identical cDNAs prepared for RT-PCR were used as the templates for qPCR. Specific primer sets were purchased from Takara Bio. qPCR was performed in 25 μL of reaction mixture containing 1× SYBR Premix Ex Taq (Takara Bio), 1× ROX Reference Dye, 0.2 μM of each primer and cDNA. PCR was conducted for 5 s at 95 °C and 31 s at 60 °C for 40 cycles. Gene expression levels were normalized using *gapdh* as an internal control. Results of ABR and qPCR are expressed as the mean ± standard error, and statistical significance was determined by one sample *t*-test.

4.5. Immunohistochemical analysis

Histological sample were made on the before 3-NP treatment and 1 day after vehicle treatment, and 6 h, 1, 2 and 3 days after 3-NP treatment ($n \geq 3$). Rats were deeply anesthetized with pentobarbital (50 mg/kg, i.p.) and perfused intracardially with 0.01 M sodium phosphate buffer (pH 7.4) containing 8.6% sucrose, followed by 4% paraformaldehyde in 0.1 M sodium phosphate buffer (pH 7.4). After decapitation, temporal bones were removed quickly and placed in the same 4% paraformaldehyde fixative. Small openings were made at the round window, oval window and apex of the cochlea. After immersion in the fixative overnight, the temporal bones were decalcified by placement in 5% EDTA and 4% sucrose in 0.1 M sodium phosphate buffer (pH 7.4) at 4 °C for 2 weeks, dehydrated, and embedded in paraffin. Transverse cochlear sections at 5-μm thickness were cut and mounted on glass slides. After rehydration, sections were treated with 0.3% hydrogen peroxide in methanol to quench peroxidase activity. For epitope retrieval, slides were boiled in citrate buffer (pH 6.0) in a microwave. After blocking nonspecific binding with 1% normal goat serum (Vector Laboratories, Burlingame, CA), the slides were incubated with monoclonal anti-CHOP (Santa Cruz Biotechnology, Santa Cruz, CA) at a 1:100 dilution at 4 °C overnight. The slides were washed and then incubated with biotinylated anti-mouse IgG (Vector Laboratories) at a 1:200 dilution, and the signal was colorized using VECTASTAIN Elite ABC kit (Vector Laboratories) and DAB Substrate kit for Peroxidase (Vector Laboratories). Some of the slides were counterstained with hematoxylin. Some of the unstained sections were processed for TUNEL histochemical staining using ApopTag Peroxidase *In Situ* Apoptosis Detection kit (Chemicon International, Temecula, CA) according to the manufacturer's protocol. The TUNEL reaction mixture was added to each sample in a humidified chamber, followed by incubation for 1 h at 37 °C for colorization with DAB. For fluorescent immunostaining, the sections were incubated with anti-CHOP at a dilution of 1:50. The sections were subsequently treated with proteinase K (DakoCytomation, Carpinteria, CA) and incubated with Alexa Fluor 568 anti-mouse IgG (Molecular Probes, Eugene, OR) at a 1:1000 dilution. Thereafter, the ApopTag Fluorescein Direct *In Situ* Apoptosis Detection kit (Chemicon) was used according to the manufacturer's protocol. The sections were then covered with PermaFluor Aqueous Mounting Medium (Thermo Shandon, Pittsburgh, PA) with DAPI (1 μg/mL; Dojindo, Kumamoto, Japan).

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ORIGINAL ARTICLE

Vestibular function of patients with profound deafness related to *GJB2* mutation

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Abstract

Conclusion: GJB2 mutations are responsible not only for deafness but also for the occurrence of vestibular dysfunction. However, vestibular dysfunction tends to be unilateral and less severe in comparison with that of bilateral deafness. *Objectives:* The correlation between the cochlear and vestibular end-organs suggests that some children with congenital deafness may have vestibular impairments. On the other hand, *GJB2* gene mutations are the most common cause of nonsyndromic deafness. The vestibular function of patients with congenital deafness (CD), which is related to *GJB2* gene mutation, remains to be elucidated. The purpose of this study was to analyze the relationship between *GJB2* gene mutation and vestibular dysfunction in adults with CD. *Methods:* A total of 31 subjects, including 10 healthy volunteers and 21 patients with CD, were enrolled in the study. A hearing test and genetic analysis were performed. The vestibular evoked myogenic potentials (VEMPs) were measured and a caloric test was performed to assess the vestibular function. The percentage of vestibular dysfunction was then statistically analyzed. *Results:* The hearing level of all CD patients demonstrated a severe to profound impairment. In seven CD patients, their hearing impairment was related to *GJB2* mutation. Five of the seven patients with CD related to *GJB2* mutation demonstrated abnormalities in one or both of the two tests. The percentage of vestibular dysfunction of the patients with CD related to *GJB2* mutation was statistically higher than in patients with CD unrelated to *GJB2* mutation and in healthy controls.

