Towards a molecular understanding of hair loss and its treatment

George Cotsarelis and Sarah E. Millar

Most common forms of hair loss (alopecia) are caused by aberrant hair follicle cycling and changes in hair follicle morphology. However, current treatments for alopecia do not specifically target these processes. We are now beginning to identify the molecules and molecular pathways that control normal hair follicle formation, cycling and growth. In parallel, new techniques are being developed for delivering molecules to hair follicles. Here, we outline the characteristics of common hair loss diseases, and discuss ways in which recent advances in hair follicle biology could be translated into effective therapies for these conditions.

Although hair disorders are not life threatening, their profound impact on social interactions and on patients’ psychological well being is undeniable. The demand for treatments for hair loss fuels a multi-billion dollar industry. Despite this, most currently marketed products are ineffective, evidenced by the fact that the FDA has approved only two treatments for hair loss. Recently there have been dramatic advances in our understanding of the molecules and pathways regulating hair follicle formation and hair growth. Here we review these findings and discuss how they might stimulate the development of new, effective therapies.

Introduction to the hair follicle

The end product of hair follicle proliferation and differentiation is the hair shaft, which, together with its surrounding root sheaths, is derived from epithelial cells. The dermal papilla, a cluster of mesenchymal cells at the base of the follicle, also plays an essential role in hair growth (Fig. 1). In humans the formation of hair follicles takes place during embryogenesis, and no new hair follicles form after birth. However, the character of individual follicles can change drastically over time. Thicker and darker hairs replace fine lightly pigmented hairs in the beard at puberty. Conversely, thick scalp hairs convert into fine small hairs later in life. Paradoxically, both processes occur in response to the hormone testosterone.

The hair follicle remodels itself during cyclical periods of growth (anagen, see Glossary), regression (catagen), rest (telogen) and shedding (exogen) (Fig. 2). During catagen, much of the follicle undergoes programmed cell death (apoptosis), reducing its size as it enters telogen. Follicular regeneration at the onset of the next anagen phase requires the activation of rarely cycling epithelial stem cells located in the permanent, bulge region of the follicle. Stem cell progeny form a new follicle matrix during early anagen, and the hair shaft and inner root sheath are derived from these relatively undifferentiated matrix cells. The size and length of the hair shaft correspond to the size of the hair follicle and to the duration of anagen, respectively. These characteristics vary considerably with body site, and change as a result of disease. Pigmentation of the hair shaft depends on hair follicle melanocytes, which reside in the hair follicle bulge and deposit melanin into the growing hair shaft. Proliferation of melanocytes occurs during early anagen, and is probably regulated by the factors that control the hair growth cycle.

Common disorders of hair growth

Alopecia, a generic term for hair loss, results from a diminution of visible hair. The most common forms of alopecia include androgenetic alopecia or common baldness, telogen effluvium, chemotherapy-induced alopecia, and alopecia areata.

Androgenetic alopecia

In androgenetic alopecia, hair follicles located in specific patterns over the male and female scalp diminish in size over time until they produce effete and cosmetically insignificant hairs (Fig. 3). Testosterone is required, along with a genetic predisposition, for androgenetic alopecia to develop in men. In women, there is no consensus on whether pattern hair loss is truly androgen-dependent, although both male- and female-pattern alopecia result in a decrease in hair follicle size accompanied by a decrease in the duration of anagen and an increase in the percentage of hair follicles in telogen. In addition, several months can transpire between hair shedding and regrowth, a lag period that is absent or fleeting in normal individuals (Fig. 3). These changes result in very short hairs and follicles devoid of hair shafts. Miniaturized hairs also lack pigmentation. In advanced androgenetic alopecia some follicles disappear and are replaced by fibrous tracts (Fig. 3).

