3.2. Iontophoresis

Iontophoresis is a method to enhance the transportation of ionic or charged molecules through a biological membrane by passing direct or periodic electric current through an electrolyte solution with an appropriate electrode polarity. This technique has been applied in the fields of transdermal drug delivery and has been shown by several groups to promote penetration of peptides or proteins such as insulin, calcitonin, or botulinum toxin through the SC [40,41,42]. The combination of electroporation and iontophoresis makes substance penetration even more effective [43]. From these reports, iontophoresis enhanced penetration of macro molecules through SC into skin, thus application of this method to TCI systems is expected. However, several problems about lack of convenience and risk of secondary infections remain because it requires power-supply equipment and may break cutaneous barrier.

3.3. Sonophoresis (low-frequency ultrasound)

Sonophoresis is a method to enhance substance penetration by disrupting the structure of the SC with low-frequency ultrasound. Cavitation is the formation of gaseous cavities in an ultrasound-coupling medium upon exposure to ultrasound and involves the rapid growth and collapse of a bubble (transient cavitation) or slow oscillatory motion of a bubble (stable cavitation) in the ultrasound field. Oscillations and collapse of cavitation bubbles disorder the lipid bilayers of the SC, thereby enhancing transport [44]. Dahlan et al. have shown that TCI using low-frequency ultrasound with tetanus toxoid (TT) induced anti-TT IgG and neutralizing antibodies [45,46]. Interestingly, Tezel et al. reported that ultrasound treatment induced LC activation and enhanced the Ag-specific immune response, suggesting it acts as a physical adjuvant [47].Although TCI using sonophoresis induced Ag-specific IgG antibody and have advantage of activating immunocompetent cells, this method require power-supply equipment and disrupt cutaneous barrier, thus they have several issues in terms of usefulness and safety.

3.4. Jet injectors

Jet injectors are devices that use pressure to deliver substances into the skin [48–51]. The first devices were multiple-use nozzle jet injectors, with which a large number of patient were vaccinated through the same fluid stream and nozzle [48,49]. However, such devices are no longer used because of cross-contamination. Recent development efforts have resulted in disposable syringe jet injectors. Simon et al. reported a clinical study of the immunogenicity of trivalent inactivated influenza vaccine administrated by the Lectra Jet M3® RA disposable syringe jet injector, which was cleared for sale and use by the U.S. Food and Drug Administration in 2009 [52]. In jet injector systems, Ag-specific immune responses are induced and administration methods are simple, but ampoules are needed in the same way as in conventional injection systems, indicating the need of a cold-chain for transport and storage.

3.5. Patch formulations

Patch formulations are one of the commonly used systems for TCI. Several groups have reported that TCI using gauze patches or adherent patches induced Ag-specific immune responses [53–57]. Application of a LT-containing single-ply polyester-rayon gauze patch onto human skin increased the anti-LT IgG titer in serum [53]. Although the other groups also have reported developing TCI systems for practical use and showed their safety and efficacy [54–57], these systems comprised a gauze patch as the TCI device. Because they require the gauze patch to be saturated with Ag solution just before application to the skin, such TCI systems are inconvenient and require cold storage and transportation of the Ag solution, as do conventional injectable vaccination systems. In addition, the disadvantage of patch-based TCI system is the requirement of skin preparation system (SPS) or cyanoacrylate skin surface stripping (CSSS) procedures to remove SC before patch application for improvement of Ag penetration into skin. These methods may carry a risk of increasing sensitivity to secondary infection by disrupting SC as a cutaneous barrier, which is a safety issue. Thus, the development of more easy-to-use and safer patch-based TCI system is desirable.

In our research group, we have developed a hydrogel patch as a TCI devise, which is made of safe materials that have already been applied to humans [58–62] and TCI formulation using a hydrogel patch was shown to induce effective immune responses to tetanus and diphtheria after application in absent of any treatment in animal models [59]. We also demonstrated its safety and efficacy by performing a clinical study of our TCI formulation for vaccination against tetanus and diphtheria in humans without disrupting SC [62].

3.5.1. Ag delivery using our hydrogel patch formulations as the TCI device

In our patch-based TCI system, we can prepare a TCI formulation by dropping Ag solution to a hydrogel patch and leaving out at room temperature for a while. The hydrogel patch formulation immersed with TexasRed (TR)-labeled OVA solution formed a concentrated Ag layer on its surface (Fig. 3A), because only water in Ag solution absorbed by hydrogel polymer.

It is very important to deliver antigenic proteins to the skin-resident APCs for induction of Ag-specific immune responses. Therefore, we analyzed biodistribution of Ag after transcutaneous administration by a hydrogel patch. There was marked penetration of the Ag into the epidermal layer of intact skin after 6-h application of a hydrogel patch containing TR-OVA to the auricle skin of mice (Fig. 3B). In human and tissue-engineered skin models, a hydrogel patch also promoted the penetration of antigenic proteins through the SC [60]. Although theories of conventional transdermal drug delivery suggest that skin structure and composition do not allow for the penetration of materials larger than 500 Da [10,11], our transcutaneous vaccination system delivered antigenic proteins (45–150 kDa) into the epidermal layer [58,59]. We proposed the following mechanisms for penetration of Ag into the skin. First, the concentrated antigenic proteins on the surface of the patch might generate a high concentration gradient of antigenic proteins in the skin, which is critical for producing the driving force needed to accelerate passive diffusion and distribution. This theory is supported by our observation that the distribution of TR-OVA in the epidermal layer was not simply a result of spreading the TR-OVA solution on the intact skin surface, and that the application of the filter paper immersed in Ag solution did not enhance either Ag penetration or antibody titer [58]. Second, humectation and hydration of the skin to which the hydrogel patch is applied might loosen intercellular gaps in the SC, which contributes to improve the penetration of water-soluble substances. According to our observations, Ag penetration via our patch system occurred mainly through the intercellular gaps of the SC. In fact, there are several reports that an increased water content in the SC leads to increased membrane fluidity and decreased electrical resistance [63,64]. Although it is possible that antigenic proteins penetrate into the epidermal layer through hair follicles – there are some reports that hair follicles allow for even nanoparticles to reach the epidermal layer in skin [65–67] – our hydrogel patch enhanced Ag penetration on a tissue-engineered skin without pores [60], suggesting that this pathway contributes little to the penetration of Ag into the skin promoted by a hydrogel patch. Through a combination of these mechanisms, our

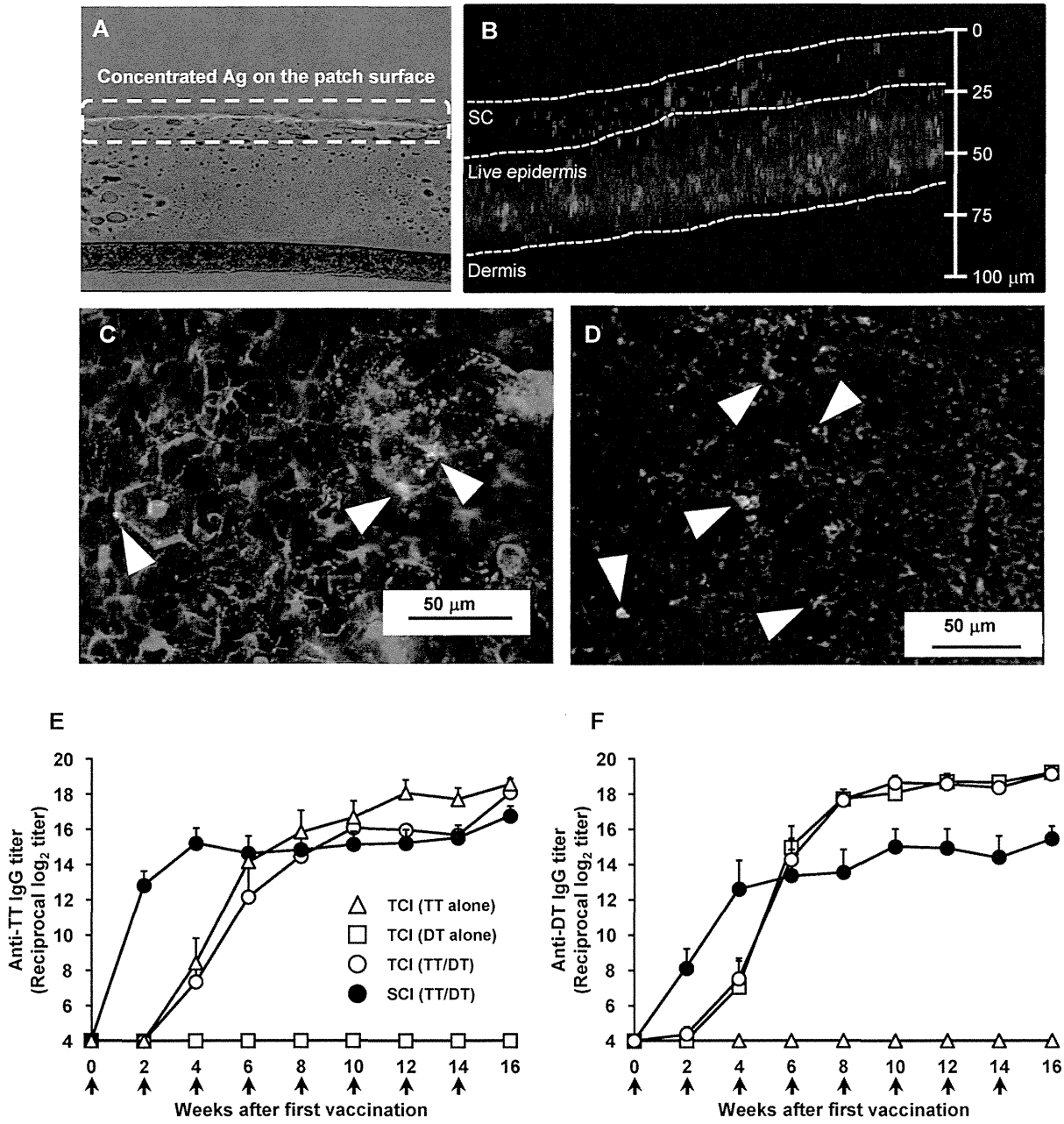


Fig. 3. Characteristics of a hydrogel patch as a TCI device. (A) Section of TR-OVA (red)-immersed hydrogel patch. (B, C, D) Localization of TR-OVA in a skin section, an epidermal sheet, and a lymph node section. TR-OVA-immersed hydrogel patches were put on auricles of C57BL/6 mice. (B) Six hours later auricles were harvested and epidermal sheets were prepared. (C) Two hours later auricles were harvested and an epidermal sheet was prepared. (D) Cervical lymph nodes were harvested 48 h after application of a patch for 24 h. The Epidermal sheets and the frozen sections were stained with Alexa488-conjugated anti-mouse langerin.The epidermal sheets (B) were photographed under a confocal laser microscope. Continuous cross-sectional views were digitally superimposed. The photograph is a longitudinal section of three-dimensional images of epidermal sheets. Epidermal sheets (C) and lymph node sections (D) were photographed under a fluorescence microscope. (B–D) red: TR-OVA as Ag, green: LCs, yellow (arrowhead): merged with TR-OVA (red) and LCs (green). (E and F) TT- or DT-specific immune responses in HWY hairless rats after transcutaneous vaccination. Hairless rats were transcutaneously vaccinated with TT alone (100 μg), DT alone (100 μg), or combined TT and DT (100 μg each) for 24 h eight times at 2-week intervals. A control group was subcutaneously immunized with combined TT and DT (100 μg each) eight times at 2-week intervals. At the indicated points, serum collected from these hairless rats was assayed for IgG titers against (E) TT or (F) DT by ELISA. Data are expressed as mean ± SE of results from 10 rats. Arrows indicate vaccination points. Arrowheads indicate yellow fluorescentspots. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

patch vaccine system promoted the penetration of water-soluble macromolecular proteins into the SC.

