

Skin models for the testing of transdermal drugs

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Abstract: The assessment of percutaneous permeation of molecules is a key step in the evaluation of dermal or transdermal delivery systems. If the drugs are intended for delivery to humans, the most appropriate setting in which to do the assessment is the in vivo human. However, this may not be possible for ethical, practical, or economic reasons, particularly in the early phases of development. It is thus necessary to find alternative methods using accessible and reproducible surrogates for in vivo human skin. A range of models has been developed, including ex vivo human skin, usually obtained from cadavers or plastic surgery patients, ex vivo animal skin, and artificial or reconstructed skin models. Increasingly, largely driven by regulatory authorities and industry, there is a focus on developing standardized techniques and protocols. With this comes the need to demonstrate that the surrogate models produce results that correlate with those from in vivo human studies and that they can be used to show bioequivalence of different topical products. This review discusses the alternative skin models that have been developed as surrogates for normal and diseased skin and examines the concepts of using model systems for in vitro–in vivo correlation and the demonstration of bioequivalence.

Keywords: percutaneous permeation, dermal delivery, transdermal, bioequivalence, ex vivo skin models, reconstructed skin

Introduction

The skin is a major physical, immunological, and sensory barrier to our environment. While it has long been used as a portal for drug delivery, it is a formidable barrier that requires appropriate technology for successful delivery. It is particularly effective in preventing large (ie, molecular weight >500) or polar molecules from entering the body. It is also a heterogeneous organ, with several delivery routes and sites that could be targeted for desirable pharmacological and immune responses. A key challenge is to deliver to the target site sufficient quantities of the drugs, peptides, vaccines, and dyes that are mainly larger and polar to achieve these responses. This may require the design of a specific chemical or physical delivery system to enhance the permeation of the active substance.

The assessment of percutaneous permeation is key to the successful development of new formulations intended for human use. It is also an important quality-control measure to ensure batch-to-batch uniformity in the pharmaceutical industry.¹ Clinical end-point bioequivalence studies have generally been used for bioequivalence assessments of locally acting products. However, this is not the most feasible approach, due to the high costs involved, as well as the lack of sensitivity in highlighting formulation differences. Alternative methods for evaluating product performance include a

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range of models. More commonly used models to conduct skin-permeation studies are *ex vivo* human or animal skin. Through the standardization of protocols and techniques, the available skin models can be useful as surrogate models for *in vivo* human skin to evaluate the bioequivalence of topical products.

This review discusses the alternative skin models that have been developed as surrogates for normal and diseased skin, and examines the concepts of using model systems for *in vitro*–*in vivo* correlation (IVIVC) and the demonstration of bioequivalence. Table 1 lists a range of appropriate skin models.

Human skin structure and function

A comprehensive review of the structure and function of skin can be found in Monteiro-Riviere.² The skin accounts for approximately 16% of human body weight, with a surface area of approximately 2 m² in adults.^{3,4} It provides a physical barrier to the environment, maintains homeostasis by limiting the loss of water, electrolytes, and heat, and protects against microorganisms, toxic agents, and ultraviolet radiation.⁵ There are three basic layers: the epidermis, the dermis, and the subcutaneous layer. Hair, nails, sebaceous glands, and sweat glands (apocrine and eccrine) are considered to be skin derivatives or appendages. Even though it is structurally continuous throughout the body, skin varies in thickness according to the age of the individual and the anatomical site.

The epidermal layer is formed from squamous epithelium and is subdivided into separate layers, according to the degree

of keratinization of the cells. The layers of the epidermis from the bottom to the surface are stratum basale (basal cell layer), the stratum spinosum (spinous or prickle-cell layer), the stratum granulosum (granular cell layer), and the stratum corneum (SC; horny layer) (Figure 1).⁶

The outermost layer of the epidermis, the SC, consists of denucleated, nonliving, flattened cells called corneocytes. There are ten to 25 layers of stacked corneocytes, which are nonhydrated cells lying parallel to the skin surface.⁵ The SC layers are united by SC lipid bilayers assembled into a “brick and mortar” arrangement.⁷

Below the SC, the remainder of the epidermis is viable tissue, called viable epidermis, containing nucleated cells called keratinocytes. The viable epidermis is a region for drug binding, metabolism, active transport, and surveillance. In addition to keratinocytes, it contains melanocytes (dendritic cells found on the basement membrane and in the basal layer), Merkel cells (functioning as mechanoreceptors involved in mediation of touch responses, found in the basal region), and Langerhans cells (dendritic cells playing a key role in protective immune function, present mainly in the stratum spinosum).²

The viable epidermis is separated from the dermis at the dermal–epidermal junction. The dermis is rich in collagen. The subcutaneous (hypodermis) layer is the deepest layer of the skin and is formed from loose connective tissue and fat (50% of the body fat), which may be more than 3 cm thick on the abdomen. The dermis and subcutaneous layers contain blood vessels, lymphatics, and nerve cells, in addition to skin appendages.⁸

Table 1 Skin models

Model	Advantages	Disadvantages
Human skin		
<i>In vivo</i>	Gold standard	Often precluded for ethical and practical reasons
<i>Ex vivo</i> skin	Best surrogate for <i>in vivo</i> humans	Not readily available, variability
Animal skin		
<i>In vivo</i>	Reasonably easy to obtain animals, can be scaled up to humans, hairless species available	Pigs: similar barrier to humans, but difficult to handle Rodents: different barrier properties from humans
<i>In vivo</i> chimeric model	Human skin xenografts on mice allows testing on living human skin	Technically difficult
<i>Ex vivo</i> skin	Easy to obtain	Different barrier properties, variability
Artificial membranes		
Simple polymeric models	Useful for studying basic diffusion mechanisms, consistent and homogenous	Not representative of human skin
Lipid-based models	Useful for screening	Not representative of human skin
Reconstructed skin models		
Reconstructed human epidermis	Built-in barrier properties	Usually more permeable than human skin
Living skin equivalents	Can be engineered to include a range of normal or disease features	Usually more permeable than human skin