Based on this knowledge, the goals for treating androgenetic alopecia include prolonging anagen, converting telogen follicles to anagen, reversing miniaturization and possibly generating new follicles. Blocking the conversion of testosterone to its more active metabolite, dihydrotestosterone, through administration of the pharmacologic agent finasteride accomplishes some of these goals and clearly benefits patients with early androgenetic alopecia; however, even drastic forms of testosterone...
To enter a dystrophic catagen stage in which the integrity of the hair shaft is compromised and the hair then breaks and falls out. Because more than 90% of scalp follicles are in anagen at any one time, these hairs are rapidly lost after chemotherapy, and thus the alopecia is rapid and extensive. Hair loss is one of the most feared side effects of chemotherapy among patients with cancer. However, hair lost following chemotherapy does eventually re-grow, presumably because the rarely cycling follicular stem cells are relatively unaffected by chemotherapy and generate a new hair follicle and hair.

Botchkarev et al. have shown that p53 is necessary for the development of chemotherapy-induced alopecia, as p53 knockout mice treated with chemotherapeutic agents remarkably do not lose their hair8. Because chemical inhibitors of p53 already exist, testing their efficacy for local inhibition of p53 in hair follicles provides a realistic possibility for preventative therapy. In an exciting recent development, Davis et al. showed that inhibition of the cell cycle regulator cyclin-dependent kinase 2 (CDK2) using a novel, topically applied CDK2 inhibitor, prevents chemotherapy-induced alopecia in rats10. Human skin maintained as grafts on immunodeficient mice was also sensitive to the actions of the CDK2 inhibitor, suggesting that this compound will be effective for preventing chemotherapy-induced hair loss in human patients.

**Alopecia areata**

Alopecia areata is an autoimmune disorder in which cells of the anagen hair bulb are attacked by lymphocytes (Fig. 4). In a process similar to that following chemotherapy, anagen follicles enter dystrophic catagen and the hair shaft breaks off. In most patients hair loss occurs in scattered patches over the scalp; however, some lose all scalp and body hair (called alopecia totalis and universalis, respectively). Gilhar31 demonstrated that alopecia areata is a T-cell inflammatory response to the follicle.

**Telogen effluvium**

Telogen effluvium, another extremely common form of alopecia, manifests as excessive shedding of hair. Several different mechanisms can cause telogen effluvium, but all result from the synchronous entry of many follicles into exogen8. For example, during pregnancy and delivery causes synchronous entry of follicles into telogen, followed by exogen (shedding). A different type of telogen effluvium is observed soon after starting medications such as minoxidil, or in response to a rapid change in the duration of daily exposure to sunlight. In these cases existing telogen follicles simultaneously enter a premature exogen phase, involving an increase in the shedding of CLUB HAIRS within weeks of the precipitating event8. This observation suggests that club hairs that are normally retained in the follicle can be actively shed. Finally, metabolic events such as fevers or medications can cause premature entry of follicles into telogen.

Although one might argue that therapies for telogen effluvium are not necessary because the follicles remain intact and generate new hairs after several months, the psychological trauma from hair shedding should not be underestimated. One treatment strategy would be to inhibit exogen, so that hair shafts would be retained in their follicles until the new hair grew to an acceptable length. This type of treatment would also benefit patients with androgenetic alopecia, which can initially present as telogen effluvium.

**Chemotherapy-induced alopecia**

Chemotherapy disrupts the proliferation of matrix keratinocytes in the anagen bulb that produce the hair shaft (Figs 1 and 2). This forces anagen follicles reduction (e.g. castration) do not result in complete reversal of miniaturization. Thus more effective treatments are required for the treatment of advanced androgenetic alopecia.


