Recent Advances of Vaccine Adjuvants for Infectious Diseases

Sujin Lee1,2* and Minh Trang Nguyen1,2

1Department of Pediatrics, Emory University, School of Medicine, 2Children’s Healthcare of Atlanta, Atlanta, Georgia 30322, USA

Vaccines are the most effective and cost-efficient method for preventing diseases caused by infectious pathogens. Despite the great success of vaccines, development of safe and strong vaccines is still required for emerging new pathogens, re-emerging old pathogens, and in order to improve the inadequate protection conferred by existing vaccines. One of the most important strategies for the development of effective new vaccines is the selection and usage of a suitable adjuvant. Immunologic adjuvants are essential for enhancing vaccine potency by improvement of the humoral and/or cell-mediated immune response to vaccine antigens. Thus, formulation of vaccines with appropriate adjuvants is an attractive approach towards eliciting protective and long-lasting immunity in humans. However, only a limited number of adjuvants is licensed for human vaccines due to concerns about safety and toxicity. We summarize current knowledge about the potential benefits of adjuvants, the characteristics of adjuvants and the mechanisms of adjuvants in human vaccines. Adjuvants have diverse modes of action and should be selected for use on the basis of the type of immune response that is desired for a particular vaccine. Better understanding of current adjuvants will help exploring new adjuvant formulations and facilitate rational design of vaccines against infectious diseases.

Keywords: Vaccine, Adjuvant, Infectious disease, Innate immunity, Adaptive immunity

VACCINES

Infectious diseases remain the second leading cause of death worldwide after cardiovascular disease, but the leading cause of death in infants and children (1). Vaccination is the most efficient tool for preventing a variety of infectious diseases. The ultimate goal of vaccination is to generate a pathogen-specific immune response providing long-lasting protection against infection (2). Despite the significant success of vaccines, development of safe and strong vaccines is still required due to the emergence of new pathogens, re-emergence of old pathogens and suboptimal protection conferred by existing vaccines. Recent important emerging or re-emerging diseases were severe acute respiratory syndrome (SARS) in 2003, the 2009 H1N1 influenza pandemic, and Ebola virus in 2014 (3). Last year, the most widespread epidemic of Ebola virus caused significant mortality in several West African countries (4). As a result, we are aware of pursuing a new approach towards the rapid development of vaccines against emerging diseases.

Three different types of vaccine are currently used in humans: live-attenuated vaccines, inactivated vaccines and subunit vaccines (5). Many of the most effective vaccines in use are live-attenuated vaccines. As an attenuated vaccine is composed of a virus or bacterium that can replicate within the host, this type of vaccine elicits robust humoral and cell-mediated immunity (CMI). Examples of live-attenuated vaccine include MMR (Measles, Mumps, Rubella), chicken pox, oral polio (Sabin), influenza (the seasonal flu nasal spray and the
Recent Advances of Vaccine Adjuvants for Infectious Diseases
Sujin Lee and Minh Trang Nguyen

Table I. The benefits of adjuvants

| Benefit                                                                 |
|-------------------------------------------------------------------------|
| 1. Decrease the dose of antigen needed (dose sparing)                   |
| 2. Decrease the number of vaccine doses needed                          |
| 3. Enhance vaccine efficacy in infants, the elderly, and immunocompromised people |
| 4. Increase functional antibody titer                                    |
| 5. Induce more rapid and long-lasting immune responses                   |
| 6. Induce robust cell-mediated immunity                                  |
| 7. Provide broad protection (cross-reactivity)                          |
| 8. Facilitate mucosal immunity                                          |
| 9. Overcome antigen competition in combination vaccines                 |

2009 H1N1 nasal spray, rotavirus and yellow fever vaccine. Inactivated (killed) vaccines (e.g., inactivated polio - Salk, Hepatitis A) are either heat-inactivated or chemically inactivated particles of the pathogen. Although these vaccines are safe and non-infectious, they stimulate only weak, short-lived and often insufficient immunity. Thus, large and multiple doses of inactivated vaccine are required to confer protective immunity (6). In contrast to live-attenuated vaccines, inactivated vaccines elicit mainly humoral immunity, with little to no induction of CMI.