As shown in Fig. 3C and D, yellow fluorescent spots, indicating that TR-OVA localization accorded with LC localization, were observed in merged images of an epidermal sheet and lymph node sections prepared from mice with intact skin, suggesting that LCs, which are cells critical for the induction of potent immune responses, captured antigenic proteins penetrated into the skin and migrated into the regional lymph node. Thus, Ag-capturing LCs, which migrated from the epidermal layer to regional lymph nodes, would greatly contribute to triggering and amplifying Ag-specific immune responses induced by transcutaneous vaccination using the hydrogel patch formulation.

3.5.2. Vaccination efficacy and safety of TCI using a hydrogel patch

In an animal model of tetanus and diphtheria infection, the vaccination efficacy of TCI using a hydrogel patch was evaluated. TCI

using a hydrogel patch elicited toxoid-specific immune responses and the serum titer of antibody in the TCI groups were equivalent to or greater than those of the subcutaneous immunization (SCI) group (Fig. 3E and F). In rats vaccinated with combined TT and DT, both TT and DT-specific IgG antibodies were detected in serum as efficiently as that in rats vaccinated with each toxoid alone, suggesting that our TCI using a hydrogel patch is applicable to a combination vaccine. As mixed inoculationis now recommended in vaccination, our TCI formulation is suitable for practical use. We also demonstrated that TCI using a hydrogel patch containing TT and DT induced little adverse reactions in local and systemic toxicity assessments [61], indicating that hydrogel patch-based TCI formulation is a non-invasive vaccination method. In addition, on the basis of IgG subclass analysis, it was suggested that our TCI using the hydrogel patch formulation predominantly elicited a Th2-type immune response rather than a Th1-type immune response [58,59]. Further analyses are necessary to elucidate the Th2-dominant mechanism in our patch vaccination.

In our hydrogel patch-based TCI system, we can simply prepare a manageable TCI formulation like general fomentations with a concentrated Ag layer on the surface of the hydrogel patch. Our TCI system using a hydrogel patch enhanced Ag penetration into the skin and induced Ag-specific immune responses by single application onto skin surface without disrupting SC. This is superior to other patch-based TCI formulation in terms of avoiding secondary infections by breaking skin barriers.

3.6. Microneedles

Patch formulations, such as the hydrogel patch, are less effective at promoting penetration of particulates and insoluble Ags through the SC. Most practical vaccine Ags are in a particulate state, for example, the less virulent strains of bacteria. The development of a different TCI system that is effective for use with all Ag forms is needed. A microneedle array contains many micrometer-sized needles that can create a transport pathway large enough for proteins and nanoparticles, but small enough to avoid pain [68–74]. Microneedle arrays can penetrate the SC barrier and deliver Ag to immunocompetent cells in the skin more efficiently than other TCI systems. In addition, the use of a disposable array is suitable for self-administration. Thus, microneedles are the most attractive devices for the development of effective TCI systems. Microneedles were first conceptualized for drug delivery in a 1976 patent [75]. Since then, several type of microneedles have been developed and they are classified into four types with respect to mechanism of action: (1) solid microneedles for pretreatment of the skin to increase permeability, (2) microneedles coated with drug that dissolves in the skin, (3) polymer microneedles encapsulating the drug that fully dissolves in the skin, and (4) hollow microneedles for infusing the drug into the skin.

Traditional microneedle arrays made from silicon, metal, stainless steel, or titanium were reported in the early stages of development, but the clinical use of microneedle arrays has faced serious obstacles because needles on microneedle arrays can fracture and remain in the skin, creating a safety issue. These conventional microneedle arrays suffer from the risk of fracture of microneedle fragments in the skin, therefore, in 2004, microneedle systems made with biocompatible or biodegradable polymers began to be developed [69], and their superior safety has led to early clinical use. This system, however, remains the risk of breaking cutaneous barrier by insertion of microneedles into skin. In manufacture of dissolving microneedles, the technical innovation is required to allow Ag to be incorporated into the matrix of microneedle material using mild procedures that do not cause the decrease of antigenicity or compromise material strength.

Our research group has developed a dissolving microneedle array (MicroHyala®; MH) as a TCI device, which was fabricated using micromolding technologies with biocompatible sodium hyaluronate as the base material and this approach demonstrated effective vaccination effects comparable to those of conventional injection systems [76–78].

3.6.1. Characteristics of our MH as a TCI device

We have developed a dissolving microneedle array, MH as mentioned above, made of sodium hyaluronate as the base material (Fig. 4A). We successfully fabricated several types of MH in various forms and lengths: konide-shaped MH (needle length 200 or 300 μm) and cone-shaped MH (needle length 300, 500, or 800 μm)

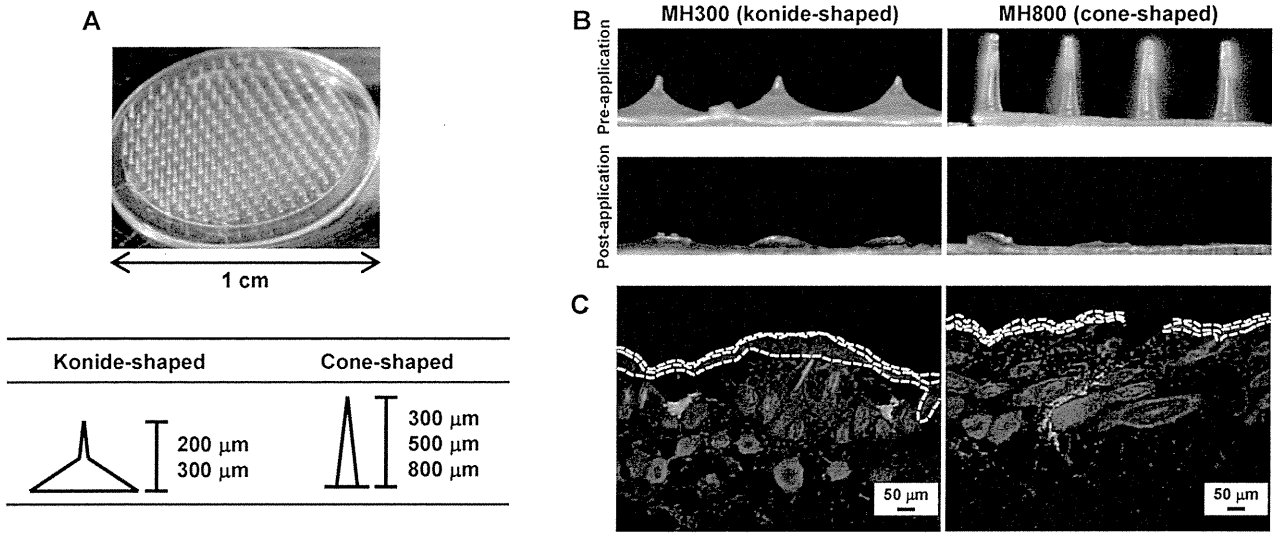


Fig. 4. Dissolving microneedle array patch (MicroHyala®; MH). (A) Bright-field micrograph of whole MH. There are two type of MH, konide-shaped MH (needle length: 200 or 300 μm) and cone-shaped MH (needle length: 300, 500, or 800 μm). (B) Bright-field micrograph of microneedles on konide-shaped MH300 or cone-shaped MH800 before or after insertion into skin. Each MH was applied on the back skin of BALB/c mice. One hour later, each MH was removed and photographed under a stereoscopic microscope. (C) Konide-shaped MH300 or cone-shaped MH800 encapsulating FITC-labeled silica particles were applied on the back skin of BALB/c mice and skin was harvested 6 h later. Frozen sections were photographed under a fluorescence microscope. The nucleus was counterstained with 4′,6-diamidino-2-phenylindole (blue). Area between the upper dotted line and the middle dotted line is the SC, area between the middle dotted line and the lower dotted line is the living epidermis, and area below the lower dotted line is the dermis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