---

**Glossary**

- **Alopecia**: Abnormal hair loss.
- **Androgenetic alopecia**: Loss of hair caused by miniaturization of genetically predisposed follicles in a male pattern (frontal recession and thinning at the vertex) or female pattern (loss of hair over the crown with sparing of the frontal hair line).
- **Alopecia areata**: Hair loss in patches caused by an autoimmune inflammatory response to the follicle.
- **Anagen**: Growing stage of the hair follicle cycle.
- **Bulb**: Lowermost portion of the anagen follicle containing rapidly proliferating cells that generate the hair.
- **Bulge**: Putative site of epithelial stem cells within the follicle outer root sheath.
- **Catagen**: Regression stage of the hair follicle cycle.
- **Club hair**: Dead hair possessing thickened base that anchors it in the follicle during telogen.
- **Exogen**: Stage of the hair follicle cycle when hair is shed from the follicle.
- **Telogen**: Resting stage of the hair follicle cycle.
- **Telogen effluvium**: Excessive shedding of hair caused by synchronous entry of many hair follicles into exogen.
mediated disease by injecting T-cells from patients into human skin grafted to immunodeficient mice. This reproduces the peri-bulbar inflammation and hair loss. Possible targets of the immune attack include matrix keratinocytes, dermal papilla cells and melanocytes. Although a genetic predisposition for this disease is supported by HLA linkage studies, whether the underlying defect lies within the hair follicle, the immune system, or both, is not known. The hair loss is potentially reversible, even after years without hair, confirming the non-scarring nature of the inflammatory process, which spares the stem cell-rich bulge area (Fig. 4).

By contrast, in scarring alopecias such as lichen planopilaris or discoid lupus erythematosus, inflammation occurs higher up in the follicle and generally involves the bulge (Fig. 4). This leads to fibrosis and permanent loss of the follicle. The inciting events in scarring alopecia are unknown, but could involve aberrant functioning of the sebaceous gland, which appears necessary for normal detachment of the inner root sheath from the hair shaft12 causing follicle rupture followed by an abnormal fibrotic wound healing process that leads to deletion of the follicle1.

Possible treatment strategies
Identification of the genes involved in both androgenetic alopecia and alopecia areata will be facilitated by microarray technology and by the availability of human and mouse genome sequences, and might ultimately reveal novel therapeutic targets. In the cases of alopecia areata and scarring alopecia, rodent models have been identified that will aid in the localization of susceptibility loci, and the screening of new treatments13,14. A rodent model is not currently available for androgenetic alopecia. However, human skin grafted to immunodeficient mice provides a potential system for investigating the molecular basis of this process, and a non-human primate model, the stump-tailed macaque (Macaca arteroides), has been used to test the efficacy of various therapies15.

Treatments for both alopecia areata and inflammatory scarring alopecias must modulate the inflammation or protect the follicle from attack by the autoimmune process. A potential approach for
developing the latter type of therapy would be to identify primary antigenic targets in the follicle bulb and induce tolerance in the corresponding population of T-cells. Ideally treatments for scarring alopecia would also involve recreating hair follicles at sites of destruction. This might require treatment with anti-fibrotic agents as well.

Molecular mechanisms regulating hair follicle morphogenesis

Formation of hair follicles in the embryo requires interactions between cells of the surface epithelium and the underlying dermis. Hair follicle precursors are first visible as thickenings or placodes in the otherwise uniform surface epithelium (Fig. 5). Placodes form in a regular array by a process that probably requires the competing activities of placode-inducing and placode-repressing molecules. Bone morphogenic protein 2 (BMP2), a repressor of placode formation, and several candidate placode-promoting molecules are initially expressed uniformly in the surface epithelium and subsequently become localized to placodes, consistent with a reaction-diffusion model of pattern formation.

Once hair follicle placodes form, epithelial signals, possibly including WNT proteins, pass from the placodes to the underlying dermis, causing the clustering of a group of cells (the dermal condensate) that will eventually form the dermal papilla (Figs. 1 and 5). Formation of the dermal papilla requires the secreted signaling molecules sonic hedgehog (SHH) and platelet derived growth factor-A (PDGF-A).