Keywords: *Vestibular evoked myogenic potentials, caloric test*

Introduction

Since a correlation between the peripheral auditory and vestibular systems has been identified both anatomically and phylogenetically, a subgroup of children with congenital deafness (CD) may be associated with vestibular and balance impairments [1–3]. Interestingly, the vestibular disturbance in these children gradually disappears as they grow up, probably because of a compensatory mechanism of the central nervous system. However, there have been only a few reports that conducted a detailed analysis of the vestibular function in adults with CD.

CD has been reported in approximately one child per 1000 births [1]. In more than half of these cases, the disease is caused by gene mutation. In particular, mutation in the *GJB2* gene, which encodes Cx26 in the gap junction, is known to be a most common cause (up to 50% of such cases) [2,3]. Gap junction channels enable the neighboring cells to exchange small signaling molecules. Immunohistochemical studies have revealed that Cx26 exists not only in the cochlea but also in the vestibular organs [4]. K^+ cycling involving gap junction protein Cx26 in the vestibular labyrinth, which is similar to that in the cochlea, is thought to play a fundamental role in the endolymph homeostasis and sensory transduction [5]. These findings suggest that mutations in the *GJB2* gene may thus cause vestibular dysfunction.

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In this study, the relationship between *GJB2* gene mutation and vestibular dysfunction in adults with CD was investigated to confirm whether or not there are any abnormalities associated with the vestibular function.

Material and methods

Subjects

The subjects in this prospective study included 21 patients with CD and 10 healthy volunteers. The patients were excluded from the study if they were being treated with ototoxic drugs or if they had a cytomegalovirus infection, bacterial meningitis, external and middle ear pathological findings, or other risk factors for inner ear damage. No participants had syndromic deafness due to pigmentary retinopathy, nephropathy, goiter, or any other diseases. Patients with vestibular dysfunction due to head trauma, brain tumor, Meniere's disease, or other conditions were also excluded from the study. All subjects underwent an otoscopic examination and were found to have a normal tympanic membrane. Audiometric testing was performed in a double-walled, sound-treated booth. All patients gave their informed consent in writing and the study was approved by the Ethics Committee of Juntendo University School of Medicine.

Genetic analysis

DNA was extracted from peripheral blood leukocytes of the subjects. The coding region of *GJB2* was amplified by PCR using the primers *GJB2*-2F 5′-GTGTGCATTCGTCTTTTCCAG-3′ and *GJB2*-2R 5′-GCGACTGAGCCTTGACA-3′. The PCR products were sequenced using the PCR primers and sequence primers *GJB2*-A 5′-CCACGC-CAGCGCTCCTAGTG-3′ and *GJB2*-B 5′-GAA-GATGCTGCTGCTTGTGTAGG-3′. These were visualized using an ABI Prism 310 Analyzer (PE Applied Biosystems, Tokyo, Japan).

Vestibular evoked myogenic potentials

The vestibular evoked myogenic potentials (VEMPs) were measured as described in a previous report [6]. Both sound stimuli of clicks (0.1 ms, 95 dBnHL) and short tone burst (500 Hz; rise/fall time, 1 ms, 95 dBnHL) were presented to each side of the ear through the headphones using a Neuropack evoked-potential recorder (Nihon Kohden Co. Ltd, Tokyo, Japan). The surface electromyographic activity was recorded with the patient in the supine position from symmetrical sites over the upper half of each sternocleidomastoid (SCM) muscle with a reference electrode on the lateral end of the upper sternum. During recording, the subjects were instructed to lift their head up or to turn the contralateral side to induce hypertonicity of the SCM. Thereafter, the electromyographic signals from the stimulated side of the SCM muscle were amplified.