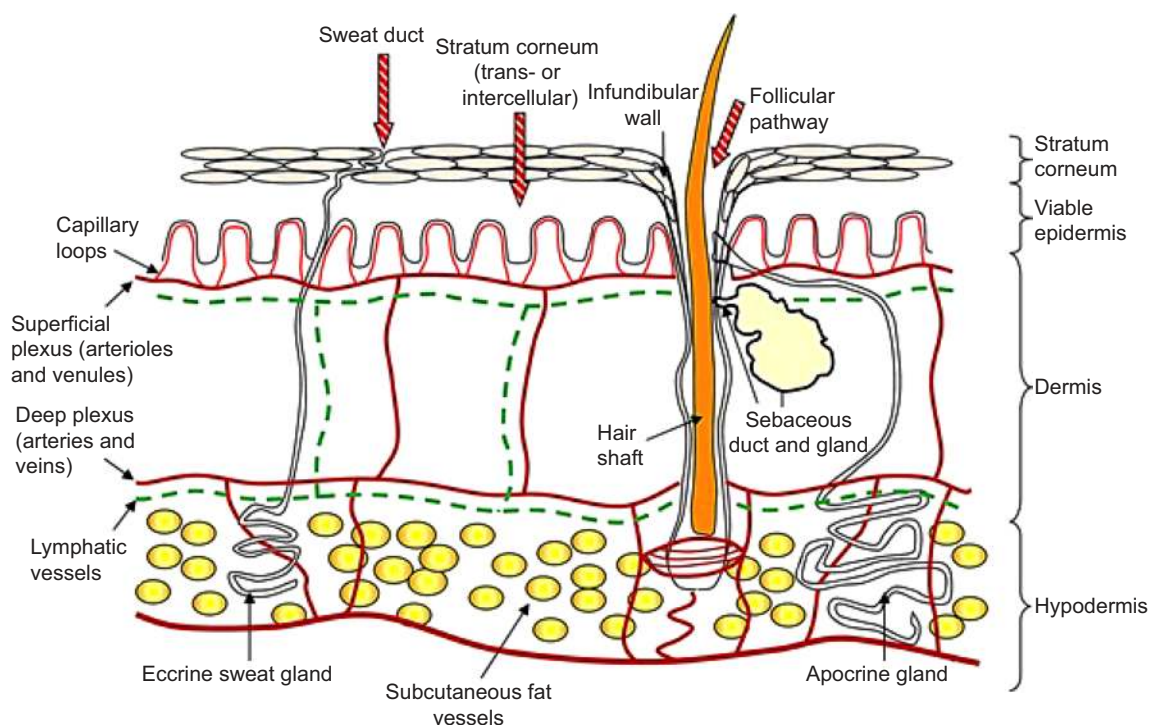


Figure 1 Structure of the skin.

The SC acts as the primary skin barrier, with the essential functions of protecting the body from the surrounding environment, providing an efficient obstacle to the permeation of exogenous molecules⁸ and microorganisms⁹ and maintaining homeostasis by preventing excessive loss of water.¹⁰ The surveillance, metabolic, and transport processes located in the deeper skin layers^{11,12} also contribute to the protective functions of the skin.

Models used to evaluate dermal absorption

Ex vivo human skin models

Measurement of dermal absorption for the purpose of targeted skin delivery, systemic delivery, or toxicological assessment should be done under the correct conditions, ideally using the gold-standard experimental model: *in vivo* human skin.¹³ However, this is not always possible, due to the high cost of human trials and concerns over applying substances or materials with potentially toxic effects. As well, *in vivo* responses may be difficult to measure and interpret and subject to significant variability. Alternative methods are needed to derive data that are reproducible and reliable and which provide a meaningful prediction of the *in vivo* human situation.¹⁴ There is a large body of work based on *ex vivo* human skin, and as we shall discuss in more detail later, some success has been achieved in correlating *in vitro* and

in vivo dermal absorption, often driven by regulators seeking a standard, robust assessment method.^{15,16}

Excised human skin is most commonly obtained from plastic surgery or cadavers, and in both cases, appropriate ethical approval is required to use the tissue. Abdominal, breast, or back skin is most convenient, due to the large areas that may be available. There are considerable differences in skin absorption across different body sites,¹⁷ attributed to such factors as differences in SC thickness,¹⁸ hydration,^{19,20} and lipid composition.²¹ Clearly, this needs to be recognized when designing studies.

As noted earlier, the SC represents the main barrier to penetration of exogenous substances into the skin,⁸ as well as controlling the loss of water from inside the body.¹⁰ It is believed that skin may be stored for up to 6 months without loss of SC barrier function,²² particularly if 10% glycerol is used as a preservative.²³ Nielsen et al also found little effect of freezing at -20°C for 3 weeks, with or without polyethylene glycol as a preservative, but significant damage with storage at -80°C .²⁴ On the contrary, other evidence suggests significant loss of barrier function, causing increased skin permeation, with frozen storage of animal skin.^{25,26} Barbero and Frascch concluded that carefully handled frozen human skin was suitable for testing the passive permeation of chemicals, when skin viability and metabolic activity were not being investigated.²³ Cellular

viability and metabolic activity within the human epidermis are likely to be reduced by frozen storage or heat.^{27,28} Our unpublished results from an MTT assay showed a complete elimination of epidermal viability following heat separation by the method of Kligman and Christophers.²⁹ For studies requiring the presence of viable epidermal tissue, such as imaging of endogenous skin autofluorescence by multiphoton tomography,³⁰ or investigations of skin metabolism,²⁸ fresh tissue is required.