A ‘second dermal’ signal from the dermal condensate to the follicular epithelium directs the proliferation and downgrowth of follicular epithelial cells into the dermis, a process that also requires SHH expression in the epithelium (Fig. 5). Mutations in follistatin (FS) and in TGFα and its receptor, epidermal growth factor receptor (EGFR), cause abnormal follicle architecture and wavy hair, suggesting essential roles for these factors in regulating follicle shape.

Formation of the inner root sheath, which functions to mold the hair shaft, and differentiation of the hair shaft itself are processes likely to be regulated by signals from the dermal papilla, and by lateral signaling between epithelial cells at different positions in the follicle relative to the dermal papilla. WNT, BMP and Notch intercellular signaling molecules and the LEF1, FOXN1 and HOXC13 transcription factors have been implicated in the regulation of hair shaft differentiation.

Ectopic expression of either SHH or a stabilized form of β-catenin in the epidermis causes the formation of additional follicles, raising the exciting possibility that these factors might form a component of therapies aimed at recreating hair follicles.
Molecular mechanisms regulating the hair growth cycle

**Anagen onset**

Signaling molecules important for hair follicle morphogenesis might be re-used in postnatal life to control follicular cycling. The factors that normally trigger the proliferation of bulge cells at the onset of anagen have not been identified, but they are thought to arise from the juxtaposed dermal papilla (Fig. 2).

Exogenous SHH is capable of initiating anagen in telogen follicles. However, the effects of a neutralizing anti-SHH antibody on hair growth suggest that SHH is normally required for the proliferation of epithelial cells slightly later in anagen, but not for conversion of telogen follicles to anagen. Mutation of mouse signal transducer and activator of transcription 3 (STAT3) prevents normal progression of telogen follicles into anagen. Anagen onset in mice is also blocked by estradiol and promoted by antagonists of estrogen receptor (ER) and parathyroid hormone responsive protein (PTHrP). Whether these factors play a role in human hair follicle cycling is not yet known.

**Anagen** is well accepted that the volume of the dermal papilla determines the number of matrix cells and size of the resulting hair shaft. Because the size of the follicle is determined during the early stages of anagen, this could be a critical time for hair follicles undergoing miniaturization in androgenetic alopecia or for follicles that are enlarging, for instance in the beard area of an adolescent boy. Some factors (e.g. hormones, drugs, morphogens) might act by enhancing or preventing miniaturization only during anagen, this could be a critical time for hair follicles.
indicating that a signal from the follicular epithelium is required to maintain these properties. Interestingly, dermal papilla cells cultured in the presence of WNT protein maintain their inductive abilities over many rounds of culture, suggesting that the epithelial signal is comprised of one or more WNT family members.

Anagen–catagen transition

The normal timing of the anagen to catagen transition depends upon the presence of FGF5. FGF5 mutant mice display a striking ‘angora’ phenotype of long hair due to prolongation of the anagen stage. By contrast, overexpression of either of the anti-apoptotic genes Bcl-X, or Bcl-2 in the outer root sheath decreases the duration of anagen, suggesting that regulation of cell survival in the outer root sheath might also play a role in control of the hair growth cycle.

Catagen

Although it is known that catagen involves massive programmed cell death, the means by which this is achieved are poorly understood at the molecular level. Analysis of mutant mice has revealed roles for transforming growth factor β1 (TGFβ1) and p75 neurotrophin receptor (p75NTR) in the timing of catagen. In mice lacking the hairless (HR) protein, a putative transcription factor, the dermal papilla fails to move upward during catagen. As a consequence, contact between the dermal papilla and stem cells in the bulge is lost, and subsequent hair growth cycles fail to occur. Mice lacking retinoid X receptor-α (RXRα) in the epidermis also display separation of the proximal and distal portions of the hair follicle and fail to initiate the first postnatal anagen. The phenotypes of mice and humans carrying mutations in the vitamin D receptor (VDR) are strikingly similar to those of HR and RXRα mutants suggesting that these proteins might be components of the same pathway important for catagen.