Purified or recombinant subunit vaccines derived from non-living vaccine antigens are poorly immunogenic and require the addition of some components to help stimulate protective immunity. In some cases, these vaccines utilize epitopes recognized and bound by antibodies or T-cells. Because subunit vaccines contain only an essential part of the antigen instead of the entire microbe, the chances of adverse reactions to the vaccine are relatively low (7). Subunit vaccines have been made for hepatitis B virus (HBV), influenza virus (injection) and pertussis (part of DTaP combined immunization). Recently developed subunit vaccines are less immunogenic and reactogenic than traditional vaccines such as live-attenuated, and inactivated vaccines. Thus, repeated boosts immunizations or the addition of adjuvant are necessary to enhance the efficacy of subunit vaccines.

NEED FOR ADJUVANTS

The word “adjuvant” is derived from the Latin adjuvare, meaning “to help” or “to aid”. Adjuvants have been defined as agents added to vaccine formulations that enhance the immunogenicity of antigens and induce protection against infection. Vaccines made from live-attenuated or inactivated pathogens can elicit robust protective immune responses because those vaccines contain naturally occurring adjuvants. In contrast, protein-based vaccines in most cases have limited immunogenicity although they have some advantages in terms of safety and cost-effectiveness. Thus, adjuvants are necessary to help these proteins become effective vaccines by inducing strong and long-lasting protective immune responses. Indeed, some protein-based vaccines have been successfully developed in use for human vaccines by mixing with aluminium salts (alum). However, new vaccine targets will require not only strong antibody responses but also robust CMI including T helper (Th) cells and cytotoxic T lymphocytes (CTL). Alum alone will be insufficient for such cases because it is a poor inducer of T cell responses. The use of appropriate adjuvants will allow for vaccine formulations that selectively trigger innate immunity and/or adaptive immunity to obtain a desired type of antigen-specific immune responses. We also describe the practical and functional reasons for why adjuvants are needed as a component in vaccines in Table I.

ADJUVANTS APPROVED FOR HUMAN VACCINES

Licensed adjuvants in use for human vaccines are listed in Table II.

Aluminium Salts (Alum)

In 1926, Glenny et al. reported the adjuvant activity of aluminium compounds utilizing a suspension of alum-precipitated diphtheria toxoid (DT) (8). Aluminium salts are the most widely used adjuvants in human vaccines. These adjuvants have been used in practical vaccination for more than 80 years and are generally considered stimulators of Th2 immunity (9,10). Until 2009 aluminium salt (referred to as “alum”) adjuvants were the only ones contained in vaccines licensed for human use in the United States. Alum is a component of licensed human vaccines such as Hepatitis A virus (HAV), Hepatitis B virus (HBV), human papilloma virus (HPV), diphtheria, tetanus, Haemophilus Influenzae Type b (Hib) and meningococcal. Although there are a number of adjuvants more potent than alum, they have not been used for human vaccine formulations due to high levels of toxicity. Surprisingly, despite the wide use of alum adjuvants in licensed human vaccines, the mechanisms of action are not well characterized. The most well-known mechanism of action of alum is the “depot effect”, first proposed by Glenny in 1925, whereby depot formation was cited to facilitate con-
Table II. Licensed vaccine adjuvants

| Adjuvant name (year licensed) | Class                     | Manufacturer | Description                                                                 | References |
|-------------------------------|---------------------------|--------------|------------------------------------------------------------------------------|------------|
| Alum (1926)                   | Mineral Salt              | Various      | Improves humoral immune responses and antigen stability.                     | (44, 45)   |
|                               |                           |              | Antigens are adsorbed to the surface. The adjuvant in > 80% of vaccines licensed for human use. Th2 type immune responses. |            |
| MF59 (1997)                   | Oil-in-water emulsion     | Novartis     | Improves humoral and cell-mediated immunity. Used in influenza vaccines.      | (21, 46)   |
|                               |                           |              | Antigen delivery.                                                            |            |
| AS03 (2009)                   | Oil-in-water emulsion     | GSK          | Improves humoral and cell-mediated immunity.                                 | (47, 48)   |
|                               |                           |              | Used in influenza during 2009 H1N1 pandemic.                                |            |
| Virosome (2000)               | Liposome                  | Berna Biotech (Crucell) | Improves humoral and cell-mediated immunity. A viroso-me is the reconstituted membrane of an enveloped virus. The vaccines for influenza and for Hepatitis A are approved products | (49, 50)   |
| AS04 (2005)                   | Alum-adsorbed TLR4 agonist | GSK          | Improves humoral and cell-mediated immunity. Combination of aluminum adjuvant with monophosphoryl lipid A (MPL) co-adsorbed. Used for HPV and HBV vaccine. | (30, 51)   |