Several different membrane types may be prepared from ex vivo human skin for use in permeation experiments. “Full-thickness skin” is prepared by removal of connective tissue and subcutaneous fat and consists of all layers down to and including the dermis.³¹ To reduce variability while retaining significant dermal thickness, full-thickness skin may be cut to approximately 500–750 μm with a dermatome.³² However, the presence of the hydrated dermis may introduce an additional, artificial barrier to permeation, particularly for more lipophilic molecules.

In contrast to the in vivo situation, where capillary circulation rapidly clears penetrated molecules, full-thickness or dermatomed skin mounted in a diffusion cell represents a situation analogous to vasoconstriction.³³ Consequently, the use of a membrane consisting of only the SC and the viable epidermis may be preferred. According to Cross and Roberts, this membrane represents a situation of “infinite dilatation”, since all material making its way past the SC barrier is immediately available to the receptor solution.³³ Atrux-Tallau et al found that dermatomed human skin and heat-separated epidermal membranes gave the same flux for caffeine, a hydrophilic compound.³⁴ Results from our group where steroids were applied to epidermal membranes, full-thickness skin, and isolated dermis showed that there was a minimal effect of increasing lipophilicity on epidermal maximum flux and a trend toward decreased dermal penetration rates.³⁵

Epidermal membranes are most commonly prepared by immersing full-thickness skin in hot water ($\sim 60^\circ\text{C}$) for approximately 1 minute.²⁹ Other techniques designed to separate the membrane at the dermal–epidermal junction include chemical treatments with ethylenediaminetetraacetic acid, ammonia, and enzymes.³² Some researchers have used the isolated SC for permeation experiments³⁶ and for desorption studies designed to study SC heterogeneity,³⁷ and the SC reservoir for water and other substances.³⁸ The SC is prepared by enzymatic methods, usually by incubation with aqueous trypsin solution, after which the digested epidermal material is rinsed and wiped off.³⁹

Ex vivo human skin: use in bioequivalence studies

For the majority of topical drug products, comparative clinical end-point studies are used to demonstrate bioequivalence to a reference drug. While this provides a direct in vivo assessment, it is also associated with a number of challenges. Clinical end points are associated with high variability (intra-subject) and low sensitivity (drug-related), which makes such studies less reliable and less efficient. The other clinical alternative is to use pharmacokinetic studies to demonstrate bioequivalence for topical products, but this is limited to particular cases where significant systemic absorption of the drug occurs. Recently, the use of techniques including in vitro permeation testing (IVPT), in vivo tape stripping, or dermatopharmacokinetics, and in vivo microdialysis or microperfusion, has been advocated for testing bioequivalence.⁴⁰

IVPT using human dermatomed skin mounted in diffusion cells is increasingly seen as a suitable tool for demonstrating bioequivalence of topical dosage forms.⁴⁰ Indeed, the generation of such data has been encouraged by regulatory agencies, such as the European Medicines Agency, the US Environmental Protection Agency, and the US Food and Drug Administration (FDA). Their utility is grounded on substantial evidence that 1) there is a good correlation between the in vitro and in vivo rates and extents of human skin absorption of a number of different substances and 2) there is good agreement on the bioequivalence of topical products seen with IVPT and in vivo clinical studies.

Currently, however, there are no approved protocols for carrying out IVPT studies. Franz et al pointed out that the demonstration of valid IVIVC is greatly dependent upon the protocols used, and they recommended that the in vitro and in vivo protocols followed should be as closely harmonized as possible to maximize the chance of achieving a good correlation.^{15,41} The work on which this conclusion was based was an analysis of historical literature data that was available to the researchers, and despite the wide variation in the way in which it was collected, their conclusion was that there was compelling evidence that it was possible to correlate IVPT data with human in vivo skin-absorption data. Others who have demonstrated good IVIVC include Hadgraft et al, who compared in vitro and in vivo delivery from nitroglycerin patches,⁴² and more recently Yang et al, who compared their own IVPT data with literature reports of in vivo estradiol delivery from patches.¹⁶

While the use of IVPT for bioequivalence has only recently been formalized, the design of in vitro permeation tests has been subject to consideration and validation for many years. In 1987, the FDA published a report on the

important factors to be considered, which included the membrane type (dermatomed skin or heat-separated epidermis?), the receptor fluid, the cell design (static or flow-through?), application (finite or infinite dose?), and temperature.⁴³

The *in vivo* dermatopharmacokinetic (DPK) method uses tape stripping to remove SC layers. The FDA has investigated the possibility of introducing a DPK method for evaluating bioavailability and/or bioequivalence of topical dermatological drug products.^{44,45} In the DPK method, it is assumed that 1) in normal circumstances, the SC is the rate-determining barrier to percutaneous absorption, 2) the SC concentration of the drug is related to the amount that diffuses into the underlying viable epidermis, and 3) SC drug levels are more useful and relevant for assessing local, dermatological efficacy than plasma concentrations.⁴⁶ It is also possible to deduce partitioning and diffusion parameters that characterize the absorption process and which can subsequently be used to predict an entire absorption profile from a single short-contact-duration experiment.⁴⁴ The technique is very operator-dependent, and care needs to be taken to apply and remove the tapes reproducibly. The success of the method is equally dependent on the development of sensitive analytical methods to quantify the amount of drug in the tapes.