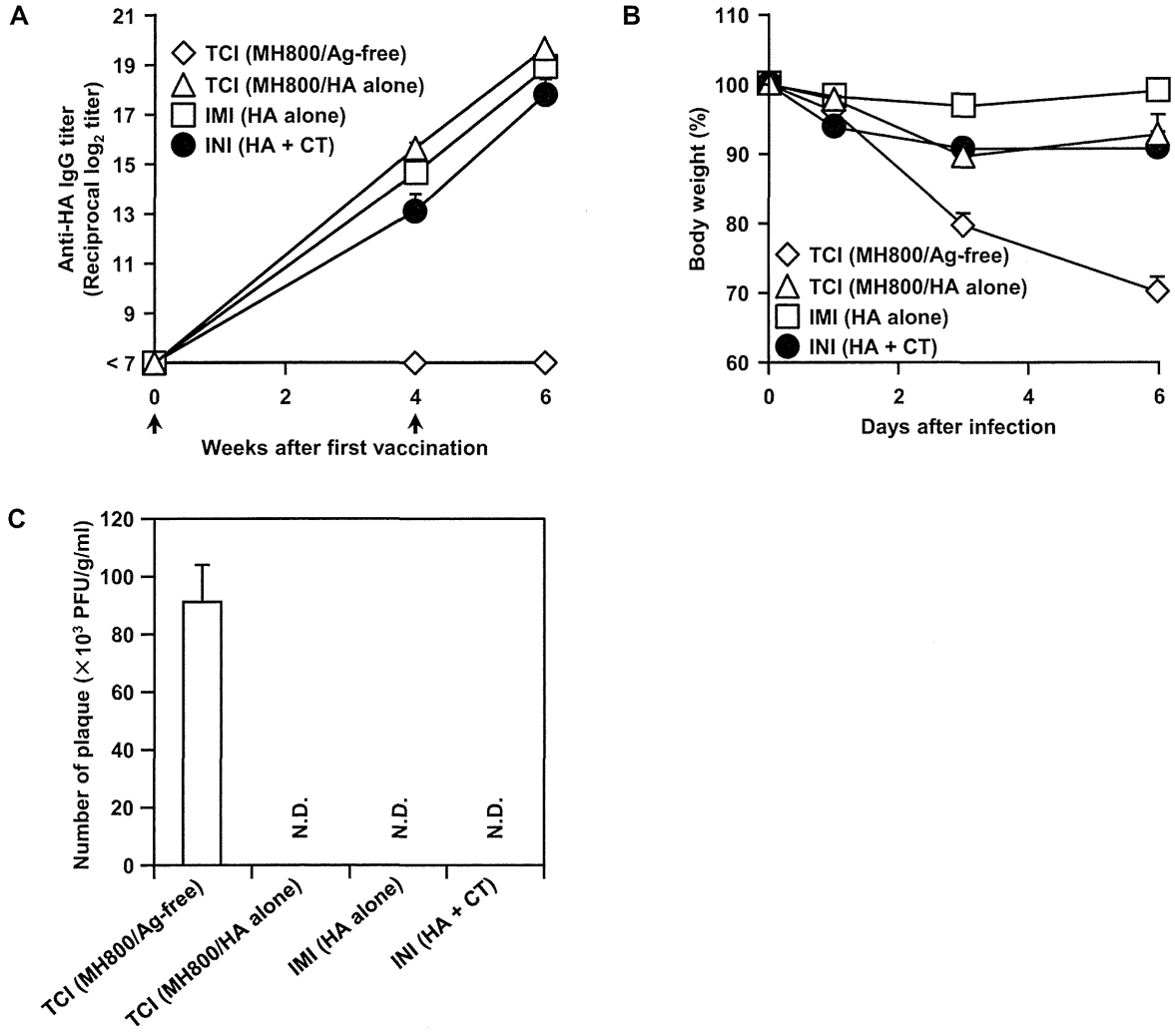


Fig. 5. Protection of vaccinated mice against challenge with influenza virus. BALB/c mice were transcutaneously vaccinated with HA from [A/PR/8/34 (H1N1)] (0.4 μg) for 6 h twice at 4-week intervals. Control groups were treated with TCI without HA, intramuscular injection of HA (0.4 μg), or intranasal application of HA (0.4 μg) combined with CT (10 μg) as an adjuvant twice at 4-week intervals. Two weeks after last vaccination, these mice were each infected intranasally with 6×10^5 PFU of the A/PR/8/34(H1N1) virus. (A) At the indicated points, sera collected from the mice were assayed for the titer of HA-specific IgG by ELISA. (B) Body weight was measured each day after infection and is presented as a percentage of the original weight before infection (day 0). (C) Six days after infection, the lungs were collected from the mice and the number of viruses in the lung homogenate was determined with a plaque assay system. Data are expressed as mean ± SE of results from (A) 13 or (B and C) 10 mice. Arrowheads indicate vaccination points.

(Fig. 4A). The microneedles on the MH were dissolved by water in the skin and thus had no danger of remaining in the skin, making our MH safer than traditional microneedle arrays made of metal or stainless steel. In fact, the microneedle tips were fully dissolved at 1 h (Fig. 4B). Application of each MH caused only temporary skin irritation and the skin barrier function after insertion recovered immediately [76], suggesting that the holes caused by insertion of each MH closed up quickly. These results suggest low probability of causing secondary infection by application of MH. In observation of skin sections after application of each MH containing fluorescein isothiocyanate (FITC)-silica particles, they were clearly detected (Fig. 4C), suggesting that the MH delivered particulate Ag into the epidermis or dermis without regard for the Ag form. In addition, the MH size can be used to control the depth of Ag delivery, meaning that each MH might deliver Ag to specific skin-resident APCs, LCs in the epidermis or several dDCs in the dermis.

3.6.2. *Vaccination efficacy and safety of TCI using MH*

We examined the efficacy of vaccination with influenza hemagglutinin (HA) Ag, which is particulate Ag. In an influenza virus challenge, TCI with HA alone elicited production of HA-specific functional IgG antibody equivalent to that after intramuscular immunization (IMI) with HA alone or INI with combined HA and CT as an adjuvant (Fig. 5A). On the other hand, little anti-HA IgA antibody was detected in the TCI and IMI groups [77]. After challenge with A/PR/8/34 influenza virus, mice in the TCI group showed no remarkable weight loss, similar to those in the IMI group and INI with CT group (Fig. 5B). In addition, the virus titer in the lungs of the TCI group was below the detection limit (Fig. 5C), demonstrating that our TCI system provided protection equal to that of IMI or INI with adjuvant. In INI system, mucosal vaccine adjuvants with high efficacy and safety for the purpose of a clinical application are necessary. As compared to INI system, our TCI could efficiently elicit Ag-specific vaccine effect without an adjuvant, which is an advantage of our TCI system.

In addition, the vaccination efficacy of TCI using MH was also demonstrated in tetanus, diphtheria, and malaria infection models. On the basis of these results, TCI system using MH suggested to induce Ag-specific immune responses against any vaccine Ags, such as soluble Ags, insolubleAgs, or particulate Ags, which conventional TCI system fail to do so.

Table 2
Clinical studiesof TCI.

Device	Antigens	Dose	Phase	Results	Ref.
Patch (SPS)	LT	37.5 μg	II	• Safety of vaccination technique • Induction of anti-LT antibody titer • 75% protection against moderate *E. coli* diarrhea, 84% against acute *E. coli* diarrhea	[53]
Patch (CSSS)	Live-attenuated measles	10^3 pfu	I/II	• Pretreatment with tape-stripping procedures • Safety • Induction of Ag-specific salivary IgA • Detection of Ag-specific IFN-γ-producing T cells	[54]
Patch (CSSS)	Inactivated influenza/tetanus vaccine	15 μg	I	• Pretreatment of abrasion by emery paper with 10% glycerol and 70% alcohol • Safety • Better seroconversion rate than IMI	[90]
Patch (hydrogel patch)	TT and DT	2 mg each	Clinical study	• Safety • Induction of neutralizing IgG antibody	[62]
Hollow microneedle	Inactivated influenza vaccine	3–6 μg	I	• Mild and transient local reaction • Induction of immunogenic responses	[91]

Thus, we can conclude that our TCI system using MH which is dissolved in the skin effectively confers protective immunity without causing serious adverse reactions in an animal model.

Conventional microneedle array made of metal or stainless steel has difficulties in clinical application because needles on microneedle arrays can fracture and remain in the skin, which is serious problem. However, the microneedles on the MH were dissolved by water in the skin and thus had no danger of remaining in the skin, indicating that TCI using MH would be attractive vaccination method in terms of both safety and efficacy.

3.7. Nanoparticles

Recent studies suggested that nanoparticles are attractive means for transcutaneous Ag delivery. By disrupting the SC as a result of the nano-bio interaction with skin lipids, antigenic proteins encapsulated in the nanoparticles can be delivered through the SC into the skin. Some researchers reported that nanoparticle vaccine compounds can penetrate via the hair follicles where there is a high density of APCs and enhanced immune responses. There are numerous nanoparticle systems available, including polymeric poly (D-L-lactic-co-glycolic acid) and poly (lactic acid) nanoparticles, biodegradable chitosan nanoparticles, and metal nanoparticles [65,79–83].

3.8. Lipid-based vesicles

In addition, lipid-based vesicles such as liposomes, transfersomes, or niosomes have structures similar to those of biological membranes and facilitate skin penetration [84–88]. When mixed with SC lipids, flexible liposomes (FLs) can carry a remarkable amount of lipid mass into the skin and can, therefore, be advantageous in promoting cutaneous drug disposition after disrupting the skin barrier with their flexible bilayers [88]. It also has been reported that FLs stimulated a transcutaneous immune response by acting as an adjuvant [89].

The design of novel formulations especially nanoscale systems, such as nanoparticles and lipid-based vesicles, can be helpful for protecting the Ag from external environment and keeping the long term activity. These properties are conductive to the application of transcutaneous vaccine. However, the development of novel nanoscale systems for TCI is limited by the low efficiency in eliciting robust immune responses.

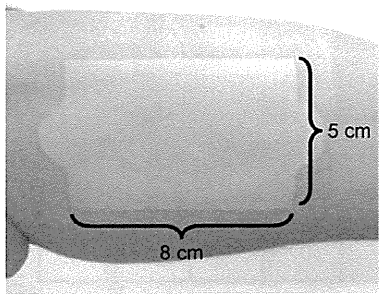
4. Clinical studies of transcutaneous vaccination

For the diffusion of the vaccine worldwide including in developing countries, patch formulations and microneedles are more suitable because of their ease of use and efficacy. Several research groups have conducted clinical studies of TCI using patch formulations or microneedle systems in recent years (Table 2). Glenn et al. first reported the results of TCI using a patch in humans [55]. Application of a patch containing LT as Ag resulted in robust LT-specific antibody responses. In addition, their group used LT to investigate patch vaccination against traveler's diarrhea in a phase II clinical trial and found that the 59 LT-patch recipients were protected against moderate-to-severe diarrhea (protective efficacy [PE] 75%) and severe diarrhea (PE 84%)[53]. LT-patch recipients who became ill had shorter episodes of diarrhea (0.5 *vs* 2.1 days) with fewer loose stools (3.7 *vs* 10.5) than recipients of placebo [55]. Since then, numerous studies of devices that serve as simple, easy-to-use, and low-invasive TCI systems have been undertaken. Etchart et al. showed that TCI of human adult volunteers with live-attenuated measles induced Ag-specific immune responses in their phase I/II clinical study [54]. Combadiere et al. demonstrated that TCI with an inactivated influenza vaccine induced a significant increase in influenza vaccine-specific CD8 responses compared with those obtained from the intramuscular route [90]. However, these TCI systems require cyanoacrylate skin surface stripping for Ag delivery into skin, which might cause skin irritation as one of the side effects.

Microneedle-based TCI systems have also been applied in clinical trials. Van Dammeet al. reported the results of a clinical study of influenza vaccination in which a hollow microneedle device (MicronJet) was used [91]. Local adverse reactions were significantly more frequent than those with intramuscular vaccination, but were mild and transient in nature. After TCI, immunogenic responses increased in humans. In addition, the safety and efficacy of several microneedle devices have been assessed in applications other than vaccination [92,93]. In the future, more clinical studies will be conducted for needle-free, easy-to-use, low-invasive, and low-cost vaccination methods.