Caloric test

The caloric test in the current study was performed as described elsewhere [7]. Briefly, 2 ml of ice-water (at 4°C) was irrigated in the external auditory meatus to induce a thermal gradient across the horizontal semicircular canal of one ear. The duration of horizontal and vertical nystagmus was recorded. The results were compared between the right and left ears.

Statistical analysis

The data are expressed as the mean ± SD. Statistical analyses were conducted using a non-repeated measures analysis of variance (ANOVA). Significant effects were further analyzed by post hoc multiple comparison tests using the Student-Newman-Keuls test. A value of $p < 0.05$ was considered to indicate statistical significance.

Results

Hearing test

The pure-tone averages of 0.5, 1.0, and 2.0 kHz are shown in Table I. The hearing impairments of CD patients ranged from severe (71–95 dB) to profound (>95 dB). The hearing levels of all controls were at the normal level (<30 dB; data not shown).

Genetic analysis

GJB2 mutations were found in nine CD patients (Table I). All three mutations have been described previously in association with deafness. Among these mutations, 235delC mutation was found in eight patients. One nonsense mutation (Y136X) and one frameshift mutation (176-191del) were also identified. In six patients with a homozygous *GJB2* mutation and one patient with a compound heterozygous

Table I. Results of hearing level, genetic analysis, and vestibular function of subjects with congenital deafness (CD)

Case no.	Hearing level (dB) Left	Right	Sex	Age (years)	Mutation in *GJB2*	VEMPs	Caloric test
Patients with *GJB2*-related CD							
1	86	98	M	26	Homo 235delC	Right decreased	Left CP
2	106	108	M	25	Homo 235delC	Right decreased	Normal
3	108	106	M	28	Homo 235delC	Right decreased	Normal
4	108	106	M	37	Homo 235delC	Normal	Right CP
5	100	106	M	32	Homo 235delC	Normal	Right poor/left CP
6	80	91	M	25	Homo 235delC	Normal	Normal
7	115	108	M	25	Y136X/235delC	Normal	Normal
Patients without *GJB2*-related CD							
8	98	98	F	24		Left decreased	Bilateral CP
9	98	115	M	26		Normal	Bilateral CP
10	97	97	M	20		Normal	Normal
11	111	108	M	31		Normal	Normal
12	100	104	F	34		Normal	Normal
13	98	95	M	21		Normal	Normal
14	91	91	M	24		Normal	Normal
15	99	101	F	26		Normal	Normal
16	99	95	F	23		Normal	Normal
17	80	68	M	27		Normal	Normal
18	96	95	M	27		Normal	Normal
19	85	73	M	23		Normal	Normal
Patients with heterozygous *GJB2* mutation							
20	73	100	M	25	Hetero 235delC	Normal	Normal
21	97	98	M	25	Hetero 176-191del16	Normal	Normal

CP, canal paresis; Poor, nystagmus was obviously weak.

mutation (case nos 1–7); their profound deafness was thought to be caused by a *GJB2* mutation. No *GJB2* mutation was identified in any of the controls.

Vestibular function

No patients or controls had any subjective symptoms of vertigo. Table I shows the results of the vestibular function in all CD patients. Abnormal responses of VEMPs and the caloric test in CD with a *GJB2*-related mutation were observed in three patients each (case nos 1–5). Three patients with a homozygous *GJB2* mutation showed asymmetrical responses in VEMPs (case nos 1–3). Three patients with a homozygous *GJB2* mutation showed asymmetrical responses in the caloric test (case nos 1, 4, and 5). One of them showed both VEMPs and the caloric test asymmetrical responses (case no. 1). One patient with a homozygous *GJB2* mutation and one patient with compound heterozygous *GJB2* mutation showed normal responses in both VEMPs and the caloric test (case nos 6 and 7). It is notable that five of the six patients with a homozygous 235delC mutation showed no abnormalities in either test. Two heterozygous patients (case nos 20 and 21) showed normal responses in both tests.

Two CD patients with no *GJB2* mutation exhibited abnormal findings for the vestibular tests (case nos. 8 and 9). One patient showed a unilateral reduction in VEMPs and bilateral canal paresis (case no. 8). Bilateral canal paresis was also observed in another patient (case no. 9).

All the controls with normal hearing showed normal responses in both the VEMPs and the caloric test (data not shown).