Microdialysis involves the insertion of an ultrathin hollow fiber as a probe into the dermis. The probe is semipermeable and perfused with sterile buffer using a microdialysis pump. This involves the exchange of the small diffusible molecules from the extracellular fluid into the probe and vice versa. This method is used to determine the concentration of the unbound drug or biomarkers at the site to establish the concentration-versus-time profile of the applied compound. There are several issues associated with microdialysis. Probe insertion in the skin can lead to inflammatory responses, as may interactions of the perfusing buffer with the tissue.^{47,48} Recovery is low for highly lipophilic molecules, which may be resolved to some extent by using albumin, cyclodextrins, and cosolvents such as ethanol and dimethyl sulfoxide in the buffer,⁴⁹ while highly protein-bound molecules may be difficult to detect, due to binding to the probe material. A major disadvantage of the method is the intrasubject variability.⁵⁰ The newer technique of dermal open-flow microperfusion (dOFM) differs from microdialysis, in that it gives continuous, membrane-free (ie, unfiltered) access to dermal fluid.⁵¹ Like microdialysis, dOFM provides a direct estimate of the time course of delivery of the permeant near its site of application. Because of the lack of interaction with a membrane in dOFM, it can be used for a wider range of compounds than microdialysis.⁴⁰ The technical difficulty of microdialysis and

dOFM means that significant operator expertise is required, and as such they are generally only available in a research setting.

Ex vivo animal skin models

The assessment of percutaneous absorption of molecules is an important step in the evaluation of any topical drug-delivery system or formulation. As we have already noted, if the dosage form is to be used in humans, the most relevant skin-absorption data should come from *in vivo* human studies. However, such studies are generally not feasible during the initial development of a novel pharmaceutical dosage form. Moreover, *ex vivo* human skin may not be readily available, and so researchers have relied on animal studies for much of the experimental data. This creates a major challenge in correlating results from *ex vivo* animal experiments with *ex vivo* and *in vivo* human studies for prediction of human percutaneous absorption.

A wide range of animal models has been used as alternatives to human skin to evaluate percutaneous permeation of substances. These include pig, mouse, rat, guinea pig, and snake models. Porcine (pig) skin is histologically similar to human skin,^{52,53} with a comparable SC thickness of 21–26 μm .^{54,55} In addition, the average hair-follicle density in porcine ear skin is 20/cm² compared to 14–32/cm² in human forehead skin.⁵⁴ As well as being similar to human skin, porcine ear skin is also convenient to obtain and has been widely used in skin-permeation studies.⁵⁶

The SC lipids are known to be important regulators of skin permeability. With this in mind, the conformational disordering and lateral packing of lipids in isolated porcine and human SC were compared using Fourier-transform infrared spectroscopy. The SC of both species differ markedly, with porcine SC lipids being arranged predominantly in a hexagonal lattice, while lipids in human SC were predominantly packed in the denser orthorhombic lattice.⁵⁷ In human as well as porcine SC, the main lipid classes are ceramide, cholesterol, and free fatty acid, and these lipid classes are present in an approximately equimolar ratio.⁵⁸ However, the compositions of free fatty acid and ceramide in the two species are different.

In a range of studies using both lipophilic^{59,60} and hydrophilic^{59,61} permeants, the permeability of pig skin was found to be similar to that of human skin, but to differ to a greater extent from dog⁶¹ or rodent skin.^{59,61} Sato et al attributed the similarity in permeability to the similar SC lipids, barrier thickness, and morphological aspects of pig and human skin.⁶¹ Nicoli et al further investigated the differences

between pig skin and rabbit ear skin, finding that although they had similar SC thicknesses, pig skin was four to seven times more permeable to hydrophilic compounds than rabbit ear skin, most likely due to its different SC lipid composition.⁶² The relationship between permeability and SC lipids is analogous to early findings by Lampe et al,⁶³ who showed the total lipid-weight percentage at various human body sites (face > abdomen > leg > plantar SC) was inversely proportional to the relative permeability of skin reported for those sites by Scheuplein and Blank.⁶⁴ Caussin et al also reported the similarity in SC lipid composition, as well as in lamellar organization, between pigs and humans.^{63,65} Interestingly, however, they also saw a substantial difference in lateral packing between the two species. As with human skin, permeation behavior was found to correlate with barrier function, as measured by transepidermal water loss in a study by Sekkat et al, who applied caffeine, lidocaine, and phenobarbital to tape-stripped pig skin.⁶⁶

Skin of rodents (mice, rat, and guinea pigs) is the most commonly used in *in vitro* percutaneous permeation studies, due to its availability, their small size, and relatively low cost. There are different hairless strains of each species that are reported to mimic the permeation properties of human skin better than the hairy variety.⁶⁷ Among rodents, rat skin is most structurally similar to human skin and it is the most frequently used rodent model. A large number of studies comparing permeation through human and rat skin have been carried out, showing that rat skin is generally more permeable than human skin across a range of permeants of different physicochemical properties,⁶⁸⁻⁷² in some cases with differences of more than an order of magnitude. For example, for compounds with log-*P*-values ranging from 0.7 to 4.5, van Ravenzwaay and Leibold⁷² found that mean *in vitro* permeation flux through rat skin was around elevenfold greater than through human skin, while a similar comparison by Schmook et al⁷¹ found flux increase of 50-fold for the relatively lipophilic molecules hydrocortisone and terbinafine.