Continuous antigen release from the injection site (11). Even though depot formation still remains somewhat controversial, recent studies have clearly demonstrated that depot formation is not required for alum adjuvanticity (12-14). Alum has been shown to facilitate humoral immunity via Th2 type immune responses (IgG1, IgE, IL-4, IL-5 and eosinophil) (10,15). The advantages of alum are high safety record, antigen stabilization and augmentation of high and long-lasting antibody titer. However, alum does not have the ability to elicit Th1 type immunity or cytotoxic T cell responses and vaccines containing alum adjuvant cannot be sterilized by filtration, frozen or lyophilized (16).

Oil-in-water (o/w) emulsions: MF59 and adjuvant system 03 (AS03)

Emulsions are unstable two-phase systems consisting of at least two immiscible liquids, combined with a surfactant for stabilization. The major benefits of using emulsions are antigen dose sparing and enhancement of antibody titer. Both MF59 (Novartis) and AS03 (GlaxoSmithKline) are squalene based oil-in-water emulsions (5,17). MF59 has been approved for the H5N1 pandemic influenza vaccine (Fluad) and also for the H1N1 influenza vaccine (Focetria and Celtura) in Europe (18,19). It recruits monocytes and macrophages into injection sites by the induction of local chemokine secretion (17). MF59 can also augment antigen uptake by dendritic cells (DCs) and activate CD4 T cells (20). As a result, MF59 generates high antibody titers with balanced IgG1:IgG2a responses. MF59 has been evaluated in conjunction with Herpes simplex virus (HSV), Human immunodeficiency virus (HIV), HBV and Cytomegalovirus (CMV) vaccine trials (21).

AS03 is included in licensed H5N1 and H1N1 pandemic influenza vaccines. Although both MF59 and AS03 contain squalene oil, they have different compositions, AS03 contains α-tocopherol. Moral et al., demonstrated that AS03 induced a non-specific activation of the immune system in mice in the presence of α-tocopherol (22). Unfortunately, recent studies have reported a possible association between narcolepsy and the use of AS03 adjuvanted H1N1 influenza vaccine (17,22).

Although oil-in-water emulsions seem to be very effective and promising adjuvants, further detailed characterization and analysis of components used in emulsion preparations need to be examined.

Virosomes

A viroso-me is a reconstituted viral envelope possessing membrane lipids and viral glycoproteins, but devoid of viral genetic information (23). The viroso-m vaccine for influenza virus (Inflexal V) is approved in Europe and Hepatitis A virus (Epaxal) vaccine is approved in Asia, Europe and South America (5). Both vaccines utilize virosomes derived from influenza virus represented by Immunopotentiating reconstituted influenza virosomes (IRIV) harboring the influenza hemagglutinin (HA) protein (24). Inflexal V is the only viroso-
Table III. Classes of clinically tested vaccine adjuvants

| Adjuvant name | Class       | Description                                                                 | Clinical phase |
|---------------|-------------|-----------------------------------------------------------------------------|----------------|
| CpG           | TLR 9 agonist | Enhances antibody titer, Th1 type immunity and CD8 T cell-mediated immunity. CpG oligonucleotides. | Phase 3        |
| Flagellin     | TLR 5 agonist | Enhances antibody titer, Th1 and Th2 type immunity. Flagellin linked to antigen. | Phase 1        |
| PolyI:C       | TLR3 agonist | Enhances antibody titer, Th1 type immunity and CD8 T cell-mediated immunity. Double-stranded RNA analogues | Phase 1        |
| AS01          | Combination  | Enhances antibody titer, Th1 type immunity and CD8 T cell-mediated immunity. Combined with MPL, QS21 and liposomes. | Phase 3        |
| AS02          | Combination  | Enhances antibody titer and Th1 type immunity. Combined with MPL, QS21 and emulsion. | Phase 3        |
| ISCOMs and ISCOMMATRIX | Combination | Enhances antibody titer, Th1 and Th2 type immunity and CD8 T cell-mediated immunity. Combined with saponin and phospholipid. | Phase 2        |
Polyriboinosinic acid-polyriboctydyl acid (poly I:C) mimics viral dsRNA and is a promising candidate for a vaccine adjuvant against intracellular pathogens. Poly I:C binds to TLR3 and enhances robust CMI and potent type I interferon response. However, the major drawback of stability and toxicity issues need to be addressed before proceeding to clinical application of dsRNAs. Recently, a clinically safe dsRNA, PolyIC analogue (Ampligen), was investigated as an adjuvant for intranasal H5N1 Influenza virus vaccines (36). Bacterial flagellin, a TLR 5 agonist, is a known immunostimulator that induces high antibody titer, and mixed Th1 and Th2 type immune responses. The D1 portion of flagellin binds to TLR 5 and can be expressed in a fusion protein with selected vaccine antigens. Due to this characteristic of flagellin, a major advantage of the TLR5-dependent adjuvant is that a fusion protein can co-deliver antigen and TLR5 agonist to the APC (37). Thus, flagellin fusion proteins are suitable adjuvants for the development of vaccines to induce robust antigen-specific immune responses. Indeed, a flagellin/ hemagglutinin-based vaccine (VAX128) and a flagellin/matrix protein 2 ectodomain (M2e) vaccine (VAX102) are in clinical trials of vaccines against influenza (38, 39). Although further studies in humans are required, it appears that TLR agonists may be attractive candidates for use in human vaccines.