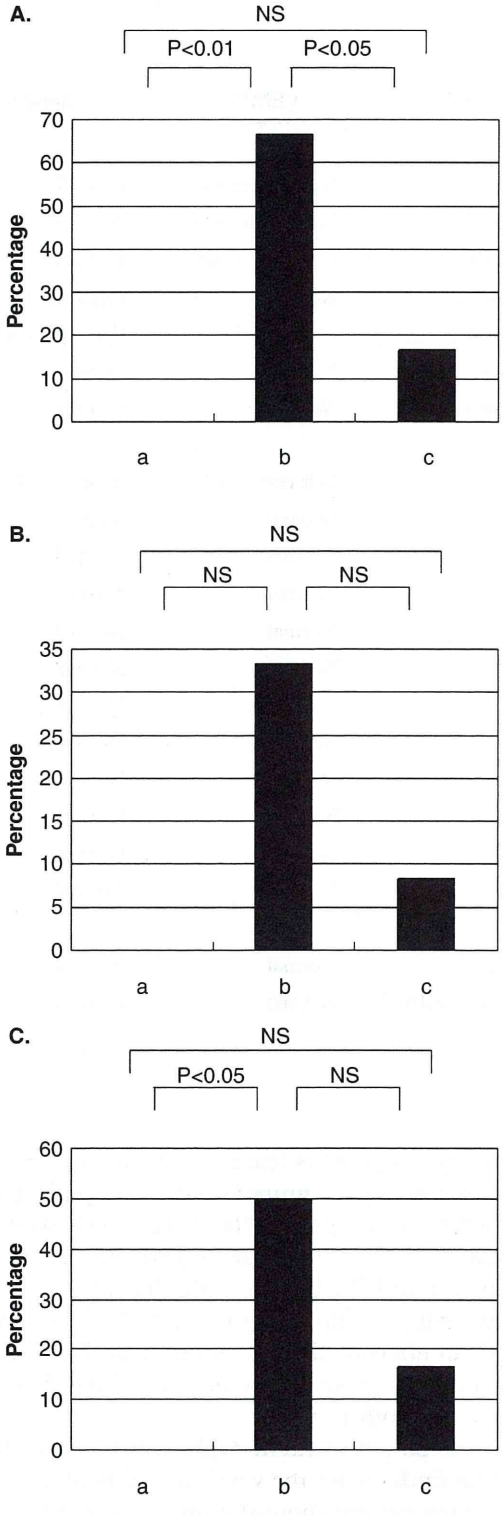

Figure 1. Comparison of the incidence of abnormality in the vestibular tests among the three groups. (A) Percentage showing abnormality in VEMPS and/or caloric test. (B) Percentage showing abnormality in VEMPs. (C) Percentage showing abnormality in the caloric test. a, Controls; b, *GJB2*-related CD subjects; c, CD subjects without *GJB2* mutations.

Statistical analysis of vestibular function in the three groups

Figure 1 shows a comparison of the controls, patients with CD related to a *GJB2* mutation, and those with CD without a *GJB2* mutation. The CD patients with *GJB2* heterozygous mutation were excluded from this statistical analysis, since their symptoms of hearing impairment are not necessarily caused by the *GJB2* mutation alone. Vestibular dysfunction showing an abnormality in VEMP and/or the caloric test significantly increased in patients with *GJB2*-related CD in comparison with those with CD without *GJB2* mutation ($p < 0.05$) and the controls ($p < 0.01$), whereas no difference was observed between CD without a *GJB2* mutation and the controls (Fig. 1A). No differences in the incidence of abnormality in VEMPs were observed among the three groups (Fig. 1B). The incidence of abnormalities in the caloric test in patients with *GJB2*-related CD differed significantly from that in the controls, but the other two comparisons were not significant (Fig. 1C).