Shed snake skin is another interesting membrane that was suggested as a suitable alternative to human skin.⁷³ This membrane, which can be obtained without killing the animal, has some similarity to human skin, in that it consists of thin, flat squamate cells surrounded by intercellular phospholipids, although it does lack hair follicles. Rigg and Barry compared permeation of fluorouracil (5-FU) through dermatomed human abdominal skin and shed skin from two snake species.⁷⁴ The permeability coefficients were similar between human and dorsal and ventral skin of one snake species, whereas there was a 30-fold increase in dorsal skin

from *Elaphe (Pantherophis) obsoleta*. These authors found no changes in 5-FU permeability in human or snake skin after acetone pretreatment, whereas Megrab et al⁷⁵ found differential responses in human and dorsal snake skin with vehicles containing different ethanol concentrations. Apart from possible interspecies differences, it is likely that solvent effects in snake skin are influenced by both the lower water content⁷⁵ and the nature of the intercellular lipids. While snake skin may be a reasonable model for human skin, it is not readily available, and doubts must exist over the quality and consistency. As Rigg and Barry noted, “[. . .] if at all possible, investigative problems should not be made more complex by selection of an animal tissue to represent human skin”.⁷⁴

It may be useful, particularly in the interpretation of dermal absorption for human risk assessment, to predict human *in vivo* dermal absorption from known *in vitro* human, *in vivo* animal, and *in vitro* animal data, the so-called triple-pack approach.⁷⁶ The animal in question is normally considered to be the rat. Human *in vivo* dermal absorption may be derived by the equation:

$$\text{in vivo human absorption} = \text{in vivo rat absorption} \times \left(\frac{\text{in vitro human absorption}}{\text{in vitro rat absorption}} \right) \quad (1)$$

Here, it is assumed that 1) the factor between *in vitro* and *in vivo* dermal absorption is the same for rats and humans and 2) the factor between rat and human skin absorption is the same *in vitro* and *in vivo*, despite the morphological species differences.

Artificial and reconstructed skin models

Artificial and reconstructed skin models are useful tools in specific circumstances, driven by the need to find convenient, reproducible alternatives to *in vivo* and *ex vivo* tests with human and animal skin. The artificial skin models range from simple homogeneous polymer materials, such as poly(dimethoxysilane) or silicone membranes through to lipid-based parallel artificial membrane-permeability assay (PAMPA) or phospholipid vesicle-based permeation-assay membranes,⁷⁷ with the latter material designed to mimic the SC. By eliminating the complexity of human or animal skin, the simple homogeneous materials are particularly useful for studying the basic mechanisms controlling passive transport through a membrane.⁷⁸⁻⁸⁰ The main advantage they have in this regard is their relative reproducibility due to their simple standardized construction. However, they are not intended to represent, nor are they capable of, representing the multitude of *in vivo* skin properties.⁸¹

The PAMPA can be used for rapid screening of passive transport.⁸² The PAMPA assay is conducted in a 96-well filter plate coated with a liquid artificial membrane to separate two compartments: one containing a buffer solution of compounds to be tested (donor compartment) and the other containing an initial fresh buffer solution (acceptor compartment). Significant correlations with gastrointestinal absorption in humans were seen with PAMPA using filters impregnated with a solution of phospholipids or hexadecane.⁸² To develop a new artificial membrane to be used in PAMPA for prediction of skin permeation, Ottaviani et al investigated the permeability coefficients of a number of compounds through human skin and the PAMPA-skin artificial membrane comprised of dimethylpolysiloxane (silicone) membranes. They reported a good correlation between the two skin models.⁸³

The FDA has encouraged the use of porous synthetic membranes for evaluating the performance of topical products, as they act as a support without posing a rate-limiting barrier.⁸⁴ Shah et al from the FDA used different microporous membranes, such as pure cellulose acetate, cellulose, and polysulfone, of similar pore sizes and thicknesses to examine the permeation of hydrocortisone from two commercial creams. They found that the hydrocortisone flux was consistent irrespective of the types of synthetic membrane.⁸⁵ Nitroglycerin drug release from commercial ointments was investigated by Wu et al⁸⁶ using ten types of commercial synthetic membranes, such as polysulfone, cellulose mixed esters, polytetrafluoroethylene, and polypropylene, with different pore size and thickness. From the results obtained in this study, the synthetic membranes may be classified into two groups: group 1, consisting of polysulfone, acrylic polymer, glass fiber, silicone, and mixed cellulose ester, showed higher drug permeation compared to group 2, which included polytetrafluoroethylene–polyethylene, mixed cellulose ester (of greater thickness), and polypropylene. The effect of membrane types upon ketoprofen drug release from a gel has also been studied. It was found that nylon exhibited the least rate-limiting effects, although it is a thicker synthetic membrane compared to others.⁸⁷

Reconstructed skin models are culture-based, with layers of human cells in culture laid down over a polymeric matrix. This allows different cell types to be incorporated to achieve a structure of the desired composition and complexity. Reconstructed models are generally designed to simulate the epidermis (reconstructed human epidermis [RHE] models) or the full human skin (living skin equivalents [LSEs]).^{22,77}

Some reconstructed skin models are produced in-house for particular research purposes, such as drug-candidate or toxicological screening⁸⁸ or the assessment of photodamage and photoprotection.⁸⁹ In one particular reconstructed model, consisting of layers of human dermal fibroblasts and human epidermal HaCaT cells, there was no change in the permeability coefficients of ibuprofen after freezing the membrane over liquid nitrogen for 24 hours or 6 months. Such a property would make reconstructed membranes attractive for general screening uses. In addition, there are commercially available RHEs (eg, EpiSkin[®], SkinEthic[®], and EpiDerm[®]) and LSEs (eg, GraftSkin[®], EpiDermFT[®], and Pheninon[®]) that have been suggested as suitable candidates for in vivo and ex vivo skin models in evaluating skin absorption, testing of cosmetic products, and for the toxicological screening of topically applied compounds. A number of studies have compared LSE and HRE models with animal and human skin.^{71,90,91} Schmoock et al studied salicylic acid, hydrocortisone, clotrimazole, and terbinafine permeation through ex vivo human (dermatomed), porcine, and rat skin, GraftSkin LSE, and SkinEthic RHE.⁷¹ The fluxes and skin accumulation were generally in the order human \leq porcine $<$ rat $<$ GraftSkin \ll SkinEthic. Comparing human and pig skin with two RHE models, Schreiber et al⁹¹ found permeation coefficients of caffeine and testosterone were both in the order human $<$ pig $<$ EpiDerm \ll SkinEthic. Schäfer-Korting et al published an extensive comparison of human epidermal membranes, porcine skin, and three RHE models – EpiDerm, EpiSkin, and SkinEthic – with a series of hydrophilic and lipophilic permeants.⁹⁰ Their general conclusions were that the RHE models, particularly SkinEthic, were significantly more permeable than the ex vivo skins, although the ranking of the permeation of the compounds through pig skin and the RHEs mirrored that through human epidermis. Interestingly, they did not observe the expected improvement in reproducibility with the RHEs compared to the ex vivo skin.