**Immune stimulating complexes (ISCOM)**

ISCOMs are another promising lipid-based adjuvant formulation. ISCOMs are spherical and ring-like structures spontaneously formed upon mixing antigens with saponin, cholesterol and phospholipid (40). The compound QS-21, a potent immunostimulatory saponin, was extensively studied as an adjuvant in various vaccines, though it has not yet been approved for human vaccine use due to the toxicity of QS-21. Since ISCOM allows for the reduction in QS-21 dose, it is being considered as a new approach to overcome the issue of toxicity. The second type of ISCOM is called ISCOMMATRIX, which doesn’t contain cholesterol. The major advantage of ISCOM and ISCOMMATRIX is their exceptional stability owing to the high affinity between saponin and cholesterol, therefore allowing them to be effective adjuvants for mucosal vaccines (41). Main benefits of these adjuvants are induction of high and long-lasting antibody titer, induction of balanced Th1 and Th2 type immunity, and induction of CMI including cytotoxic T cell responses (42). The adjuvant properties of ISCOM and ISCOMMATRIX are currently being evaluated in clinical trials of influenza, HCV and HPV. Collectively, usage of ISCOM and ISCOMMATRIX as adjuvants could be an alternative approach in vaccine development against infectious pathogens.

**Adjuvant systems (AS)**

Adjuvant systems (GSK) refer to various combinations of classical adjuvants such as aluminum salts, o/w emulsions, liposomes and immunostimulators designed to adjust the adaptive immune responses against pathogens (30). The challenge for this strategy is to define the best combination for an effective and safe formulation in which individual components can synergize with one another to elicit a more robust immune response. As described in Table II, AS03 and AS04 have been approved as adjuvants in several human vaccines. Here, we will discuss AS01 and AS02, which are in recent development. AS02 is identical to AS03 (α-tocopherol+squalene) with the addition of MPL and QS21. While AS03 induces biased Th2 type immune responses, AS02 induces high antibody titer and dominant Th1 type immune responses owing to the addition of MPL. Although some local and systemic reactogenicity has been reported, AS02 is in clinical trials for various vaccine applications, including malaria, HBV, HPV, tuberculosis, and HIV (15). AS01 combines three components such as liposomes, MPL and QS21 (15). Unlike AS02, AS01 was designed to improve CD8 T cell responses, AS01 induces robust Th1 type immune responses, enhances antigen presentation to APC, and induces high antibody titer. Recent studies demonstrated that an AS01 malaria vaccine induces increased IgG titers and polyfunctional CD4 T cells expressing IL-2, IFN-γ, TNF-α, or CD40L (43). Several clinical trials are in progress with AS01-containing vaccine candidates against infectious pathogens, including HIV, tuberculosis and malaria.