The findings summarized above suggest several potential therapeutic opportunities. Inhibition of FGF5 could possibly be used to prolong anagen and produce longer hair, whereas PTHrP antagonists and SHH might be effective for inducing anagen onset in androgenetic alopecia. Treatments involving SHH must be designed to minimize the dose and duration of exposure to this molecule, as expression of ectopic SHH in the skin can induce the formation of basal cell carcinoma. The finding that WNTs can maintain the inductive properties of cultured dermal papilla cells raises the exciting possibility of cloning and expanding such cells in culture and reintroducing them to the scalp to induce the formation of new hair follicles. Possibly, allogeneic dermal cells could be used because male dermal sheath cells were able to generate hair follicles in a female recipient. Given that hairs in different regions of the scalp are differentially affected by androgenetic alopecia, and this property appears to be intrinsic to the hair follicle, it might prove possible to use this method to generate relatively testosterone-resistant follicles. It will clearly be important to determine whether testosterone sensitivity is innate to the dermal or epithelial component of the follicle, and to demonstrate whether or not epithelial cells in bald scalp are competent to generate large terminal hair follicles in response to an inductive dermal signal. Techniques for effective transfer of cultured dermal papilla cells into bald skin would also have to be developed for this approach to be successful.

If bald scalp is not competent for hair follicle induction by dermal papilla cells, an alternative approach for de novo generation of hair follicles would be to engineer hair follicles in vitro, perhaps by combining hair follicle stem cells with dermal papilla cells. This approach would enable one to alter the characteristics of the cells by gene therapy. Such a scenario requires the ability to isolate hair follicle stem cells. Potential markers for these cells include cytokeratins 15 and 19, β1 integrin, α6 integrin and lack of proliferation markers such as transferrin receptor.

Gene therapy

The potential power of gene therapy technology has become more apparent recently with the identification of many molecules important in hair biology, and with the cloning of genes mutated in several inherited human hair diseases (Table 1). Li and Hoffman pioneered the introduction of foreign DNA into hair follicle cells using topical lipoplexes (DNA–liposome mixtures) by successfully transducing mouse hair follicle keratinocytes.
in vivo\textsuperscript{47}. To date, this approach has been used to correct the albino mutation in mouse hairs\textsuperscript{48}, to immunize mice against hepatitis B virus\textsuperscript{49} and to express a reporter gene in human hair shaft progenitor cells\textsuperscript{50} (Fig. 6). These studies demonstrate that different cell populations within the follicle, including melanocytes and antigen-presenting cells (Langerhans cells) in addition to keratinocytes, can be targeted using a relatively straightforward topical technique. In the future, specific cell populations could be targeted by changing the composition of the liposomes or by using transgenes with promoters that are active in distinct cell types. For example, stem cells in the bulge might be targeted by the use of the cytokeratin 15 promoter\textsuperscript{45}. The timing of expression could also be controlled by addition of inducible promoter elements to the transgenes.

The type of gene therapy could be tailored to the type of alopecia. For example, in genetic disorders of the hair shaft, caused by single gene mutations (see Table 1), long-lasting correction of the hair follicle genotype would be necessary. Stem cells would be ideal targets in this case because of their long lifespan\textsuperscript{44}. Theoretically, transgenes integrated into the bulge cell genome would result in long-term expression in bulge cells and their progeny. By using RNA–DNA oligonucleotides single base pair mutations can be permanently repaired both \textit{in vitro} and \textit{in vivo}. Retroviral vectors can also be used to permanently alter genotype\textsuperscript{51}. Although the efficiency of repair using these approaches is low, optimization, perhaps using adjunctive peptides to increase cellular and nuclear uptake, could overcome this problem\textsuperscript{52,53}.