We performed a clinical study of our original hydrogel patch formulation containing combined TT and DT in humans (Fig. 6A and B) [62]. In the safety assessment to evaluate local adverse responses at 0 h and 24 h after patch removal, a TCI formulation containing TT and DT was shown not to induce local severe adverse events (Fig. 6C). As shown in Fig. 6D, anti-TT IgG and anti-DT IgG increased (paired-*t* test; $p < 0.01$) following the first vaccination using the

A



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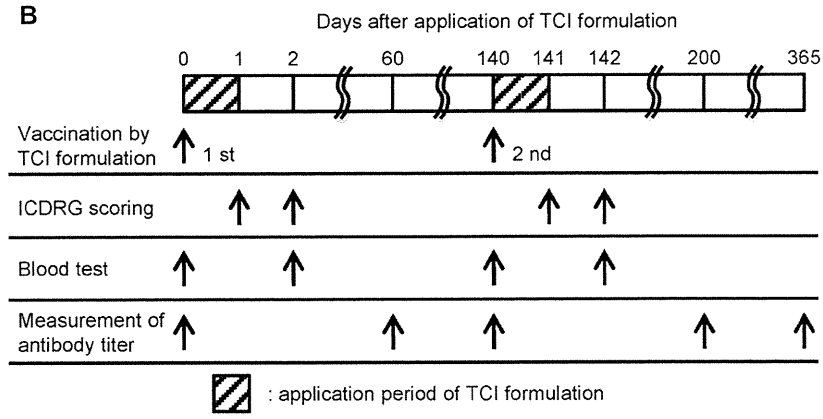

C

Time after patch removal	ICDRG score			
	-	?+	+	++
0 h	17/27 (63.0%)	4/27 (14.8%)	6/27 (22.2%)	0/27 (0.0%)
24 h	15/26 (57.7%)	2/26 (7.7%)	9/26 (34.6%)	0/26 (0.0%)

D

IU/mL	Anti-TT antibody titer			
	First vaccinatin		Second vaccination	
	Day 0	Day 60	Day 140	Day 200
< 0.1	8	7	2	2
0.1 - 1.0	15	9	3	3
1.0 - 5.0	4	9	0	0
5.0 <	0	2	0	0
Total	27	27	5	5
Range	< 0.1 - 1.83	< 0.1 - 6.47	< 0.1 - 0.46	< 0.1 - 0.63
Genometric mean	0.22	0.39	0.09	0.12

IU/mL	Anti-DT antibody titer			
	First vaccinatin		Second vaccination	
	Day 0	Day 60	Day 140	Day 200
< 0.1	1	1	1	0
0.1 - 1.0	17	8	3	4
1.0 - 5.0	7	12	1	1
5.0 <	2	6	0	0
Total	27	27	5	5
Range	< 0.1 - 2.87	< 0.1 - 6.15	< 0.1 - 1.09	< 0.1 - 1.33
Genometric mean	0.56	1.06	0.24	0.31

Fig. 6. Clinical study of a TCI formulation using a hydrogel patch. (A) A hydrogel patch (5 cm × 8 cm) containing TT and DT (2 mg each) was applied on the left brachial medial skin for 24 h. (B) Experimental design about clinical study of TCI formulation using a hydrogel patch contatining TT and DT. Each experiment was conducted at the indicated points. (C) Local adverse events after applying the TCI formulation. Twenty-four hours after application, the TCI formulation was removed from the investigational sites. Skin irritation reactions were scored according to the classification of the International Contact Dermatitis Research Group (ICDRG) to assess local adverse responses at 0 h and 24 h after removal. The data represent the number and percent of subjects who showed each symptom. –: negative reaction; ?+: doubtful reaction (faint erythema only); +: weakly (non-vesicular) positive reaction (erythema, infiltration, and possibly papules); ++: strongly(vesicular) positive reaction (erythema, infiltration, papules, and vesicles). (D) Toxoid-specific IgG titer before (Day 0 or Day 140) and 60 days (Day 60 or Day 200) after first or second application of TCI formulation. At indicated points, serum was collected and anti-TT or DT IgG titer was determined by ELISA.

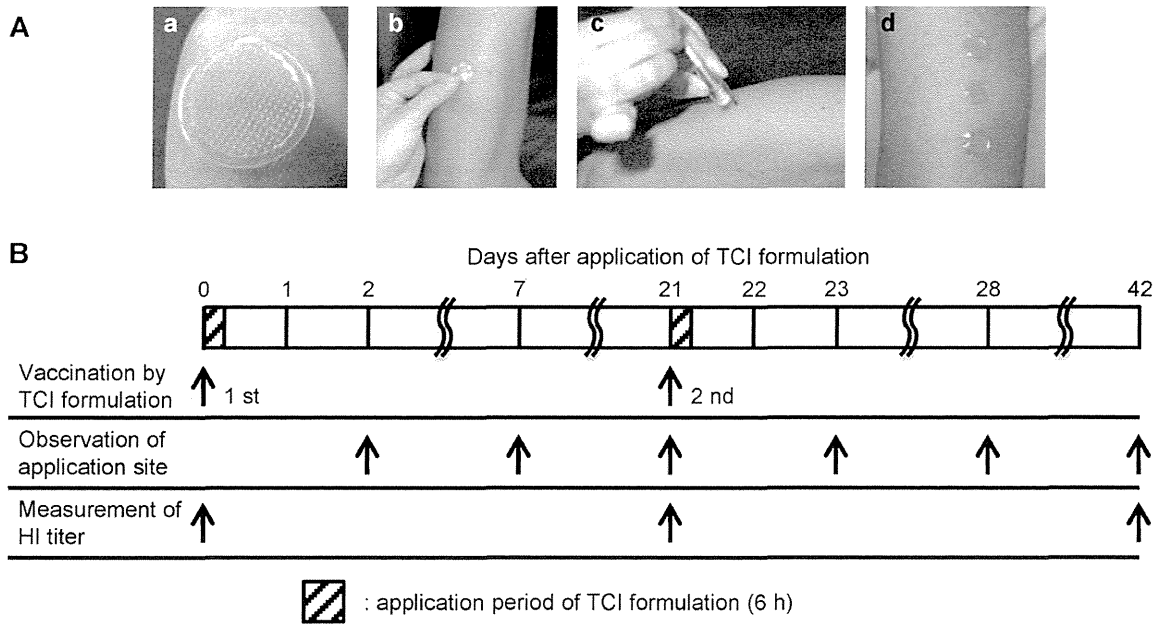

Fig. 7. Clinical study of a TCI formulation using a MH. (A) Schematic drawing of transcutaneous vaccination procedure. a; bright-field micrograph of whole MH, b: putting MH on left brachial lateral skin. c: Application of MH with an applicator. d: Covering with an adhesive tape. (B) Experimental design about clinical study of TCI formulation using a MH containing trivalent influenza HA Ags. Each experiment was conducted at the indicated points.

TCI formulation, indicating that a single application of our TCI formulation could induce an immune response in humans. We also administered a second vaccination to five subjects in whom neither antibody titer was significantly increased by the first vaccination. The IgG titers increased in a part of subjects following the second vaccination, suggesting that an additional application increases the efficacy of the TCI formulation. Antibody titers on day 365 after application of the TCI formulation were maintained at a higher level than those on day 0 in all subjects examined, although antibody titers tended to be lower on day 365 than on day 60 [62]. Conventional patch-based TCI systems require the pre-treatment of disrupting or removing SC, but our hydrogel patch achieved Ag penetration into skin without removing the SC and Ag-specific antibodies were produced in some subjects by a single application in humans, which represents a safety and efficacy advantage.

We also conducted a clinical evaluation of TCI using MH (Fig. 7). Ag-free konide-shaped MH300, cone-shaped MH500, and cone-shaped MH800 as TCI devices were applied on left brachial lateral skin (Fig. 7A) and they caused no serious local or systemic adverse reactions (in preparation). To evaluate the efficacy of vaccination (Fig. 7B), we used trivalent influenza HA Ags. HA-containing cone-shaped MH800 induced HA-specific IgG responses against three HA Ags without severe adverse events (in preparation), indicating that our MH-based TCI system was safe and efficacious in humans.

These simple, easy-to-use, low-invasive, and effective TCI formulations might be applicable for mass treatment in the event of an outbreak and for increasing vaccination rates in developing countries. We expect that our TCI system as an innovative vaccination method will be put to practical use at an early date and greatly will contribute to decrease the mortality and morbidity by infectious diseases.

5. Conclusion and future perspectives

The development of vaccines, which represent the only basic prophylaxis against infectious diseases, is drawing attention worldwide. The main objective of vaccine development is the establishment of manufacturing technologies that supply safe and effective vaccine Ag rapidly and stably, but the problem of how to carry out enough vaccinations to prevent infectious diseases remains to be solved. In order to distribute the vaccine across the world to people who need it, especially those in developing countries, easy-to-use, low-cost, and low-invasive vaccination methods instead of conventional injection systems are required. TCI offers an attractive avenue for the development of needle-free prophylaxis. The main challenge to be addressed during the development of TCI systems is to ensure accurate delivery of Ag to the epidermis and dermis through the SC. As we introduced in this review, various approaches to overcome the SC barrier have been developed and basic, preclinical, or clinical studies of these approaches have been conducted.

Recent studies have demonstrated that intradermal vaccine delivery to skin-resident APCs can increase the magnitude of the immune response rather than IMI. For example, some studies evaluating intradermal delivery of influenza vaccine have suggested that dose sparing relative to IMI can be achieved [94,95]. Nowadays, INTANZA®/IDFlu® is marketed as a new trivalent inactivated influenza vaccine administered by the intradermal route. Thus, TCI systems targeting the skin immune system are attractive vaccination methods that can supplant conventional IMI or SCI in terms of not only ease and safety but also efficacy.

Practical use of these easy-to-use, low-cost, low-invasive, and effective transcutaneous vaccination methods in the near future would contribute to a global countermeasure against infectious disease and would greatly benefit countries with poor vaccination rates.

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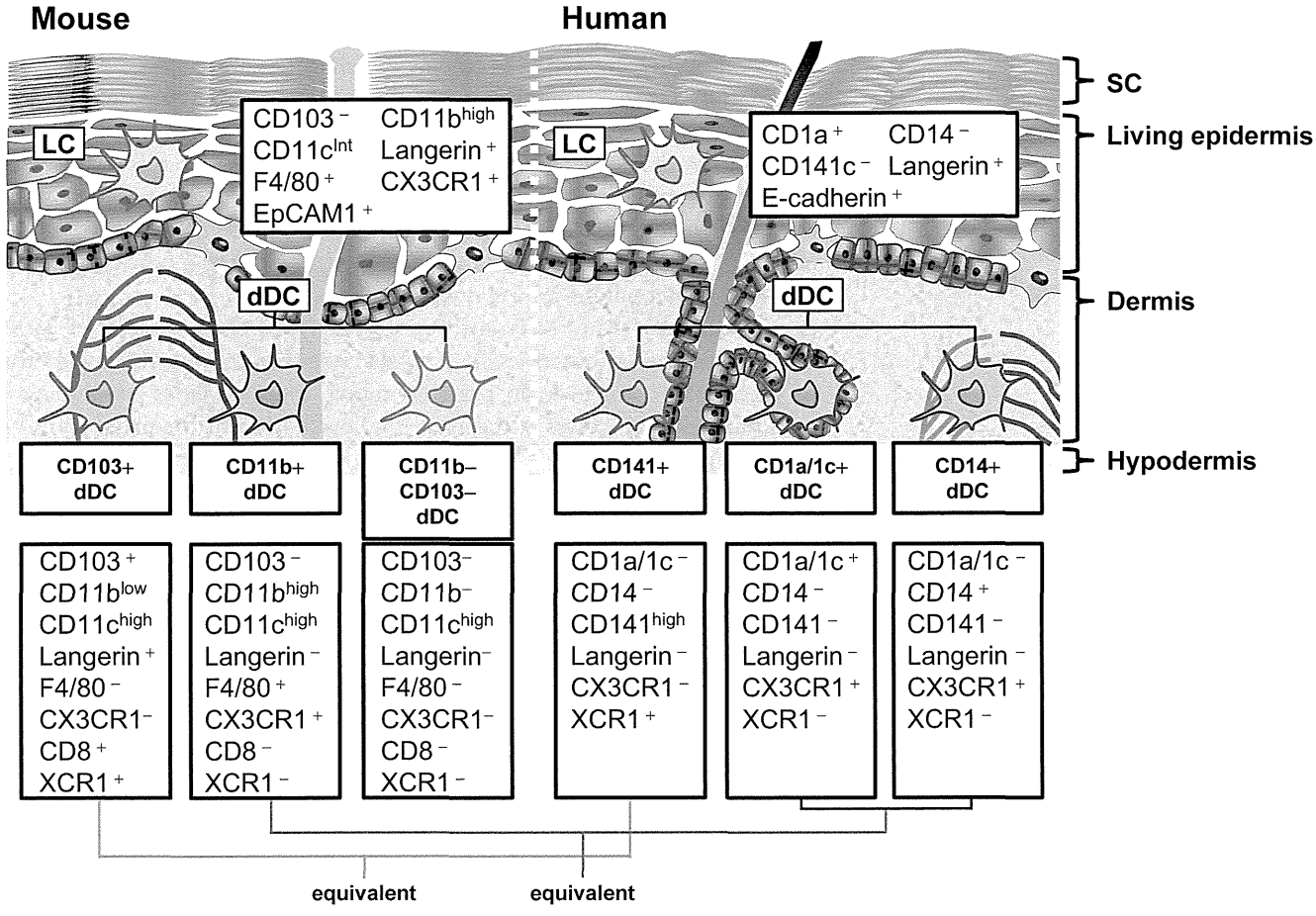

Fig. 1
Skin immune system.
The skin is enriched with various immunocompetent cells such as LCs, keratinocytes, and several dDCs. Keratinocytes are mainly involved in the induction of innate immunity. LCs and dDCs capture external Ag, migrate into regional lymph nodes, present Ag to T cells, and activate Ag-specific T cells and B cells. Activated T cells and B cells migrate to each tissue and induce Ag-specific immune responses. SC: stratum corneum; LC: Langerhans cell; DC: dendritic cell; Ag: antigen.