**CONCLUSIONS AND PERSPECTIVES**

The ultimate goal of vaccination is to generate potent and long-term protection against diseases. Such protective immunity can be elicited by using vaccine formulations containing appropriate antigens and adjuvants. Adjuvants are important components of vaccines and can affect the outcomes of vaccination. Past approaches of vaccine formulation with adjuvants were focused on single-type adjuvants such as alum or emulsions. However, newer vaccine targets require the induction of well-defined CMI in addition to high titer of antibody. Consequently, new immunostimulant adjuvants in vaccine formulations are needed in order to stimulate robust
immune responses including humoral immunity and CMI. As great progress has been made in the field of adjuvant research over last two decades, vaccinologists are now able to select an appropriate adjuvant from classical adjuvants, immunostimulants or combinations thereof to enhance vaccine efficacy. Taken together, recent successful clinical studies conducted with new adjuvants suggest that a panel of novel immunostimulant adjuvants will be utilized for human vaccine formulations in a near future. The availability of these adjuvants in various combinations will facilitate the rational design of vaccines against infectious diseases.

**CONFLICT OF INTEREST**

The authors declare no conflict of interest.

**REFERENCES**

1. Fauci, A. S. 2001. Infectious diseases: considerations for the 21st century. *Clin. Infect. Dis.* 32: 675-685.
2. Leroux-Roels, G. 2010. Unmet needs in modern vaccinology: adjuvants to improve the immune response. *Vaccine* 28 Suppl 3: C25-C36.
3. Chan, E. H., T. F. Brewer, I. C. Madoff, M. P. Pollack, A. L. Sonnicker, M. Keller, C. C. Freifeld, M. Blench, A. Mawudeku, and J. S. Brownstein, 2010, Global capacity for emerging infectious disease detection, *Proc. Natl. Acad. Sci. U. S. A.* 107: 21701-21706.
4. WHO Ebola Response Team. 2014, Ebola virus disease in West Africa—the first 9 months of the epidemic and forward projections, *N. Engl. J. Med.* 371: 1481-1495.
5. Riese, P., K. Schulze, T. Ebensen, B. Prochnow, and C. A. Guzman, 2013, Vaccine adjuvants: key tools for innovative vaccine design, *Curr. Top. Med. Chem.* 13: 2562-2580.
6. Baxter D. 2007, Active and passive immunity, vaccine types, excipients and licensing, * Occup. Med. (Lond)* 57: 552-556.
7. Reed, S. G., M. T. Orr, and C. B. Fox, 2013, Key roles of adjuvants in modern vaccines, *Nat. Med.*, 19: 1597-1608.
8. Glenny, A. T., C. G. Pope, H. Waddington, and U. Wallace, 1926, Immunological notes, XVII–XXIX, *J. Pathol. Bacterial.* 29: 31-40.
9. Brewer, J. M. 2006, (How) do aluminium adjuvants work?, *Immunol. Lett.* 102: 10-15.
10. Lindblad, E. B., 2004, Aluminium adjuvants—in retrospect and prospect, *Vaccine* 22: 3688-3688.
11. Glenny, A. T., and C. G. Pope, 1925, The antigenic effect of intravenous injection of diphtheria toxin, *J. Pathol. Bacterial.* 28: 273-278.
12. Hutchinson, S., R. A. Benson, V. B. Gibson, A. H. Pollock, P. Garside, and J. M. Brewer, 2012, Antigen depot is not required for alum adjuvanticity. *FASEB J.* 26: 1272-1279.
13. Awate, S., L. A. Bahiuk, and G. Mutwiri, 2013, Mechanisms of action of adjuvants, *Front. Immunol.*, 4: 114.