By contrast, short-term expression might be preferred for the treatment of polygenic disorders in which the primary goal is modulation of the hair cycle. Transient and controlled expression of morphogenic and regulatory factors should minimize adverse effects. Transient expression can be achieved by targeting hair follicle progenitors with plasmid DNA\textsuperscript{50} or adenoviral vectors\textsuperscript{32} at the onset of anagen. Because the characteristics of the lower follicle determine the characteristics of the new hair, the transient action of the plasmid might be sufficient to cause prolonged changes in the appearance of the hair. This strategy might be particularly appropriate for treating androgenetic alopecia with genes that might enlarge the follicle (such as SHH) or for the treatment of alopecia areata, in which most follicles are arrested at anagen onset and should be susceptible to transfection. Perhaps introducing genes that encode for anti-inflammatory cytokines or other immune modulators could protect the follicle against the autoimmune attack.

### Table 1. Single gene mutations affecting human hair growth

<table>
<thead>
<tr>
<th>Disease</th>
<th>Affected gene</th>
<th>Role of encoded protein</th>
<th>Hair phenotype</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monilethrix</td>
<td>hHb6 or hHb</td>
<td>Hair keratin (structural protein)</td>
<td>Thin fragile hair with a beaded appearance under light microscopy</td>
<td>55</td>
</tr>
<tr>
<td>Netherton’s syndrome</td>
<td>SPINK5</td>
<td>Serine protease inhibitor LEKT1</td>
<td>Defective hair shaft differentiation (‘bamboo hair’)</td>
<td>56</td>
</tr>
<tr>
<td>Generalized atrichia with papular lesions</td>
<td>Hairless (HR)</td>
<td>Putative transcription factor</td>
<td>Failure of first postnatal hair growth cycle</td>
<td>57</td>
</tr>
<tr>
<td>Generalized atrichia with papular lesions</td>
<td>VDR</td>
<td>Vitamin D receptor</td>
<td>Failure of first postnatal hair growth cycle</td>
<td>58</td>
</tr>
<tr>
<td>Human nude</td>
<td>WHN</td>
<td>Transcription factor</td>
<td>Hair shafts fail to emerge from skin</td>
<td>59</td>
</tr>
<tr>
<td>X-linked hypohidrotic ectodermal dysplasia</td>
<td>Ectodysplasin (EDA)</td>
<td>Intercellular signaling molecule</td>
<td>Sparse hair</td>
<td>60</td>
</tr>
<tr>
<td>Autosomal hypohidrotic ectodermal dysplasia</td>
<td>Ectodysplasin receptor (EDAR)</td>
<td>Receptor for ectodysplasin</td>
<td>Sparse hair</td>
<td>61</td>
</tr>
<tr>
<td>Ectodermal dysplasia/familial incontinentia pigmenti</td>
<td>IKK-gamma (NEMO)</td>
<td>Kinase required for activation of the transcription factor NF-kB</td>
<td>Sparse hair</td>
<td>62</td>
</tr>
<tr>
<td>Naxos disease</td>
<td>Plakoglobin</td>
<td>Adhesion molecule</td>
<td>Woolly hair</td>
<td>63</td>
</tr>
<tr>
<td>Ectodermal dysplasia/skin fragility syndrome</td>
<td>Plakophilin 1</td>
<td>Desmosomal adhesion molecule</td>
<td>Sparse hair</td>
<td>64</td>
</tr>
<tr>
<td>Menkes’ disease</td>
<td>ATP7a</td>
<td>Copper-transporting P-type ATPase</td>
<td>Hair loss; abnormal hair texture</td>
<td>65</td>
</tr>
<tr>
<td>Tricho-rhino-phalangeal syndrome type I</td>
<td>TRPS I</td>
<td>Zinc finger protein, putative transcription factor</td>
<td>Sparse and unruly scalp hair</td>
<td>66</td>
</tr>
<tr>
<td>X-linked dominant chondrodysplasia punctata</td>
<td>EBP</td>
<td>$\Delta(8), \Delta(7)$ sterol isomerase emopamil-binding protein</td>
<td>Coarse hair, alopecia</td>
<td>67</td>
</tr>
<tr>
<td>Giant axonal neuropathy</td>
<td>Gigaxonin (GAN)</td>
<td>Unknown</td>
<td>Curly or kinky hairs</td>
<td>68</td>
</tr>
</tbody>
</table>
Although an understanding of hair follicle biology at the cellular level will undoubtedly lead to many new molecular targets for the treatment of alopecias, as each hair follicle traverses through its own hair cycle, essentially independent of its neighbors, a high degree of complexity emerges when attempting to predict the effects of cycle–altering compounds on the appearance of the entire scalp. Computer models of human hair growth that simulate the appearance of the scalp as it changes over time in response to treatment or disease are needed. These types of models will aid in pinpointing which parameters are most important for the overall appearance of the hair.