As of 2013, reconstructed skin models had received Organization for Economic Co-operation and Development approval for testing of skin corrosion, acute skin irritation, and phototoxicity.²² None is currently approved for testing of skin absorption. Further work is needed to validate the various models, particularly the LSEs, for this purpose, although they may be useful for in vitro screening. Interestingly, Schäfer-Korting et al concluded that the tested RHEs were applicable to both finite- and infinite-dose studies.⁹⁰

Models for skin diseases

The skin is not only a convenient portal to the systemic circulation but also a logical site of application for treatment

of various localized skin disorders, such as skin cancers, inflammatory illnesses, and damaged skin. As the investigation of disease mechanisms and new therapies is usually difficult or impossible in humans, it is necessary to use alternative methods. Models representing normal or healthy skin are appropriate to test the delivery and targeting of topically applied drugs or other substances, often for the purpose of evaluating the delivery system used. However, models that are designed to mimic the effects of disease states can be used to study the delivery and effects of topical therapies or to gain insight into the molecular mechanisms responsible for particular diseases. In the following sections, we review some of the various animal and artificial models that have been applied to studies of skin diseases. Some recently published studies using animal and reconstructed human skin models for the study of skin diseases, including their use in therapeutic screening, are summarized in Tables 2 and 3.

Ex vivo animal models for skin diseases

A plethora of *in vivo* animal models employing fish, guinea pigs, mice, rats, rabbits, and pigs have been developed to mimic human skin diseases. Some recent reviews have focused on the most widely studied areas of melanoma,⁹² atopic dermatitis,⁹³ and psoriasis.⁹⁴ Other applications include skin infections (eg, acne, viral infections), damaged skin (eg, wounding, photo-damaged skin), hair disorders (eg, different types of alopecia), and skin cancers, such as basal and squamous cell carcinomas. A significant number of models use genetically engineered mice, due to the fact that many human skin diseases are caused by gene mutations.⁹⁵ These animal models have been extensively used for the understanding of disease mechanisms and to a lesser extent for the clinical evaluation of drug candidates. For example, epidermal VEGF-knockout mice were used to identify a specific role for epidermal VEGF in the maintenance of epidermal permeability-barrier homeostasis and pointed to the disruption of VEGF pathways in the development of psoriasis.⁹⁶ In very recent work by Rossbach et al,⁹⁷ histamine H₄ receptor (H₄R)-knockout mice showed significant reductions in ovalbumin-induced skin lesions analogous to those caused by atopic dermatitis. Their findings suggested that H₄R could be a new therapeutic target in allergic skin diseases like atopic dermatitis.

In addition to melanoma, mouse models have been used particularly for the other common skin cancers, squamous cell carcinoma,^{98–103} and basal cell carcinoma.^{104–106} An overview of animal models for a wide range of skin conditions,

with an emphasis on their application to drug discovery, has been published by Avci et al.¹⁰⁷

Of particular interest are the chimeric models, in which living human skin is grafted on to the skin of severe combined immunodeficient (SCID) mice. In this way, responses or treatments can be studied in living human skin. For example, targeted Kv1.3-cell immunotherapy was shown to be effective in reducing human epidermal thickness and the number of CD3⁺ lymphocytes in an SCID mouse–human psoriatic skin xenograft model, leading the authors to propose the investigated therapy for treatment of psoriasis and possibly other inflammatory skin conditions.¹⁰⁸ Similar investigative work in psoriasis used the SCID mouse–human psoriatic skin xenograft model to identify a role for Hsp90 in signaling pathways that are upregulated in psoriasis. Mice treated orally with the Hsp90 inhibitor Debio 0932 showed a reduction in xenograft epidermal thickness.

The xenograft model has also been used for investigation of cancer targets and therapies. Targeted oral¹⁰⁹ or intravenous¹¹⁰ treatments in SCID mouse–human melanoma xenografts caused significant reductions in tumor proliferation and size in BRAF- and ALDH⁺-specific melanomas.^{109,110}

Reconstructed skin models for diseases

Today, there are increasing regulatory restrictions on the use of animals, and the availability of excised human diseased skin is limited. For these reasons and following the advances in tissue engineering, the development of artificial *in vitro* human skin models to mimic both healthy and diseased skin has intensified. Another important benefit of using artificial skin models is that they allow the incorporation of specific disease characteristics in a controlled and relatively reproducible manner. *In vitro* models have been developed for a wide range of skin diseases, such as inflammatory disorders, fungal infections, skin cancer, photodamaged skin, and wounding. A general review has recently been published by Kùchler et al.²² The models are generally developed in-house by researchers, with the goals of understanding disease mechanisms and progression, or less commonly to use as screening tools for the assessment of therapeutic modalities. A major challenge in the use of these models is to assess whether they are relevant to and predictable of the *in vivo* situation.