EXPERT OPINION

Transcutaneous vaccines – current and emerging strategies

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Introduction: Vaccination, which is the major fundamental prophylaxis against illness and death from infectious disease, has greatly contributed to the global improvement of human health. However, the disadvantages of conventional injection systems hamper the delivery of vaccination technologies to developing countries. The imminent practice of easy-to-use vaccination methods is expected to overcome certain issues associated with injectable vaccinations. One innovative method is the transcutaneous immunization (TCI) system.

Areas covered: Two major strategies for TCI are discussed in this review. One is to promote antigen permeation of the skin barrier by patch systems or nanoparticles. The other is the delivery of antigens into the skin by electroporation and microneedles in order to physically overcome the skin barrier. Moreover, adjuvant development for TCI is discussed.

Expert opinion: Many different approaches have been developed for TCI, which have the potential to be effective, easy-to-use and painless methods of vaccination. However, in practical terms, the guidelines concerning the manufacturing processes and clinical trial evaluation of the procedures have not kept pace with the development of these novel formulations. The accumulation of information regarding skin characteristics and the properties of TCI devices will help refine TCI system development guidelines and thus lead to the improvement of transcutaneous vaccination.

Keywords: adjuvant, clinical study, microneedle, skin, transcutaneous vaccination

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1. Introduction

Vaccination, which is the major fundamental prophylaxis against illness and death from infectious disease, has greatly contributed to the global improvement of human health. The epidemic of emerging infectious diseases, such as severe acute respiratory syndrome [1], the highly pathogenic avian influenza (H5N1) [2], and the threat of reemergence of infectious diseases, such as tuberculosis [3] and malaria [4], emphasizes the importance of vaccination. An example of the global threat of infectious disease is the recent outbreak of swine influenza A (H1N1), which was declared to have a Phase VI pandemic status by the World Health Organization in June 2009 [5]. However, the use of injections as the major vaccination system is painful, requires medical personnel with technical skill and comes with the risk of needle-related disease and injuries. Moreover, antigen solutions require cold storage and transportation systems [6,7]. These disadvantages associated with conventional injection systems hamper the delivery of vaccination technologies to developing countries. As a result, 4,000 children die every day from diseases that are preventable by vaccination [8]. The imminent practice of easy-to-use vaccination methods is expected to overcome some issues of injectable vaccinations. In addition, the development of new vaccination systems to enable worldwide mass treatment is critical for avoiding pandemics. An innovative approach that resolves these issues

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Article highlights.

- Transcutaneous vaccination holds great promise because skin has numerous varied immunocompetent cells.
- A number of clinical studies have been conducted for transcutaneous vaccination using TCI devices, such as the patch system and jet injector.
- TCI devices using microneedles, particularly self-dissolving microneedles, are attractive from both safety and efficacy aspects.
- For more effective transcutaneous vaccination, the development of adjuvants using TLR ligands is in progress.
- The accumulation of information and preparation of guidelines are important for practical use of transcutaneous vaccination.

This box summarizes key points contained in the article.

and that is attracting great attention is the transcutaneous immunization (TCI) system [9,10].

In this article, we summarize the recently developed pharmaceutical and physical strategies and adjuvants for the enhancement of TCI.

2. Skin as a vaccination target

The skin is an organ that is constantly exposed to the risk of invasion by foreign substances. It is composed of three layers: the stratum corneum (SC), epidermis and dermis (**Figure 1**). SC operates as a 'physical barrier' to limit substance penetration. In addition, the skin acts as an 'immunological barrier' and contains various immunocompetent cells, such as Langerhans cells (LCs), keratinocytes, dermal dendritic cells (dDCs), macrophages, mast cells and T cells [11-15]. Keratinocytes account for ~ 90% of the total epidermal cell population and play an important role in innate immunity in the skin by producing a wide range of cytokines, chemokines and antimicrobial peptides in response to challenge. LCs in the epidermis and dDCs in the dermis have critical roles as potent antigen-presenting cells (APCs) against external antigens. In TCI, LCs and dDCs capture antigens/pathogens, migrate to the peripheral draining lymph nodes, process and present the antigen to the naïve T cells and initiate immune responses. Additionally, some researchers have reported that LCs and dDCs have the different functions as APCs; LCs induce humoral immune response and dDCs perform antigen cross-presentation by MHC class I [16], and TCI could induce immunoglobulin A (IgA) production in mucosal tissues [17]. This suggests that antigen delivery to the epidermis and dermis beneath SC promotes the induction of a strong and/or various immune responses, such as humoral, cellular and mucosal immunity. However, administration of the antigen solution onto the skin surface fails to result in penetration of SC and delivery of sufficient antigen into the skin [18-20]. Therefore, a number of studies are underway to improve various transcutaneous vaccination systems (**Figure 2**).

3. Transcutaneous vaccination techniques

As it is not easy for large proteins and viral particles to penetrate SC under normal conditions, the following two major strategies for TCI have been developed: i) promote antigen permeation of the skin barrier and ii) deliver the antigen into the skin by physical methods in order to overcome the skin barrier. Several devices have undergone clinical studies (**Table 1**).

3.1 Promoting antigen penetration through SC

Studies have been reported in which transcutaneous permeation of the antigen is increased, rendering it more readily available for uptake by APCs. In addition, the development of micro/nanometer drug delivery systems, such as liposomes and nanoparticles, as alternatives for transcutaneous vaccination is attracting attention.

3.1.1 Patch

The patch is one of the most commonly used systems for transcutaneous vaccination. Glenn *et al.* and McKenzie *et al.* reported that application of the vaccine patch (containing 50 µg *Escherichia coli* heat-labile toxin; LT) after removal of SC by tape stripping, increases the IgG titer to levels comparable to those obtained after active toxin infection and those induced by the oral cholera vaccine [21,22]. This vaccination system, known as the skin preparation system (SPS) was successful in Phase I and Phase II clinical studies against travelers' diarrhea (**Table 1**) [23,24]. Both preclinical and clinical investigations have shown that TCI results in mucosal immunity to LT, which may contribute to protection [22,24]. Moreover, influenza vaccination with LT using SPS showed improved immune responses in the elderly [25]. A cyanoacrylate skin surface stripping (CSSS) procedure has been developed for removing SC [26-28]. Transcutaneous influenza vaccination using CSSS promoted both CD4 and CD8 T-cell immune responses in humans (**Table 1**) [27,28]. In addition, cytotoxic T cells (CTLs) were induced by peptide immunization against melanoma using CSSS [26]. However, the development of a more easy-to-use and safer vaccination patch system is expected because SPS or CSSS require treatment to disrupt SC before patch application.

We have developed a hydrogel patch that was shown to induce effective immune responses against tetanus toxoid (TT) and diphtheria toxoid (DT) after application in the absence of any treatment (**Figure 2A**) [29-32]. The hydrogel patch was prepared with cross-linked HiPAS™ acrylate medical adhesives (CosMED):octyldodecyl lactate:glycerin: sodium hyaluronan. The rationale supporting this mechanism is that the concentrated antigen on the patch surface generates a high concentration gradient of antigen, thereby producing the driving force to promote substance penetration. We previously conducted a clinical study with a hydrogel patch containing TT/DT and confirmed the safety and efficacy in humans (**Table 1**) [33].

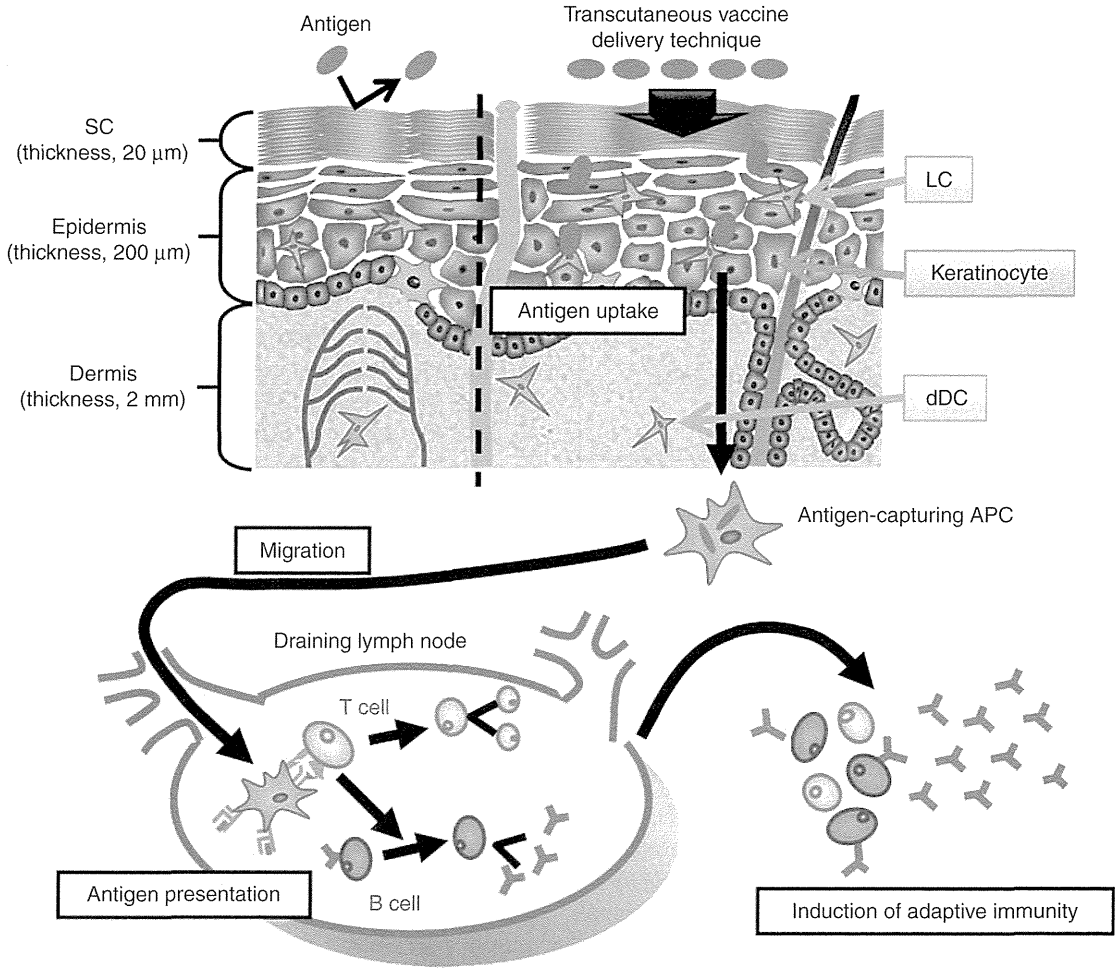

Figure 1. The induction mechanism of immune responses by a transcutaneous vaccine delivery technique.