A wealth of recent discoveries, combined with the production of conditional and inducible knockout mice, the development of microarray technologies for analysis of the expression profiles of large numbers of genes under different conditions, the availability of human and mouse genomic sequence information, and advances in gene therapy techniques, combine to make this an exciting time for hair biologists. Our current challenge is to utilize these advances for the development of safe and effective therapies for hair disease.

References
3 Cotsarelis, G. et al. (1999) Label-retaining cells reside in the bulge area of pilosebaceous unit: implications for follicular stem cells, hair cycle, and skin carcinogenesis. Cell 61, 1329–1337
9 Botchkarev, V.A. et al. (2000) p53 is essential for chemotherapy-induced hair loss. Cancer Res. 60, 5002–5006
14 Zheng, Y. et al. (1998) SII is expressed in sebaceous glands and is disrupted in the asebia mouse. Nat. Genet. 23, 268–270
26 Millar, S.E. et al. (1999) WNT Signaling in the Control of Hair Growth and Structure. Dev. Biol. 207, 133–149
27 Lin, M.H. et al. (2000) Activation of the Notch pathway in the hair cortex leads to aberrant differentiation of the adjacent hair-shaft layers. Development 127, 2421–2432
28 Kulesha, H. et al. (2000) Inhibition of Bmp signaling affects growth and differentiation in the anagen hair follicle. EMBO J. 19, 6664–6674
Gene therapy strategies for urological dysfunction

Michael B. Chancellor, Naoki Yoshimura, Ryan Pruchnic and Johnny Huard

Novel molecular techniques such as conventional and ex vivo gene therapy, and tissue engineering have only recently been introduced to the field of urology. The lower urinary tract is ideally suited for minimally invasive therapy, and also ex vivo approaches would limit the risk of systemic side effects. Muscle-derived stem cells have been used successfully to treat stress incontinence, and rats with diabetic bladder dysfunction benefited from nerve growth factor (NGF)-based gene therapy. Nitric oxide synthase and caspase-7 might provide suitable gene therapy targets for erectile dysfunction and benign prostatic hyperplasia, respectively.

Until recently, there has been little research on gene therapy for the urinary tract. Most of the previous work focused on urinary tract malignancies such as prostate and bladder cancer. However, this situation has changed radically in the past two years. What is stirring this interest in gene therapy for urinary tract dysfunction? First, the pharmaceutical industry is beginning to realize the significance of these disabilities and the potential market size that urological diseases represent. Second, the lower urinary tract is ideally suited for minimally invasive molecular medicine therapy as it implies a lower risk of systemic toxicity. All of the lower urinary tract can be reached either percutaneously or through endoscopy.

In this review, we will focus on gene therapy strategies for three important urological conditions: urinary incontinence, erectile dysfunction and benign prostatic hyperplasia. We will discuss how both viral and nonviral gene therapy might be applicable. In addition, we will present some studies that illustrate the feasibility of muscle-derived stem cell injection that might be a foundation not only for tissue engineering but also ex vivo gene therapy.

Bladder dysfunction and urinary incontinence

Urinary incontinence is a serious medical and social condition in the USA and all over the world. It has recently become a hot research topic in the pharmaceutical industry for several reasons. First, the tremendous number of patients suffering...