50 mice per group, 6–8 weeks old) were used to immunize mice with the protease inhibitor phenylmethylsulfonyl fluoride (1 mM) (Sigma, St. Louis, MO) and stored at −80 °C until assayed for viral titers or cytokine levels with cytokine ELISA. Spleens were collected for the evaluation of cellular immune responses and cytokine ELISA. Spleens were collected for the evaluation of cellular immune responses and cytokine ELISA.

Virus-specific antibody-secreting cells (ASC) in the bone marrow were determined by a modification of the ELISPOT assay. Briefly, 96-well plates were coated overnight at 4 °C with purified inactivated A/Brisbane/5200/07 at a final concentration of 4 μg/ml and blocked for 2 h with 10% fetal calf serum prior to sample addition. Bone marrow single cell suspensions collected at 4 days after challenge (1×10⁶/well) in cRPMI were plated directly on coated blocked plates and were incubated at 37 °C for 18 h. Samples were enumerated in an ELISPOT reader (Cellular Technology, Shaker Heights, OH) and the results shown as the number of ASC per 10⁶ cells. Plasma cell numbers of vaccinated mice were considered positive if the number of spots were higher than the sum of non-infected group spots + 3×SD/Dev.

**Statistics.** The statistical significance of the differences was calculated by two-tailed unpaired Student’s t-test and one-way ANOVA (one-way analysis of variance including Bonferroni’s multiple comparison test) or two-way ANOVA. For statistical description of the figures, *denotes p<0.05; **denotes p<0.005 and ***denotes p<0.0001. Unless otherwise stated, independent experiments were run at least in triplicate.

1. Fiore, A. E. et al. Prevention and control of influenza: recommendations of the Advisory Committee on Immunization Practices (ACIP), 2008. MMWR Recomm Rep 57, 1–60 (2008).
2. Osterholm, M. T. Preparing for the next pandemic. N Engl J Med 352, 1839–1842 (2005).
3. Camilli, B. et al. An influenza B outbreak during the 2004/2005 winter in appropriately immunized elderly people living in a nursing home. Vaccine 28, 7536–7541 (2010).
4. Iorio, A. M. et al. An influenza A/H3 outbreak during the 2004/2005 winter in elderly vaccinated people living in a nursing home. Vaccine 24, 6615–6619 (2006).
5. Baldo, V. et al. Immunogenicity of three different influenza vaccines against homologous and heterologous strains in nursing home elderly residents. Clin Dev Immunol 2010, S1798 (2010).
6. Bickel, M. et al. Low rate of seroconversion after vaccination with a split virion, adjuvanted pandemic H1N1 influenza vaccine in HIV-1-infected patients. AIDS 24, F31–35 (2010).
7. Cooper, C. et al. Immunogenicity is not improved by increased antigen dose or booster dosing of seasonal influenza vaccine in a randomized trial of HIV infected adults. PloS one 6, e17758 (2011).
8. Nolan, T. et al. Immunogenicity of a monovalent 2009 influenza A(H1N1) vaccine in infants and children: a randomized trial. JAMA : the journal of the American Medical Association 303, 37–46 (2010).
9. Babu, E. R., Misurski, D. A. & Witthuhn, B. A. G. Kinetics of timing of seasonal influenza vaccination on effectiveness and cost-effectiveness in pregnancy. Am J Obstet Gynecol 204, S128–140 (2011).
10. Blanchard-Rohner, G. & Siegrist, C. A. Vaccination during pregnancy to protect infants against influenza: why and why not? Vaccine 29, 7542–7550 (2011).
11. Clarke, C. E. & McComas, K. Seeking and Processing Influenza Virus Information: A Study of Health Care Workers at a Large Urban Hospital. *Health Commun* (2011).

12. Medina, R. A. & Garcia-Sastre, A. Influenza A viruses: new research developments. *Nat Rev Microbiol* 9, 590–603 (2011).

13. Guan, R. et al. Structural basis for the sequence-specific recognition of human ISG15 by the N1 protein of influenza virus. *Proceedings of the National Academy of Sciences of the United States of America* 108, 13468–13473 (2011).

14. Sridharan, H., Zhao, C. & Krug, R. M. Species specificity of the NS1 protein of influenza B virus. *Proceedings of the National Academy of Sciences of the United States of America* 2011.

15. Nichol, K. L. & Trenant, J. J. Vaccines for seasonal and pandemic influenza. *J Infect Dis* 194 Suppl 2, S111–118 (2006).

16. Fiore, A. E. et al. Prevention and control of influenza with vaccines: recommendations of the Advisory Committee on Immunization Practices (ACIP). *MMWR Recomm Rep* 59, 1–62 (2010).

17. Beyer, W. E., Nauta, J. J., Palache, A. M., Giezeman, K. M. & Osterhaus, A. D. Immunogenicity and safety of inactivated influenza vaccines in primed populations: a systematic literature review and meta-analysis. *Vaccine* 29, 5785–5792 (2011).