The disadvantage of using the patch system is the requirement for large quantities of antigen, because each 2 mg TT/DT was applied in our clinical study and the amount of antigen penetrating the skin was a few percentage of the antigen applied to the skin in rats. Finding a suitable adjuvant for TCI to reduce the dose of antigen is also an important factor for the practical use of transcutaneous vaccination using the patch.

3.1.2 *Nanoparticles*

Nanoparticles are promising entities as antigen carriers for transcutaneous vaccination because of the nano–bio interaction with skin lipids, and the consequent induction of transient and reversible openings in SC [34]. In addition, nanoparticle vaccines can penetrate hair follicles where there is a high density of APCs, target the carried antigens toward APCs and increase the immune response [34-36]. Another advantage is the possibility of encapsulating both the antigen and adjuvant in the same particle, which is suggested to enhance the immune response [37].

The most common nanoparticles have been prepared using polylactic acid (PLA) or/and poly (lactic-*co*-glycolic acid) [38]. Fluorescence-labeled nanoparticles were detected in the duct of hair follicles, indicating that nanoparticles can penetrate the skin barrier through hair follicles. Although ovalbumin (OVA)-loaded PLA nanoparticles elicited lower antibody responses than OVA in aqueous solution, they were more efficient at cytokine induction [39]. Chitosan is currently being explored as a biomimetic material for the development of drug delivery systems. Its biodegradability, biocompatibility, low toxicity and simple and mild preparation methods make it an attractive candidate [40,41]. Several reports have indicated that the antigen is protected from degradation by conjugation with the chitosan nanoparticle. The chitosan nanoparticle may act as an adjuvant by functioning as a depot and being more efficiently taken up by dendritic cells than plain antigens because their size and structure are similar to those of microorganisms [42-44].

3.1.3 *Elastic vesicles*

As mentioned above, formulation of antigens in particulate carriers is popular in vaccine delivery. Recently, elastic

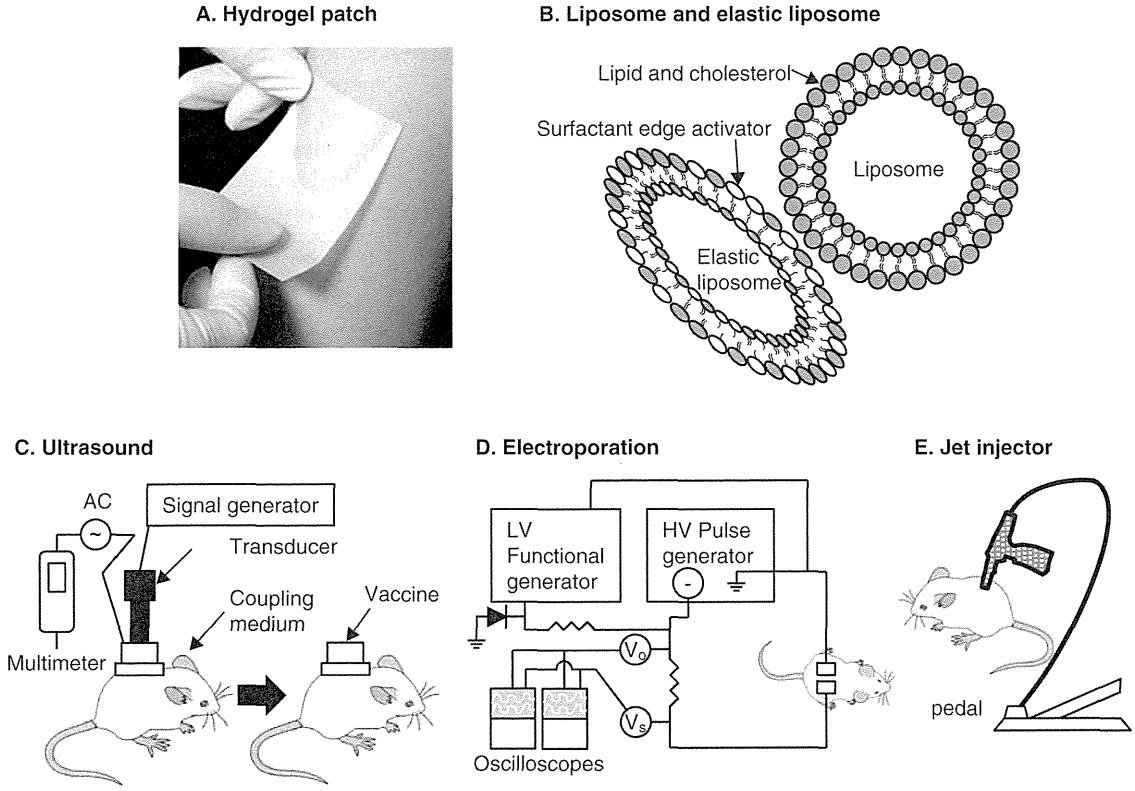

Figure 2. Schematic illustration and photographs of transcutaneous vaccination devices. (A) Hydrogel patch; **(B)** liposome and elastic liposome; **(C)** ultrasound; **(D)** electroporation and **(E)** jet injector.

Table 1. Clinical studies of transcutaneous vaccine delivery.

Formulation or device	Vaccine	Phase	Dose	Company	Refs.
Patch					
SPS	LT for travelers' diarrhea	III	37.5 μg	IOMAI/	[24]
	Trivalent inactivated seasonal influenza	II	45 μg LT	Intercell	[25]
CSSS	Inactivated influenza/tetanus or subunit influenza	I	15 μg		[27,28]
	Melanoma or HIV epitopes	I	4 – 16 mg		[26]
Hydrogel patch	TT/DT	clinical study	2 mg each	CoSMED	[33]
Jet injector					
PMED™	Influenza DNA	I	1 – 4 μg	Pfizer	[66,70]
(Powder)	DNA melanoma gp100	I	0.5 – 1 μg		[68]
	Malaria DNA	I	2.5 mg		[71,72]
Biojector®	HIV DNA	I	1 mg	Bioject	[74]
(Liquid)	Inactivated hepatitis A	I	1440 EL. U		[73]
Microneedle					
MicronJet®	Trivalent seasonal influenza HA	I	3 – 6 μg	NanoPass	[96]

CSSS: Cyanoacrylate skin surface stripping; DT: Diphtheria toxoid; HA: hemagglutinin; LT: *Escherichia coli* heat-labile toxin; PMED: Particle-mediated epidermal delivery; SPS: Skin preparation system; TT: Tetanus toxoid.

vesicles, which have a flexible bilayer composed of phospholipid, surfactant and water, have been used as they are thought to penetrate SC more easily compared to conventional liposomes (Figure 2B). With a similar structure to biological membranes, transfersomal systems, including deformable liposomes and niosomes, have been formulated for the topical/transdermal delivery of bioactive compounds, such as antibiotics, proteins and nucleic acids.

Transfersomes® are ultradeformable liposomes generated by incorporation of a surfactant into the lipid bilayer [45]. The use

of Transfersomes to formulate antigens in TCI has been reported in a few studies. When antigens, such as human serum albumin, gap junction protein or TT are used, potent humoral immune responses are induced in murine models with antibody levels comparable to those obtained through subcutaneous injection [46-48]. Variants of elastic vesicles have also been evaluated in TCI, such as ethosomes, which have a high percentage of ethanol introduced into the vesicles, or niosomes, which are constructed from nonionic surfactants and cholesterol. TCI of hepatitis B surface antigen (HBsAg)-loaded ethosomes (composed of soya phosphatidylcholine and ethanol) has been reported to induce an immune response comparable to intramuscular injection of HBsAg–alum [49]. Bovine serum albumin (BSA)-loaded niosomes, composed of Span 60, Span 85, cholesterol and stearylamine, were coated with a modified polysaccharide, O-palmitoyl mannan, for targeted delivery to LCs. This niosomal formulation elicited significantly higher serum IgG titers compared to alum-adsorbed BSA or plain uncoated niosomes in TCI, but the titers were still lower than those obtained after intramuscular injection of an equivalent dose of BSA–alum [50]. Thereafter, the optimization of niosomes with respect to the composition or dose is needed for improving efficacy and practical use.

3.2 Physical techniques for TCI

Many studies have reported that topical application of the vaccine formulation alone cannot yield an adequate immune response. This creates an attractive challenge for developing physical methods to overcome SC.

3.2.1 *Ultrasound*

Low-frequency ultrasound (**Figure 2C**) is known to increase the skin permeation of large molecules and enable transcutaneous vaccination. Ultrasonic TCI offers a needle-free and painless immunization and can increase anti-TT antibody titer [51]. The use of ultrasound can be defined as a physical adjuvant for TCI because slight LC activation was observed after ultrasound in the absence of antigen [52]. Low-frequency ultrasound application to the skin is known to extract skin lipids, cause the formation of defects and lacunar spaces within the skin and create highly permeable localized transport regions in the skin. Thus, liposome application to sonicated skin could allow/enhance liposome/antigen flux into the skin and consequently enhance TCI. Liposome application repaired the skin damage caused by ultrasound, although greater damage caused by skin sonication in the presence of sodium dodecyl sulfate was not repaired [53]. This suggests that synergistic effects between liposomes and ultrasound for TCI may be possible. However, it should be considered that vaccination by ultrasound requires the use of bulky, specialized equipment.

3.2.2 *Electroporation*

Increased molecular transport results from structural rearrangements to the cell membrane [54]. Electroporation (**Figure 2D**) results in transient structural perturbation of lipid bilayer membranes, including SC, in response to high-voltage pulses. This technique extends the transfection efficiency to many skin cells [55,56]. Previously, electroporation was widely used as a transcutaneous drug delivery system. Compared to injection, electroporation is less invasive because of the new availability of noninvasive probes. A study has shown that exodus of LCs from the skin was stimulated, and the OVA-specific CTL response to the vaccine delivered by needle-free electroporation was equivalent to that of intradermal injection [57]. Efficient priming of immune responses by human immunodeficiency virus DNA electroporation in conjunction with a protein boost may give rise to long-term immunity [58,59]. However, similar to ultrasound, the electroporation technique requires a specialized device.