Inflammatory and autoimmune diseases for which artificial skin models have been developed include psoriasis,^{111,112} atopic dermatitis,^{113,114} and eczematous dermatitis.¹¹⁵ In most cases, the specific pathway leading to expression of the disease state was induced by suitable interventions, such as stimulation by psoriasis-associated cytokines,¹¹² or in the

Table 2 In vivo animal disease models

Disease model	Characteristics	Drug delivered	Reference
Psoriasis mouse model	Epidermal VEGF-knockout mice used to identify specific role for VEGF in permeability-barrier maintenance		Elias et al ⁹⁶
Atopic dermatitis mouse model	Histamine H ₁ (H ₁ R)-knockout mice used to show H ₁ R modulates inflammation in a chronic allergic dermatitis setting	H ₁ R antagonists partially mimicked effects of H ₁ R knockout	Rosbach et al ⁹⁷
Dermatophytosis guinea-pig model	Tinea corporis induced by application of <i>Trichophyton mentagrophytes</i> TIMM1 I89 inoculum on dorsal skin	Luliconazole	Koga et al ¹²¹
Irritant dermatitis hairless guinea-pig model	Induced by daily exposure for 4 days to sodium lauryl sulfate	Basic, carbomer, isopropyl palmitate, glycerol, canola oil, and bisabolol creams	Andersen et al ¹²²
Squamous cell carcinoma mouse model	Dorsal UVB irradiation (minimal erythema dose) of SKH1 hairless mice UV-induced T7 SCC line subcutaneously injected in the back of SKH1 hairless mice UV radiation of SKH1 hairless mice	Diclofenac (anti-inflammatory COX2 inhibitor) as preventive drug Ingenol mebutate 17AAG (heat-shock protein 90 inhibitor) alone or in conjunction with UVR treatments Curcumin	Burns et al ⁹⁸ Cozzi et al ⁹⁹ Singh et al ¹⁰⁰ Sonavane et al ¹⁰¹
Basal cell carcinoma mouse model	Human skin SCC cell line SRB12-p9 subcutaneously injected into severe combined immunodeficiency (SCID) mice		
	Two-stage skin-carcinogenesis model in FVB/N mice: 1) topical treatment with carcinogen agent (DMBA), 2) tumor-promoter treatment (TPA), and 3) oral dose with a BRAF inhibitor (PLX4270)	5-Fluorouracil (5-FU)	Viros et al ¹⁰²
	Dorsal UVB irradiation (minimal erythema dose) of SKH1 hairless mice	5-Aminolevulinic acid (5-ALA) in conjunction with photodynamic therapy (PDT)	Wang et al ¹⁰³
Basal cell carcinoma mouse model	Neonatal irradiated Ptch1 ^{-/-} mice as a model of Hedgehog (Hh)-signaling pathway-dependent tumors	MK-4101, potent inhibitor of Hh-signaling pathway, had robust antitumor activity	Filocamo et al ¹⁰⁴
	BCC mouse model used to identify molecular mechanisms regulated by Sox9, leading to tumour initiation and invasion		Larsimont et al ¹⁰⁵
Melanoma mouse model	Induced in <i>PTCH</i> -knockout mice by 1) treatment by tamoxifen administered intraperitoneally and 2) ionizing irradiation	CUR61414 (an inhibitor of the Hh signal-transduction molecule Smoothened)	Tang et al ¹⁰⁶
	Tumor spheroid of B16/F0 melanoma cells subcutaneously inoculated in the auricle of NMRINu/Nu or C57/BL6 mice	Bortezomib (inhibitor of the 26S proteasome)	Schröder et al ¹²³
	B16BL6 melanoma cells subcutaneously injected into the notum of C57BL/1 mice	Curcumin	Chen et al ¹²⁴
Human-SCID mouse xenograft model: psoriasis	B16 melanoma cells subcutaneously injected in the hip of BALB/c nude mice	Mitoxantrone (DNA-synthesis and -transcription inhibitor)	Yu et al ¹²⁵
	SCID mouse-human psoriasis skin model used for targeted topical immunotherapy	Kv1.3 channel blocker PAP-1	Kundu-Raychaudhuri et al ¹⁰⁸
Human-SCID mouse xenograft model: melanoma	Identified an intronic mutation as molecular basis for a RNA splicing-mediated RAF inhibitor-resistance mechanism and a pre-mRNA-splicing interference as a potential therapeutic strategy for drug resistance in BRAF melanoma	Vemurafenib, potent RAF-kinase inhibitor	Salton et al ¹⁰⁹
Human-SCID mouse xenograft model: melanoma	Effects of chemical inhibition of ALDH1 on the response of human melanoma xenografts to chemotherapy and the effects of ALDH1A1 RNA silencing on melanoma growth and metastasis; ALDH1 inhibition may be useful in melanoma treatment	ALDH1 inhibitors (eg, diethylaminobenzaldehyde) added to dacarbazine chemotherapy	Yue et al ¹¹⁰

Abbreviations: UVB, ultraviolet B; SCC, squamous cell carcinoma; DMBA, 7,12-dimethylbenz-(a)anthracene; BCC, basal cell carcinoma; mRNA, messenger RNA; BRAF, v-Raf murine sarcoma viral oncogene homolog B; RAF, a serine/threonine protein kinase product of BRAF gene; ALDH, aldehyde dehydrogenase; SCID, severe combined immunodeficient; VEGF, vascular endothelial growth factor.

generation of atopic dermatitis by downregulation of filaggrin¹¹³ or treatment with an inflammatory cocktail.¹¹⁴ Some of the models were developed as potential screening tools for drugs to treat the expressed disease states.^{112,114}

Skin-cancer models were constructed by incorporating various tumor entities within the three-dimensional (3-D) matrix, including cultured melanoma¹¹⁶ cells, an A375 metastatic melanoma cell line,¹¹⁷ and melanoma-tumor