18. Koyama, S. et al. Plasmacytoid dendritic cells delineate immunogenicity of influenza vaccine subtypes. *Sci Transl Med* 2, 23ra24 (2010).

19. Gross, P. A. Reactogenicity and immunogenicity of bivalent influenza vaccine in one- and two-dose trials in children: a summary. *J Infect Dis* 136 Suppl 6, S616–625 (1977).

20. Koutsonanos, D. G. et al. A controlled double-blind comparison of reactogenicity, immunogenicity, and protective efficacy of whole-virus and split-product influenza vaccines in children. *J Infect Dis* 136, 623–632 (1977).

21. Skountzou, I., Quan, F. S., Jacob, J., Compans, R. W. & Kang, S. M. Transcutaneous immunization with inactivated influenza virus induces protective immune responses. *Vaccine* 24, 6110–6119 (2006).

22. Reed, L. J., M., H. A simple method of estimating fifty percent endpoints. *The American Journal of Hygiene* 27, 493–497 (1938).

23. Zhu, Q. et al. Incorporation of glycosylphosphatidylinositol-anchored granulocyte- macrophage colony-stimulating factor or CD40 ligand enhances immunogenicity of chimeric simian immunoiondeficiency virus-like particles. *J Virol* 81, 1083–1094 (2007).

24. Simon, J. K. et al. Immunization by vaccine-coated microneedle arrays protects against lethal influenza virus challenge. *J Infect Dis* 204, 592–598 (2011).

25. Koutsonanos, D. G. et al. Transdermal influenza immunization with vaccine-coated microneedle arrays. *PloS one* 4, e4773 (2009).

26. Sullivan, S. P. et al. Dissolving polymer microneedle patches for influenza vaccination. *Nat Med* 16, 915–920 (2010).

27. Zhu, Q. et al. Immunization by vaccine-coated microneedle arrays protects against lethal influenza virus challenge. *Proceedings of the National Academy of Sciences of the United States of America* 106, 7968–7973 (2009).

28. Sun, J., Madan, R., Karp, C. L. & Braciale, T. J. Immunization by vaccine-coated microneedle arrays protects against lethal influenza virus challenge. *J Infect Dis* 204, 592–598 (2011).

29. Skountzou, I., Quan, F. S., Jacob, J., Compans, R. W. & Kang, S. M. Transcutaneous immunization with inactivated influenza virus induces protective immune responses. *Vaccine* 24, 6110–6119 (2006).

30. Reed, L. J., M., H. A simple method of estimating fifty percent endpoints. *The American Journal of Hygiene* 27, 493–497 (1938).

31. Skountzou, I., et al. Incorporation of glycosylphosphatidylinositol-anchored granulocyte- macrophage colony-stimulating factor or CD40 ligand enhances immunogenicity of chimeric simian immunoiondeficiency virus-like particles. *J Virol* 81, 1083–1094 (2007).

32. WHO/CDSS/CSR/NCS. WHO Manual of Animal Influenza Diagnosis and Surveillance. *Department of Communicable Disease Surveillance and Response* (2002).

33. Crotty, S., Aubert, R. D., Gildewell, J. & Ahmed, R. Tracking human antigen-specific memory B cells: a sensitive and generalized ELISPOT system. *J Immunol Methods* 286, 111–122 (2004).

Acknowledgements

We thank Derek O'Hagan, Gene Palmer and others at Novartis Vaccines and Diagnostics for providing us with the H1N1 A/Brisbane/59/2007 influenza subunit vaccine. This study was carried out at the Emory Vaccine Center and the Georgia Tech Center for Drug Design, with support in part by U.S. National Institutes of Health grants EB006369 and AI074579. Dimitrios G. Koutsonanos is a trainee of IPIRIC/CEIRS (Influenza Pathogenesis and Immunology Research Center/Centers of Excellence for Influenza Research and Surveillance) and supported by contract 5 HHSN266200700006C from NIH/NIH.

Author contributions

DGK and IS conceived and designed the project. DGK, and IS prepared the figures and did the statistics. DGK executed the majority of the experiments. EVV, AS, VGZ, ESE, MT and IS assisted in the execution of the experiments. DGK and IS wrote the manuscript. BW and MRP edited the manuscript. All authors reviewed the final version of manuscript.

Additional information

Competing financial interests: Mark R. Prausnitz serves as a consultant to companies, is a founding share-holder of companies and is an inventor on patents licensed to companies developing microneedle-based products. This possible conflict of interest has been disclosed and is being managed by Georgia Institute of Technology and Emory University.

License: This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 3.0 Unported License. To view a copy of this license, visit http://creativecommons.org/licenses/by-nc-sa/3.0/.

How to cite this article: Koutsonanos, D.G. et al. Delivery of subunit influenza vaccine to skin with microneedles improves immunogenicity and long-lived protection. *Sci. Rep.* 2, 357; DOI:10.1038/srep00357 (2012).