3.2.3 *Jet injector*

The jet injector (**Figure 2E**) delivers powder or liquid antigen into the skin by air pressure using compressed helium [60-62]. Many studies have been conducted using epidermal powder immunization, showing protective immune responses against influenza, hepatitis B and DT, with doses ranging from 0.2 to 5 μg [63,64]. This device has been acquired by Pfizer (particle-mediated epidermal delivery; PMED™) to target dry powder DNA vaccines, primarily to the epidermis of the skin (**Table 1**) [65-72]. The disruption by this system causes mild side effects, such as application-site burning, which usually resolves within hours [66,70]. On the other hand, Biojector® has been developed as a liquid jet injector by Bioject (**Table 1**) [73,74]. A higher proportion of people who received the hepatitis A DNA vaccine using Biojector as a liquid jet injector seroconverted with hepatitis A virus compared with vaccination using an injection [73]. Although hand-size device was developed and handling of device was to be easy-to-use, jet injector is poor method in prevalence of vaccination because of the strong pain.

3.2.4 *Microneedle*

The most widely used method to overcome the skin barrier is intradermal injection, which enables precise and reproducible delivery of antigens into the dermis. Some studies reported that the efficacy of influenza intradermal injection was greater than that of conventional intramuscular injection, suggesting that vaccination targeting the skin is promising [75,76]. However, traditional intradermal injection requires well-trained healthcare workers, which has led to the development of new devices for intradermal injection. One example is the Becton Dickinson (BD) microinjection system, Soluvia™ [77,78]. This is a prefilled syringe with a single 1.5 mm long, 30 G intradermal needle designed to deliver 100 – 200 μL fluid. It is now commercially available for a trivalent seasonal influenza vaccine (Sanofi-Pasteur) [79]. These studies underline the effectiveness of the skin as an immunization site, but intradermal injection still employs the use of long needles and is painful. A minimally invasive means of vaccinating healthy people by TCI is desirable.

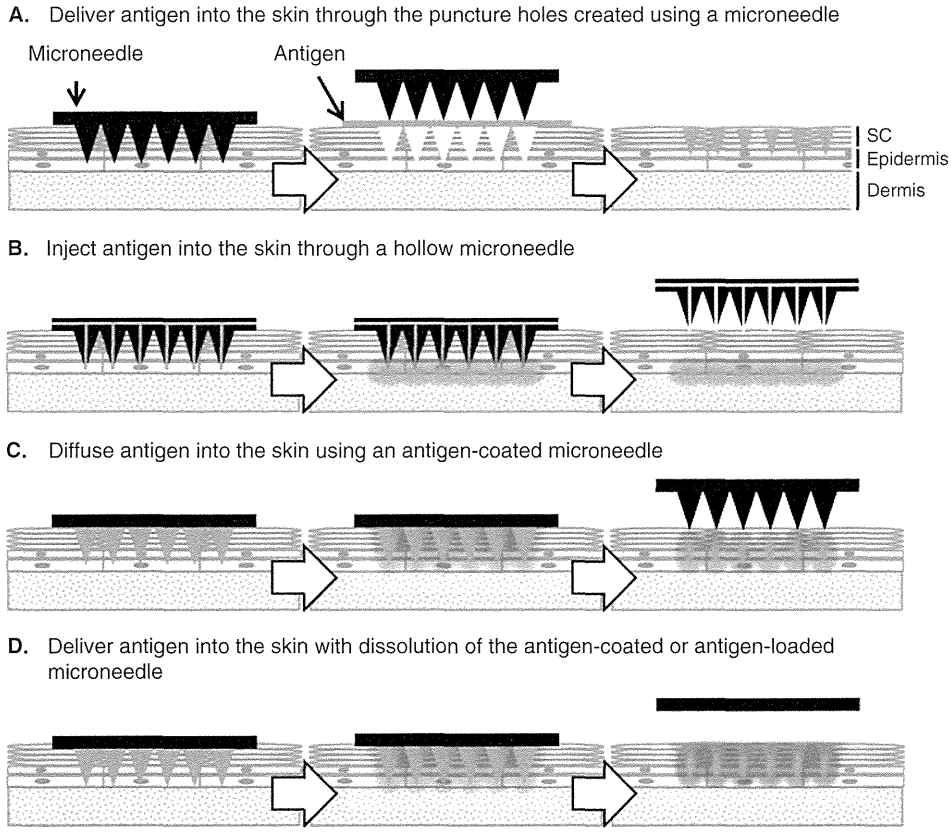

Figure 3. Examples of transcutaneous delivery using microneedle. (A) Solid microneedle; **(B)** hollow microneedle; **(C)** coated microneedle and **(D)** dissolving microneedle.

One approach toward painless TCI is to dramatically reduce the needle size so that they are barely perceptible. The concept of the microneedle array for drug delivery essentially dates back to a patent, filed in 1976, by Gerstel and Place [80]. However, it was not until the 1990s that the technique became viable, as by this time, fabrication techniques had become available to produce these microneedle arrays in a potentially cost-effective manner.

In this context, the term 'microneedle' refers to needles shorter than 1 mm. Microneedles only need to pierce the 15 to 20 µm thick SC before reaching the viable epidermis. However, the skin is an elastic, heterogeneous tissue and is slightly stretched *in vivo*. The mechanical and structural properties of the skin significantly vary with age, skin type, hydration level, body location and among individuals [81]. To ensure effective and reproducible piercing regardless of these factors, microneedles need to be much longer than 20 µm [82]. Other parameters, such as microneedle diameter, insertion depth, microneedle tip geometry and microneedle density also influence skin perforation and antigen delivery [82-84]. For instance, very thin microneedles are fragile, which results in an increased risk of fracture in the skin [85]. In addition, increased microneedle density can give rise to the 'bed of nails' effect and does not improve antigen delivery [82].

Various strategies using microneedle technology were developed for transdermal drug delivery, including TCI [86-88], because microneedle approach is one of the most easy-to-use methods by just applying it on the skin. The important strategies are summarized below (**Figure 3**).

3.2.4.1 Solid microneedles

The first method using microneedles involves perforation of the skin with solid microneedle arrays and application of antigens to the skin surface for subsequent diffusion into the skin (**Figure 3A**). Henry *et al.* demonstrated a four-order-of-magnitude increase in permeability for calcein and BSA through human epidermis *in vitro* after penetration with a microneedle array of 150 µm long needle [89]. Banks *et al.* reported that the flux across the microneedle array pretreated skin was augmented by increasing the charge of the drug [90]. In addition, it was reported that 200 nm particles can diffuse through conduits formed by a solid microneedle array (300 µm long, 4 × 4 array), which was applied at a speed of 3 m/s using an electric applicator [91]. In the absence of such an applicator, no conduits were formed. In the efficacy assessment of TCI, pretreatment of the skin using the same type of microneedle array led to a 1,000-fold increase in antibody titer after

topical application of DT in mice [92]. The immune response was further boosted by co-application of cholera toxin (CT), suggesting that selective addition of adjuvants may lower the antigen dose required [93]. A 3M has developed the microstructured transdermal system using coated or uncoated solid microneedles. In collaboration with VaxInnate, these microneedles will be used for the delivery of an influenza vaccine.

As a variant of the treatment using solid microneedles, a post-treatment method was developed [94]. The skin was painted with a vaccine solution and then gently scraped by microneedles to expose the epidermis to the vaccine without causing pain sensation. Using BD's OnVax® device, which has a microneedle length ranging from 50 to 200 µm over a 1 cm^2 area, stronger and less variable immune responses were achieved compared to intramuscular and intradermal injection with the same dose of hepatitis B DNA vaccine (100 µg). Moreover, 100% seroconversion was achieved after only two vaccinations, whereas only 40 – 50% conversion was obtained by intramuscular injection.

In general, pre- or post-treatment with the microneedle array is considered a simple approach for TCI that has great potential, but parameters such as dose and application time should be optimized.

3.2.4.2 Hollow microneedles

During pretreatment with a solid microneedle array, antigen delivery is dependent on passive diffusion along the conduits created by the microneedles. Although this is a relatively easy approach from a technical point of view, it is difficult to optimize the antigen quantity required to activate immune cells in the skin because of limited transport through the conduits. Hollow microneedle arrays can inject the vaccine to a well-defined depth in the skin by precisely steering the flow rate using a syringe or a pump (**Figure 3B**).

Hollow microneedles are made of various materials, such as silicon, metal and glass [95]. Recently, the potential of hollow microneedles for vaccination has received attention as it can be used for both TCI and intradermal vaccination depending on the microneedle length. Influenza vaccination (3.3 µg of hemagglutinin [HA] per strain) using a hollow microneedle array (450 µm long, 4 × 1, MicronJet developed by Nanopass) induced immune responses similar to those induced by intramuscular injection of 15 µg HA per strain to human volunteers (**Table 1**) [96].

The main technical demands are avoiding leakage and clogging of the microneedles during injection. Whereas clogging can be prevented using a beveled tip [83], the short-length needle increases the chance for leakage. Therefore, optimization of the flow rate, needle length and localization of the opening are demanded. In addition, the hollow microneedle formulation has the disadvantage of requiring cold chain storage and transportation of antigen solutions in addition to the injection system.

3.2.4.3 Coated microneedles

Microneedle arrays precoated (**Figure 3C**) with 1 µg OVA induced a 100-fold increase in immune response compared to intramuscular injection of the same dose [97]. The titanium microneedles in the array were 300 µm long and were applied to the skin using an impact insertion applicator. Furthermore, an extensive study was conducted on the influence of OVA-coated microneedle properties on the immune response. The immune response was found to be dose-dependent, but practically independent of depth of delivery, density of microneedles or area of application. Interestingly, OVA vaccination with short microneedles (225 µm) in a high-density array (725 microneedles/cm^2) induced an immune response similar to that induced by longer microneedles (600 µm) in a low-density array (140 microneedles/cm^2) [82]. This led to the development of the macroflux system, which is now undergoing a Phase I clinical study for TCI with an influenza vaccine. Efficacy using coated microneedles was reported for various antigens including OVA, H3N2 influenza antigen, inactivated influenza virus and hepatitis C DNA.

Coatings are usually applied by dipping the microneedle into a vaccine formulation [98,99]. Another method is to use gas jet coating to achieve a more uniform coating of densely packed microneedles [100]. Coated microneedle arrays may not be very attractive for transdermal drug delivery as only a limited quantity of active compounds can be coated onto the microneedle. However, this quantity might be sufficient for antigens to elicit a protective immune response. In addition, one of the advantages of coated microneedles is that dried antigen adhered to the surface of the microneedles may improve the long-term stability [101]. It was reported that coating reduced the immunogenicity of the vaccine, thus requiring trehalose to partially retain the activity [102,103].

A method of combining coated microneedles with electroporation has been developed [104]. The EasyVax™ device inserts coated microneedle arrays into the skin, followed by electrical pulses, to deliver DNA into the cells. Neutralizing antibody titers induced by TCI with a smallpox DNA vaccine using this system were greater than those induced by the traditional live virus vaccine administered by scarification. However, the main drawback of this approach for practical use is the complexity of the device.