14. Marrack, P., A. S. McKee, and M. W. Munks, 2009, Towards an understanding of the adjuvant action of aluminium, *Nat. Rev. Immunol.*, 9: 287-293.
15. Reed, S. G., S. Bertholet, R. N. Coler, and M. Friede, 2009, New horizons in adjuvants for vaccine development, *Trends Immunol.*, 30: 23-32.
16. Gupta, R. K., 1998, Aluminum compounds as vaccine adjuvants, *Adv. Drug Deliv. Rev.* 32: 155-172.
17. O'Flaherty, D. T., G. S. Ott, E. De Gregorio, and A. Seubert, 2012, The mechanism of action of MF59—an innately attractive adjuvant formulation, *Vaccine* 30: 4341-4348.
18. Podda, A. 2001, The adjuvanted influenza vaccines with novel adjuvants: experience with the MF59-adjuvanted vaccine, *Vaccine* 19: 2672-2680.
19. Gasparini, R., F. Schioppa, M. Lattanzi, M. Barone, D. Casula, M. Pellegrini, K. Veitch, and N. Gaitatzis, 2010, Impact of prior or concomitant seasonal influenza vaccination on MF59-adjuvanted H1N1v vaccine (Focetria) in adult and elderly subjects, *Int. J. Clin. Pract.* 64: 432-438.
20. Calabro, S., M. Tortoli, B. C. Baudcher, A. Pacitto, M. Cortese, D. T. O'Hagan, G. E. De, A. Seubert, and A. Wick, 2011, Vaccine adjuvants alum and MF59 induce rapid recruitment of neutrophils and monocytes that participate in antigen transport to draining lymph nodes, *Vaccine* 29: 1812-1823.
21. O'Hagan, D. T., G. S. Ott, G. V. Nest, R. Rappuoli, and G. D. Giudice, 2013, The history of MF59® adjuvant: a phoenix that arose from the ashes, *Expert Rev. Vaccines* 12: 13-30.
22. Morel, S., A. Didierlaurent, P. Bourgijnon, S. Delhaye, B. Baras, V. Jacob, C. Planty, A. Elouahabi, P. Harvengt, H. Carslen, A. Kieland, P. Chomez, N. Garcon, and M. M. Van, 2011, Adjuvant System AS03 containing alpha-tocopherol modulates innate immune response and leads to adaptive immunity, *Vaccine* 29: 2461-2473.
23. Brito, L. A., and D. T. O'Hagan, 2014, Designing and building the next generation of improved vaccine adjuvants, *J. Control Release* 190: 563-579.
24. Almeida, J. D., D. C. Edwards, C. M. Brand, and T. D. Heath, 1975, Formation of virosomes from influenza subunits and liposomes, *Lancet* 2: 899-901.
25. Moser, C., M. Amacker, A. R. Kammer, S. Rasi, N. Westerfeld, and R. Zurbriggen, 2007, Influenza virosomes as a combined vaccine carrier and adjuvant system for prophylactic and therapeutic immunizations, *Expert Rev. Vaccines* 6: 711-721.
26. Cusi, M. G. 2006, Applications of influenza virosomes as a delivery system, *Hum. Vaccin.* 2: 1-7.
27. Medzhitov, R. 2001, Toll-like receptors and innate immunity, *Nat. Rev. Immunol.* 1: 135-145.
28. Coffman, R. L., A. Sher, and R. A. Seder, 2010, Vaccine adjuvants: putting innate immunity to work, *Immunity* 33: 492-503.
29. Gustafsson, G. I., and M. J. Rhodes, 1992, Bacterial cell wall products as adjuvants: early interferon gamma as a marker for adjuvants that enhance protective immunity, *Res. Immunol.* 143: 483-499.
30. Garcon, N. P., Chomez, and M. M. Van, 2007, GlaxoSmithKline Adjuvant Systems in vaccines: concepts, achievements and perspectives, *Expert Rev. Vaccines* 6: 723-739.
31. Descamps, D., K. Hardt, B. Spiessens, P. Izurieta, T. Verstraeten, T. Breuer, and G. Dubin, 2009, Safety of human papillomavirus (HPV)-16/18 AS04-adjuvanted vaccine for cervical cancer prevention: a pooled analysis of 11 clinical trials, *Hum. Vaccin.*, 5: 352-360.