Discussion

In this study, vestibular tests were performed in CD patients with or without a *GJB2* mutation by measuring the VEMPs and using the caloric test. Only one report has previously investigated the vestibular function of patients with *GJB2*-related CD [8]. The authors noted that five of the seven patients showed no VEMP responses bilaterally and that only one case had a unilateral pathological response in the caloric test, which led to the conclusion that CD with a *GJB2* mutation is associated with severe saccular dysfunction. However, in the present study, there were no patients showing the absence of both VEMP and a caloric response. Todt et al. [8] showed the existence of *GJB2* mutations that do not cause CD (polymorphisms), thus suggesting a considerable bias. Furthermore, patients with low-grade hearing loss were included in their study. In contrast, all of the *GJB2* mutations detected in the present study are known to cause CD in the Asian population [9]. In addition, the present study included only patients with severe to profound hearing loss, which would therefore clarify the correlation between CD and *GJB2* mutations. Among the seven patients with *GJB2*-related CD, five (71.4%) showed abnormal responses in either or both tests. The incidence was apparently and significantly higher than that in patients with CD without a *GJB2* mutation (2/13: 15.4%). Moreover, the incidence in the controls significantly differed from that in patients with CD related to a *GJB2*

mutation but not in those with CD without *GJB2* mutation. Therefore, these findings support the hypothesis that *GJB2* mutations play a critical role in the disturbance of the vestibular function.

GJB2 mutations cause profound deafness and the associated mechanism has been discussed in several studies [10,11]. A recent study showed that *GJB2* is indispensable in the normal development of the organ of Corti and normal hearing on the basis of the study in *Gjb2* dominant-negative mutant mice [12]. Despite the widespread expression of Cx26 in both the cochlear and vestibular organs [4], the vestibular function impairment of the patients with a *GJB2* mutation is not as severe as the hearing dysfunction observed in the present study. Two hypotheses have been proposed to explain this inconsistency between hearing and balance function. One hypothesis is based on the fact that two temporal bone studies performed in patients with *GJB2*-related hearing impairment in the previous study revealed that one patient had mild vestibular hydrops and saccular degeneration, while another patient had a dysplastic neuroepithelium of the saccule [13,14]. This suggests that a *GJB2* mutation can cause morphological dysplasia in not an entire organ, but in part of the vestibular organs. This is contrast to the cochlea of these patients, which showed nearly total dysplasia of the organ of Corti. These histopathological studies support the results of the vestibular dysfunction of patients with *GJB2*-related CD in the present study. The other hypothesis is based on the presence of several connexins such as Cx26, Cx30 (encoded by *GJB6*), Cx31 (encoded by *GJB3*), and Cx32 (encoded by *GJB1*) in the inner ear. A previous study showed all of these connexins to be distributed in the vestibular organs [15]. Cx30 gene knockout mice had hair cell loss in the saccule, which was restored by the over-expression of the Cx26 gene [16]. Therefore, the specific loss of Cx30 causes vestibular dysfunction, which can be compensated by other types of connexins. The present clinical study in which a complete defect of Cx26 resulted in a definitive but partial dysfunction of vestibular end organs can be explained by the compensation of other connexins normally expressed in the vestibule. Further studies are required to clarify the relationship between connexins and the vestibular function.

Although there was a statistically significant difference in the objective examination of the vestibular function among patients with *GJB2*-related CD, those with CD without a *GJB2* mutation, and healthy controls, none of these subjects had any vestibular symptoms regardless of the presence or absence of a *GJB2* mutation. The peripheral vestibular dysfunction predicted in individuals with the *GJB2* mutation may be compensated by the central vestibular system in young patients with deafness, as shown in the present study. However, aging is known to affect both the peripheral and central vestibular system [17]. In patients with a *GJB2* mutation, the vestibular symptoms may progress with aging. Another problematic point regarding patients with CD related to *GJB2* mutations is cochlear implantation, which has been reported to cause vestibular dysfunction, such as a reduction of the caloric responses [18] and a decrease in the VEMP responses [19]. It is thought that the mechanical damage caused by the insertion of the electrode may induce vestibular dysfunction [20]. In the present study, four patients with *GJB2*-related deafness showed unilateral vestibular dysfunction, while only one of them had bilateral dysfunction. Therefore, it should be emphasized that the assessment of the vestibular function in patients with *GJB2*-related CD is important to determine which side of the ear should be selected to insert the cochlear implant.

Conclusions

A *GJB2* mutation is responsible not only for deafness but also for vestibular dysfunction. However, such vestibular dysfunction is likely to be unilateral and less severe in patients with a *GJB2* mutation than in those with bilateral deafness.

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実験動物を用いた内耳細胞治療研究へのアプローチ

神谷　和作・池田　勝久

Experimental Approaches to Inner Ear Cell Therapy Using Laboratory Animals

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Recently, a number of clinical studies on cell therapy have been reported and used in clinical practice for several intractable diseases. Inner ear cell therapy for sensorineural hearing loss also has been studied using some laboratory animals, although to date reports on successful hearing recovery have been few.