Table 3 Reconstructed skin-disease models

Disease model	Characteristics	Drug delivered	Reference
Psoriasis	Full-thickness skin model closely resembling in vivo epidermal architecture used to identify IL-17-responsive genes in psoriasis	Ixekizumab (IL-17 antagonist)	Chiricozzi et al ¹¹
	Human psoriatic skin equivalents used to study cytokine-induced gene expression	Retinoic acid, cyclosporine A	Tjabringa et al ¹²
Atopic dermatitis	3-D reconstructed human epidermis model used to show filaggrin downregulation in the epidermis of atopic patients, either acquired or innate, may be directly responsible for some of the disease-related alterations	Inflammatory cocktail (polyinosinic–polycytidylic acid, TNF α , IL-4, and IL-13)	Pendaries et al ¹³
Atopic dermatitis	Compromised reconstructed epidermis mimicking AD-related inflammation in vitro		Rouaud-Tinguely et al ¹⁴
3-D model of dermatitis	Human foreskin fibroblasts HaCaT cells Memory-effector (CD45RO ⁺) T cells Scaffold material: tat tail collagen type I, fibronectin	Dexamethasone and tacrolimus	Engelhart et al ¹⁵
3-D model of melanoma	3-D human skin reconstruct model incorporating melanocytic cells		Li et al ¹⁶
3-D skin-reconstruction model of metastatic melanoma	Human malignant melanoma cells (A375) Normal human-derived epidermal keratinocytes (NHEKs) Normal human-derived dermal fibroblasts (NHDFs) Scaffold material: collagen type I	Roscovitine (cyclin-dependent kinase inhibitor)	Mohapatra et al ¹⁷
3-D organotypic skin-melanoma spheroid model	Human melanoma cell lines SBCL2 (RGP), WM-115 (VGP), and 451-LU (MM) Human primary keratinocytes Human primary fibroblasts Scaffold material: rat tail collagen type I	TRAIL + ultraviolet B radiation TRAIL + cisplatin	Vörsmann et al ¹⁸
3-D model of human cutaneous squamous cell carcinoma	Primary NHEKs Primary NHDFs, SCC12B2 and SCC13 cell lines Scaffold material: rat tail collagen type I Pretreatment with EGF	Erlotinib (tyrosine-kinase inhibitor)	Commandeur et al ¹⁹
3-D model of scleroderma fibrosis	Model useful for testing in vivo the progression of scleroderma and to screen for antifibrotic drugs	Nilotinib, a tyrosine kinase inhibitor; human monoclonal anti-PDGFR antibodies	Luchetti et al ²⁰

Abbreviations: IL, interleukin; TNF α , tumor necrosis factor alpha; 3-D, three dimensional; NHEKS, Normal human-derived epidermal keratinocytes; TRAIL, tumor necrosis factor-related apoptosis-inducing ligand; SBCL-2 (RGP), an early radial growth phase cell line; WM-115 (VGP), a vertical growth phase cell line; MM, metastatic melanoma; NHDF, normal human-derived dermal fibroblasts.

spheroids,¹¹⁸ as well as various cutaneous squamous cell carcinoma cell lines.¹¹⁹ Like the inflammatory models, these were used to study disease progression and targeted therapeutic interventions. Mohapatra et al¹¹⁷ used the cyclin-dependent kinase inhibitor roscovitine to inhibit growth of the A375 cells within the dermal layer of the 3-D matrix. Using combination therapies, Vörsmann et al¹¹⁸ showed significant advantages in using their 3-D melanoma model to deliver in vivo-like responses compared to a standard 2-D monolayer culture.

A novel chimeric model consisting of a human artificial 3-D skin construct grafted onto the back of SCID mice has also been reported.¹²⁰ The bioengineered skin, containing human keratinocytes and fibroblasts isolated from skin biopsies of healthy donors or scleroderma patients, was generated ex vivo and then grafted onto the back of SCID mice. Results implicated the involvement of a PDGF

receptor-mediated pathway in the disease and confirmed the suitability for testing in vivo the disease progression-screening antifibrotic drugs.

Summary and conclusion

Despite ethical concerns, the use of animals or isolated animal skin models to assess percutaneous absorption of molecules is frequently reported. These models are generally more widely available than human skin, and prove important in basic research to improve our understanding of the processes, pathways, and driving forces of various agents across the skin barrier. However, because of a large number of animal skin models described in the literature, it may be difficult to compare the results obtained across various species, in addition to the variations in experimental methodology used with a specific skin model, such as type of diffusion cells, body site, skin temperature, receiver

media, application dose, and diffusion area. Therefore, it is important to emphasize that *in vitro* and animal models provide important tools for screening a series of drug formulations, evaluation of skin permeation-enhancing properties and mechanism of action of the carrier systems, and estimation of rank of skin transport for a series of drug molecules. Also, the majority of the work on synthetic membranes for transdermal and topical delivery studies has been focused on the use of polymeric materials, usually silicone based. Such membranes are ideal for replacing *ex vivo* skin, as they can be prepared with a defined thickness, are easy to handle and store, are comparatively cheap, inert, and provide reproducible results. Despite all of these advantages, they cannot completely replace human or animal skin for prediction of skin absorption *in vivo*. These membranes generally lack the type of barrier normally provided by the SC in *ex vivo* or *in vivo* skin, and this may lead to some false-positive results in toxicity studies and permeation studies. Therefore, we recommend that where possible, human skin should be used in skin-permeation studies.

A wide range of skin models for testing skin absorption for cutaneous and transdermal delivery has been developed. There is an increasing need, largely driven by regulatory authorities and industry, to ensure that the models and testing protocols are standardized and reproducible, and are validated to show that they accurately reflect the *in vivo* situation.

Disclosure

The authors report no conflicts of interest in this work.

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