32. Beran, J. 2008, Safety and immunogenicity of a new hepatitis B vaccine for the protection of patients with renal insufficiency including pre-haemodialysis and haemodialysis patients, *Expert Opin. Biol. Ther.*, 8: 235-247.

33. Didierlaurent, A. M., S. Morel, I. Lockman, S. I., Giannini, M. Bisteau, H. Carlsten, A. Kielland, O. Vosters, N. Vanderheyde, F. Schiavetti, D. Larocque, M. M. Van, and N. Garcon, 2009, AS04, an aluminum salt- and TLR4 agonist-based adjuvant system, induces a transient localized innate immune response leading to enhanced adaptive immunity, *J. Immunol.*, 183: 6186-6197.

34. Krieg, A. M. 2006, Therapeutic potential of Toll-like receptor activation, *Nat. Rev. Drug Discov.*, 5: 471-484.

35. Eng, N. F., N. Bhardwaj, R. Mulligan, and F. az-Mitoma, 2013, The potential of 1018 ISS adjuvant in hepatitis B vaccines: HEPLISAV review, *Hum. Vaccin. Immunother.*, 9: 1661-1672.

36. Hasegawa, H., T. Ichinohe, A. Ainai, S. Tamura, and T. Kurata, 2009, Development of mucosal adjuvants for intranasal vaccine for H5N1 influenza viruses, *Ther. Clin. Risk Manag.*, 5: 125-132.

37. Duthie, M. S., H. P. Windish, C. B., Fox, and S. G. Reed, 2011, Use of defined TLR ligands as adjuvants within human vaccines, *Hum. Vaccin.*, 259: 178-196.

38. Taylor, D. N., J. J., Treanor, E. A. Sheldon, C. Johnson, S. Umlauf, I. Song, U. Kavita, G. Liu, L. Tussey, K. Ozer, T. Hofstaetter, and A. Shaw, 2012, Development of VAX128, a recombinant hemagglutinin (HA) influenza-flagellin fusion vaccine with improved safety and immune response, *Vaccine* 30: 5761-5769.

39. Turley, C. B., R. E., Rupp, C. Johnson, D. N., Taylor, J. Wolfson, I. Tussey, U. Kavita, L. Stanberry, and A. Shaw, 2011, Safety and immunogenicity of a recombinant M2e-flagellin influenza vaccine (STF2,ixM2e) in healthy adults, *Vaccine* 29: 5145-5152.

40. Morein, B., B. Sundquist, S. Hoglund, K. Dalsgaard, and A. Osterhaus, 1984, Iscom, a novel structure for antigenic presentation of membrane proteins from enveloped viruses, *Nature* 308: 457-460.

41. Garcia, A., and J. B. De Sanctis, 2014, An overview of adjuvant formulations and delivery systems, *APMIS* 122: 257-267.

42. Lowgren, B., K., B. Morein, and A. D. Osterhaus, 2011, ISCOM technology-based Matrix M\(^{\text{TM}}\) adjuvant: success in future vaccines relies on formulation, *Expert Rev. Vaccines* 10: 401-403.

43. Cummings, J. F., M. D. Spring, R. J., Schwenk, C. F. Ockenhouse, K. E., Kester, M. E., Polhemus, D. S. Walsh, I. K. Yoon, C. Prosperi, I. Y., Juompan, D. E. Lanar, U. Krzych, B. T. Hall, I. A. Ware, V. A., Stewart, J. Williams, M. Dowler, R. K. Nielsen, C. J. Hillier, B. K., Giersing, F. Dubovsky, E. Malkin, K. Tucker, M. C. Dubois, J. D. Cohen, W. R. Ballou, and D. G. Heppner, Jr, 2010, Recombinant Liver Stage Antigen-1 (LSA-1) formulated with AS01 or AS02 is safe, elicits high tier antibody and induces IFN-gamma/IL-2 CD4\(^{+}\) T cells but does not protect against experimental Plasmodium falciparum infection, *Vaccine* 28: 5135-5144.

44. Ofeszycka, E., and E. C. Lavelle, 2014, Immunomodulatory properties of the vaccine adjuvant alum, *Curr. Opin. Immunol.*, 28: 1-5.

45. De, G. E., E. Tritto, and R. Rappuoli, 2008, Alum adjuvanticity: unraveling a century old mystery, *Eur. J. Immunol.*, 38: 2008-2071.

46. O'Hagan, D. T., G. S., Ott, and N. G. Van, 1997, Recent advances in vaccine adjuvants: the development of MF59 emulsion and polymeric microparticles, *Mol. Med. Today* 3: 69-75.

47. Garcon, N., D. W. Vaughn, and A. M. Didierlaurent, 2012, Development and evaluation of AS03, an Adjuvant System containing alpha-tocopherol and squalene in an oil-in-water emulsion, *Expert Rev. Vaccines* 11: 349-366.

48. Atmar, R. L., and W. A. Keitel, 2009, Adjuvants for pandemic influenza vaccines, *Curr. Top. Microbiol. Immunol.*, 333: 323-344.

49. Schwendener, R. A. 2014, Liposomes as vaccine delivery systems: a review of the recent advances, *Ther. Adv. Vaccines* 2: 150-182.

50. Moser, C., M. Muller, M. D. Kaeser, U. Weydemann, and M. Amacker, 2013, Influenza virosomes as vaccine adjuvant and carrier system, *Expert Rev. Vaccines* 12: 779-791.

51. Garcon, N., M. Wettenдорf, and M. M. Van, 2011, Role of AS04 in human papillomavirus vaccine: mode of action and clinical profile, *Expert Opin. Biol. Ther.*, 11: 667-677.