Previously, we developed a novel rat model of acute sensorineural hearing loss due to fibrocyte dysfunction induced by a mitochondrial toxin and performed cell therapy with bone marrow mesenchymal stem cells (MSCs). In this study, we injected MSCs into the lateral semicircular canal; a number of these stem cells were then detected in the injured area in the lateral wall. Rats with transplanted MSCs in the lateral wall demonstrated a significantly higher hearing recovery ratio than the untreated controls. These results suggested that mesenchymal stem cell transplantation into the inner ear may be a promising therapy for patients with sensorineural hearing loss due to degeneration of cochlear fibrocytes.

In this article, we review studies on inner ear cell therapy using some laboratory animals including rodents such as mice and rats, and primates such as cynomologus monkeys (Macaca fascicularis).

Key words : inner ear, cell therapy, sensoryneural hearing loss, stem cell

はじめに

感音性難聴の原因は多岐にわたるが，近年の遺伝子改変動物開発技術の向上や多種のモデル動物の開発により多くの病態メカニズムが解明に近づいている．すべての先天性疾患の中でも頻度の高い遺伝性難聴においては，難聴家系や突然変異難聴マウスの遺伝子解析によって多くの遺伝性難聴原因遺伝子が同定されている．初期に発見された遺伝性難聴の原因の多くは内耳有毛細胞の変性または機能的・形態的異常であったため，多くの研究者が有毛細胞を中心に難聴の病態メカニズム解明に取り組んできた．哺乳類の有毛細胞は再生能力を持たないため遺伝子導入などによる有毛細胞再生の誘導も盛んに研究されてきた[1)2)]．その一方で内耳への細胞移植による有毛細胞の修復の試みも行われているが，特殊なリンパ液で満たされた内耳の構造的特徴から，聴力を保持しつつ標的部位に移植細胞を到達させ分化させることは容易ではない．そのため有毛細胞の修復には多種のモデル動物を用いた多くの検討実験が必要と考えられる．近年有毛細胞以外にも蝸牛線維細胞などの機能異常が単独で難聴病態の引き金となることも明らかとなっており，多様な治療戦略が求められている．幹細胞の損傷部への移動能力や組織環境（ニッシェ，niche）による分化誘導を十分に検討すれば細胞治療は内耳組織変性に対する治療にも応用可能と考えられる．著者らの報告では実験的に蝸牛線維細胞のみに傷害を与えたラットへ半規管外リンパ液を経由した細胞液還流法を用いることにより，損傷部の修復と聴力回復率を高めることに成功した[3)]．現在はヒト疾患に近い遺伝性難聴モデル動物への各種の幹細胞移植に取り組んでいる．また，サル類を用いた細胞移植アプローチの検討も今後応用性を高めるためには非常に重要であるため現在，カニクイザルによる検討を行っている．各種のモデル動物の特徴を考慮した細胞移植実験検討を

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積み重ねることにより，将来的には有毛細胞も標的とした多様な難聴に対する聴力回復も不可能ではないと考えられる．本稿では各種実験動物を用いた内耳への細胞治療研究に関する知見について報告する．