3.2.4.4 Dissolving microneedles

Conventional microneedles suffer from the risk of fracture, which might leave metals, stainless steel or silicon microneedle fragments in the skin. The use of dissolvable or biodegradable materials containing vaccine components is an elegant way to deliver a vaccine without the possibility of microneedles breaking off in the skin (**Figure 3D**). Moreover, dissolving microneedles leave no biohazardous sharp medical waste and remove the risk of secondary infection by used needles.

The first microneedles were made of maltose [105] and later, development of dextrin microneedle array was reported for the delivery of insulin and erythropoietin [106,107]. Recently,

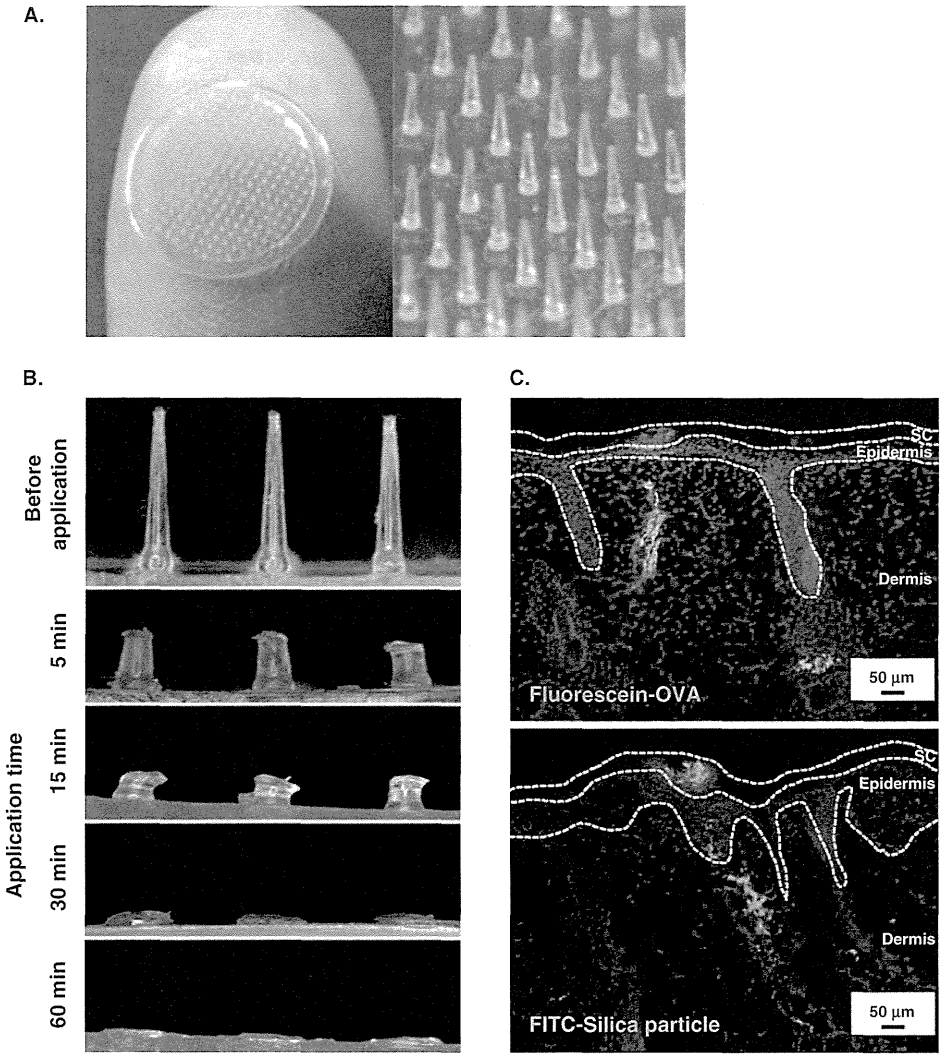

Figure 4. Photographs of MH and observation of microneedles and skin after MH application. (A) MH is made of hyaluronic acid and contains 200 microneedles/ patch (0.8 cm^2). **(B)** MH of 800 μm long needle were applied to the back skin of Wistar ST rats for the indicated times. After removal of MH, the microneedles remaining on MH were photographed using a stereoscopic microscope. **(C)** Fluorescein-OVA (green) or FITC-silica particle (green)-containing MH of 800 μm long needle were applied to the back skin of Wistar ST rats for 6 h. The skin was harvested and frozen. Frozen sections (6 μm thick) were photographed under a fluorescence microscope. The nucleus was counterstained using DAPI (blue).

Sullivan *et al.* showed that immunization with polymeric dissolving microneedles containing inactivated influenza virus induced a strong antibody and cellular response and provided protection against challenge by influenza [108]. The manufacture of dissolving microneedles requires technical expertise to allow the antigen to be incorporated into the matrix of the microneedle material using mild procedures that do not cause antigen breakdown or compromise material strength. The high temperatures required to mold polymers led to significant drug loss. The microneedles used by Sullivan *et al.* are made by a photo-polymerization method, which uses UV light to form microneedles without compromising β-galactosidase activity. Companies, such as Theraject and BioSerenTach, are currently developing dissolving microneedle systems for vaccine delivery. The Theraject VaxMAT, made of a sugar matrix containing vaccine components, is fabricated in various lengths from 100 to 1,000 μm and is assembled with an adhesive patch. After application, the microneedles dissolve and the antigen diffuses into the epidermis and dermis within a few minutes.

We have developed a self-dissolving microneedle patch (MicroHyala®; MH) made of biocompatible hyaluronic acid (**Figure 4A**) [109,110]. Our MH was prepared in various lengths from 200 to 800 μm and in two shapes of microneedle; konide and cone [109]. Sixty minutes after application, the microneedles had dissolved completely and delivered both

Table 2. Development of adjuvants for transcutaneous vaccination.

Transcutaneous adjuvant	Antigen	Immune response	Refs.
CT, CTB	DT	IgG	[111]
	TT	IgG	[111]
	OVA	IgG, IgG2a, CTL, $CD4^+$	[115,116]
	Influenza	IgG, IgG1, $CD4^+$	[113,114]
LT	TT	IgG, IgG1	[112]
Imiquimod	OVA	CTL	[121]
CpG ODN	TT	IgG, IgG2a	[112]
	Influenza	IgG2a, $CD4^+$	[113,114]

CT: Cholera toxin; CTB: B subunit of cholera toxin; CTL: Cytotoxic T cell; DT: Diphtheria toxoid; LT: *Escherichia coli* heat-labile toxin; ODN: Oligodeoxynucleotide; OVA: Ovalbumin; TT: Tetanus toxoid.

soluble and particulate material into the skin (Figure 4B and 4C). We previously reported that TCI using MH effectively induced immune responses against various antigens in animal models, and furthermore, the application of MH resulted in minimal skin irritation in rats [110]. Moreover, we conducted a clinical study to assess the safety of the MH device in humans and showed that our new MH is a practical and safe device for use in human immunization. A clinical study using influenza HA antigen-containing MH is in progress, and we have confirmed that TCI using MH induced immune responses without severe side effects (unpublished data).

4. Adjuvant development for TCI

In TCI, the co-application of adjuvants with the antigen is required for induction of a strong immune response. Aluminum hydroxide hydrate and Freund's adjuvant are commonly used as immune adjuvants. However, these adjuvants are not useful in TCI because their relatively large sizes do not permit skin penetration. Adjuvants for TCI can be divided into bacterial enterotoxin and toll-like receptor (TLR) ligands (Table 2).

4.1 Bacterial enterotoxins

Bacterial enterotoxins have high adjuvant activity and are most often used preclinically for TCI. CT and LT are the most intensively studied [73]. CT and LT not only produce anti-CT and anti-LT antibodies but also improve the total immune response and affect the quality of the immune response (Table 2) [111-114]. In addition to antibody responses, it was shown that CT can induce a CTL response [115] and that A and B subunits of CT (CTA and CTB) are responsible for the expression of different cytokines from restimulated lymphocytes isolated from the spleens of immunized mice [116]. However, the safety cannot be assured because LT or CT, which are toxins, can cause excessive tissue injury or necrosis. Difficulties have been encountered applying the toxin to the human skin, and additional studies are required to elucidate how toxins affect immune responses.

4.2 TLR ligands

TLRs are important signal molecules when cells sense danger [117] and are expressed on the surface of LCs, dDCs and keratinocytes. Therefore, purified or synthetic TLR ligands are expected to be suitable adjuvants for vaccination purposes [118,119]. One example is imiquimod, which is a ligand for TLR7 and TLR8. Imiquimod induced migration of LCs and resulted in the production of IFN-α and TNF-α (Table 2) [120-122]. Another ligand is cytosine–phosphate–guanine (CpG) oligodeoxynucleotide (ODN). By signaling through TLR9, CpG ODN enhanced the vaccine's immunogenicity and induced antibody production and proinflammatory cytokines, such as TNF-α and IFN-γ [113,114]. Various TLR ligands are currently being developed as effective adjuvants for practical use.

5. Conclusion

The skin is an important immunological site and has the potential to be an ideal non- or low-invasive vaccination site, although it possesses a complex barrier. TCI provides effective, easy-to-use and painless vaccination with little side effect and safer handling than conventional injections. The main challenges of TCI are ensuring accurate delivery of antigens into the epidermal or dermal skin tissue where LCs and dDCs are present, and to activate specific immune response. Many different approaches have been developed of which several ways may lead to successful TCI, and clinical studies of some devices have been conducted. However, satisfactory guidelines about the standard for formulation and evaluation of safety and efficacy have not yet been regulated because of the novelty of this formulation. Various information about the characteristics of skin as a target and the fundamental properties of TCI devices may lead to the establishment and refinement of guidelines for TCI formulation. Such guidelines will encourage researchers and pharmaceutical companies to develop practical TCI systems.

6. Expert opinion

Many strategies, in particular microneedle devices [123-125], have been developed for TCI systems. Such strategies could be easy-to-use methods of vaccination. For the practical use of these TCI formulations, the safety and efficacy of TCI must be confirmed. Therefore, knowing the function of immunocytes, such as APCs, T cells, macrophages and keratinocytes, in the skin is important. Analysis of the immunological characteristics of each type of cell (e.g., surface marker expression and cytokine production) can help elucidate the molecular and/or cellular mechanisms that underlie the immunity of the skin. In addition, recent studies using two-photon confocal microscopy or genetically modified mice have enabled direct observation of the kinetics and distribution of immune cells in the skin and the interaction between APCs and T cells in draining lymph nodes and

have lead to understand skin immunity *in vivo* [126,127]. Such studies are useful for the development/improvement of transcutaneous vaccination formulations and can guarantee the safety and efficacy of TCI systems. Moreover, transcutaneous delivery of adjuvant is required for more effective immune responses, the reduction of antigen dose and/or number of administrations and the expansion of applications to various diseases. Advances in understanding the functional properties of immunocytes in the skin contribute to the development of adjuvants suitable for TCI by providing information on the delivery target of antigen and adjuvant. Thus, if the bias of immune responses can be controlled by the appropriate selection of TCI methods and/or adjuvants, TCI systems could be used to create strategies against Alzheimer's disease, autoimmune diseases and cancer. Basic scientific research must be actively evolved to the translational research to assess application of TCI systems to human. We believe that the practical use is achieved early by promoting the consistent studies from basic research to clinical trial led by TCI researchers including us.

Declaration of interest

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