内耳細胞治療実験に用いられる実験動物

外傷，騒音，感染，薬物障害，血流障害，加齢に起因する聴覚障害動物モデルは多く開発されており，細胞治療研究のための有用な実験モデルとして活用することができる．著者らはミトコンドリア阻害薬を用いて蝸牛線維細胞のみに損傷を与えるモデルラットを開発し，この細胞移植実験に成功している．しかしこのような実験的に内耳損傷を誘導した動物モデルがヒトと同等な内耳組織障害および機能的障害を忠実に再現しているかという点に関しては実証することは困難である．これに対し原因タンパク質がすでに特定されている遺伝子改変動物または突然変異動物はヒト遺伝性難聴の病態の多くが一致していると考えられる．細胞移植によりそのタンパク質が担う機能を回復させることができれば，幹細胞が正常に分化し失われていたタンパク質機能を取り戻した結果として聴力が回復したことを実証しやすい．有毛細胞の変性が顕著にみられるモデル動物としては，アッシャー症候群原因遺伝子（Pcdh15[4]，Cdh23[5]，Sans[6]，Harmonin[7]，MyosinVIIa[8]など）の突然変異動物あるいは遺伝子改変動物が，明白な表現型を持つため有毛細胞の研究に広く用いられている．これらの進行性の組織変性は重度であり有毛細胞の変性から連鎖的にラセン神経節細胞の消失へとつながる場合も多い．そのため細胞治療による細胞の生着・分化の検討は可能であるが聴力改善の検討は現段階で容易ではないと思われる．蝸牛線維細胞を標的とした場合，有毛細胞変性を伴わず蝸牛線維細胞のみに変性を持つ Brn4 欠損マウス[9]，Otospiralin 欠損マウス[10]が有効であると考えられる．これらの聴力改善の可能性は有毛細胞を標的とした細胞治療より格段に高いと思われる．ヒト遺伝性難聴でもっとも高頻度に出現するコネキシン26の遺伝子欠損マウスおよび優性阻害トランスジェニックマウス[11]は同遺伝子が蝸牛線維細胞および支持細胞に主に発現するため，著者らの行った骨髄間葉系幹細胞移植も有効であると考えられる．

蝸牛線維細胞を標的とした骨髄間葉系幹細胞移植

蝸牛ラセン靭帯およびラセン板縁を構成する蝸牛線維細胞はナトリウムポンプとギャップジャンクションによる蝸牛内イオンの能動輸送および受動輸送という単純な機能を担っている．しかしながら蝸牛線維細胞の傷害は複数の先天性および後天性難聴の主要因となることが示され，その重要性が近年示唆されている．とくにヒト非症候性難聴 DFN3 の原因因子 Brn4 の遺伝子欠損マウス[9]や otospiralin 欠損マウス[10]では蝸牛線維細胞の変性を主要因とした聴力低下が実証され，有毛細胞を含むコルチ器と同様に正常聴力を維持するうえで重要性の高い細胞群であることが明確に示された．また複数の加齢性難聴モデル動物においても蝸牛線維細胞の変性が他の細胞に先立ち開始することが報告されている[12)～14)]．また蝸牛線維細胞は単一細胞としての機能が単純であるにもかかわらず内耳機能における重要性が高いという点から，高度に分化した有毛細胞に比べて細胞治療が成功する可能性が格段に高いと考えられる．これらのことから蝸牛線維細胞は多種の感音難聴に対する新規治療法確立への重要な標的となりうると考えられる．著者らは薬剤

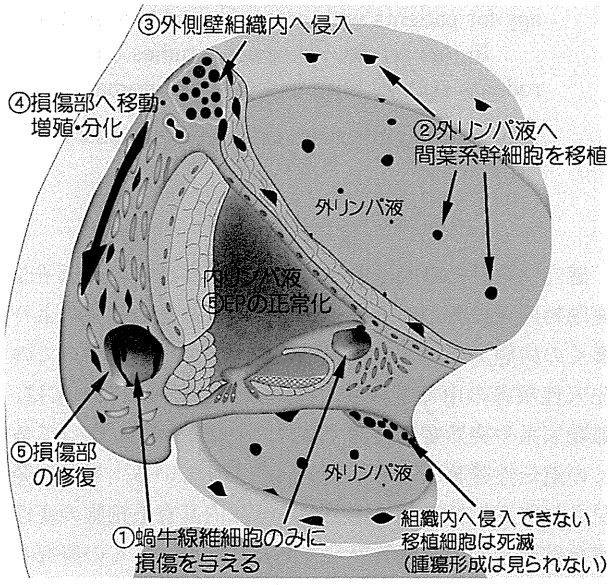

図 1　蝸牛線維細胞をターゲットとした骨髄間葉系幹細胞移植での損傷部の修復および推測された移植細胞の移動経路
薬剤投与によりらせん靭帯およびらせん板縁に選択的に損傷を与え①，その後外リンパ液へ骨髄から採取した間葉系幹細胞を半規管からの還流により投与②した結果，投与した間葉系幹細胞が外側壁組織内へ進入し④，移動・増殖・分化④により損傷部の修復⑤を促進し高周波数音域の聴力回復率が有意に上昇した．（Reprinted from Am J Pathol Am J Pathol 2007, **171**：214 ～ 226 with permission from the American Society For Investigative Pathology）