

**Figure 3.** Regeneration and apoptosis of rat cochlear fibrocytes after 3NP administration. Double staining of BrdU (red) and TUNEL (green) assay 3 days (**A–C**) and 42 days (**D–F**) after 3NP administration. **B** and **E**: Schematic illustration for **A** and **D**. Green areas indicate the areas of apoptosis and red points indicate BrdU-positive cells. **C** and **F**: Higher magnification of the squared areas in **A** and **D**. A BrdU- and TUNEL-double-positive cell (yellow) was also observed (**arrow**). Nuclei (blue) were stained by TOPRO-3. SL, spiral limbus; LW, lateral wall; OC, organ of Corti. Scale bars = 50  $\mu$ m.

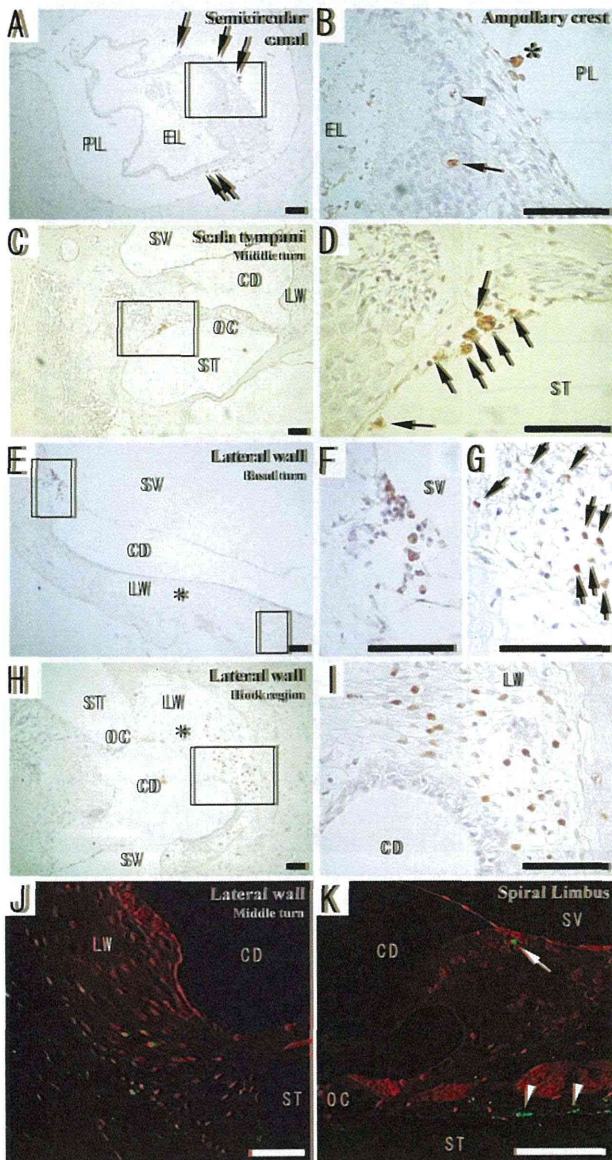
expression of Cx30 was very weak (Figure 5, A–C), and these cells did not show the punctate staining pattern at the site of contact with neighboring fibrocytes suggestive of gap junction connections (Figure 5C). Likewise, Cx26 staining spots at attachment sites to neighboring fibrocytes were not clearly observed (Figure 5, D–F). The transplanted MSCs occasionally displayed a morphology of dividing cell, suggesting that the MSCs can proliferate after their invasion into the lateral wall (Figure 5B). In contrast, within the middle part of the lateral wall near the injured region, most of the BrdU-positive cells and neighboring BrdU-negative fibrocytes strongly and similarly expressed Cx30 in the cytoplasm (Figure 5, G–I). In this area, Cx26 was also expressed by BrdU-positive cells in a similar staining pattern to BrdU-negative neighboring fibrocytes (Figure 5, J–L). BrdU-positive cells were observed even in the area where fibrocytes were not found (ie, the area without blue nuclear staining) and demonstrated Cx26 expression at the tips of their cytoplasmic processes (Figure 5, K and L; arrowheads). Moreover, these cells occasionally showed a morphology of the dividing cell (Figure 5, K and L; arrows). Nuclei of some MSCs appeared small and irregular, but signs of apoptosis such as fragmentation of nuclei were not detected in such MSCs. In addition, MSCs showed immunostaining of both Cx30 and Cx26 not only in cytoplasm and cell membrane but also in a part of nucleus, although these

proteins were not distributed in nuclei of normal cochlear fibrocytes (Figure 5, C, F, I, and L).

A summary of the histological observations shown in Figures 2, 4, and 5 and our hypothesis for the movement of transplanted MSCs are represented in the schematic illustration in Figure 6. In brief, after the perilymphatic perfusion with MSC suspension, MSCs settled on the surface of the scala tympani and the scala vestibuli within the cochlea. The injuries to cochlear fibrocytes caused by 3NP induced secretion of some chemokines from the injured area. With these stimulating signals, MSCs in the scala vestibuli invaded the lateral wall while maintaining their round shape. Then these MSCs migrated toward the injured area while maintaining the capacity for proliferation. The MSCs that reached the injured area continued to proliferate and repaired the disconnected gap junction network.

#### *Acceleration of Hearing Recovery by MSC Transplantation*

To evaluate the effect of MSC transplantation on hearing recovery in 3NP-treated rats, we monitored the ABR thresholds for 2 weeks after 3NP administration. In rats in which MSCs were transplanted without previous 3NP treatment (Figure 7, A–C), no significant threshold shift was recorded,



**Figure 4.** MSCs prelabeled with BrdU and transplanted into the inner ear of 3NP-treated rats at 11 days after the transplantation. **B, D, F, G, and I** are high-magnification images of the squared area of the left panels (**A, C, E, and H**). A number of BrdU-positive cells were observed (**A, arrows**), and some BrdU-positive cells were attached to the surface of the ampullary crest (**B, asterisk**) or had invaded the tissue (**B, arrow**). An **arrowhead** indicates BrdU-positive cells that appeared to be rejected by the recipient tissue. **C** and **D**: In the scala tympani, a mass of MSCs (**arrows**) was observed on the bone surface. In the cochlear lateral wall, MSCs were detected within the tissue (**E, asterisk** indicates the injured area). A number of MSCs were detected in the apical part of the lateral wall (**F**), and many MSCs were detected within the injured area of the cochlear lateral wall (**G, arrows**). **H** and **I**: A large number of BrdU-positive cells were detected near the injured area (**asterisk**) of the lateral wall at the hook region of the cochlea. **J** and **K**: Immunofluorescent staining of MSCs in the middle turn of cochlea. Only one MSC was observed in the spiral limbus (**K, arrow**). **Arrowheads** indicate MSCs that appear to be attached to the surface of the basilar membrane. Nuclei were stained with propidium iodide (red). PL, perilymph; EL, endolymph; SV, scala vestibuli; CD, cochlear duct; ST, scala tympani; LW, lateral wall; OC, organ of Corti. Scale bars = 50  $\mu$ m.

indicating that there was no significant hearing loss caused by the transplantation operation itself. Of the 12 rats that received MSC transplantation after 3NP treatment, the six rats who demonstrated MSC invasion of the lateral wall by

**Table 1.** Number of Rats in Which Mesenchymal Stem Cells (MSCs) Were Observed in the Cochlear Tissue 11 Days after MSC Transplantation

	Rats tested	MSC survival	Invasion into lateral wall
3NP + MSC	12	12	6
MSC only	7	7	1

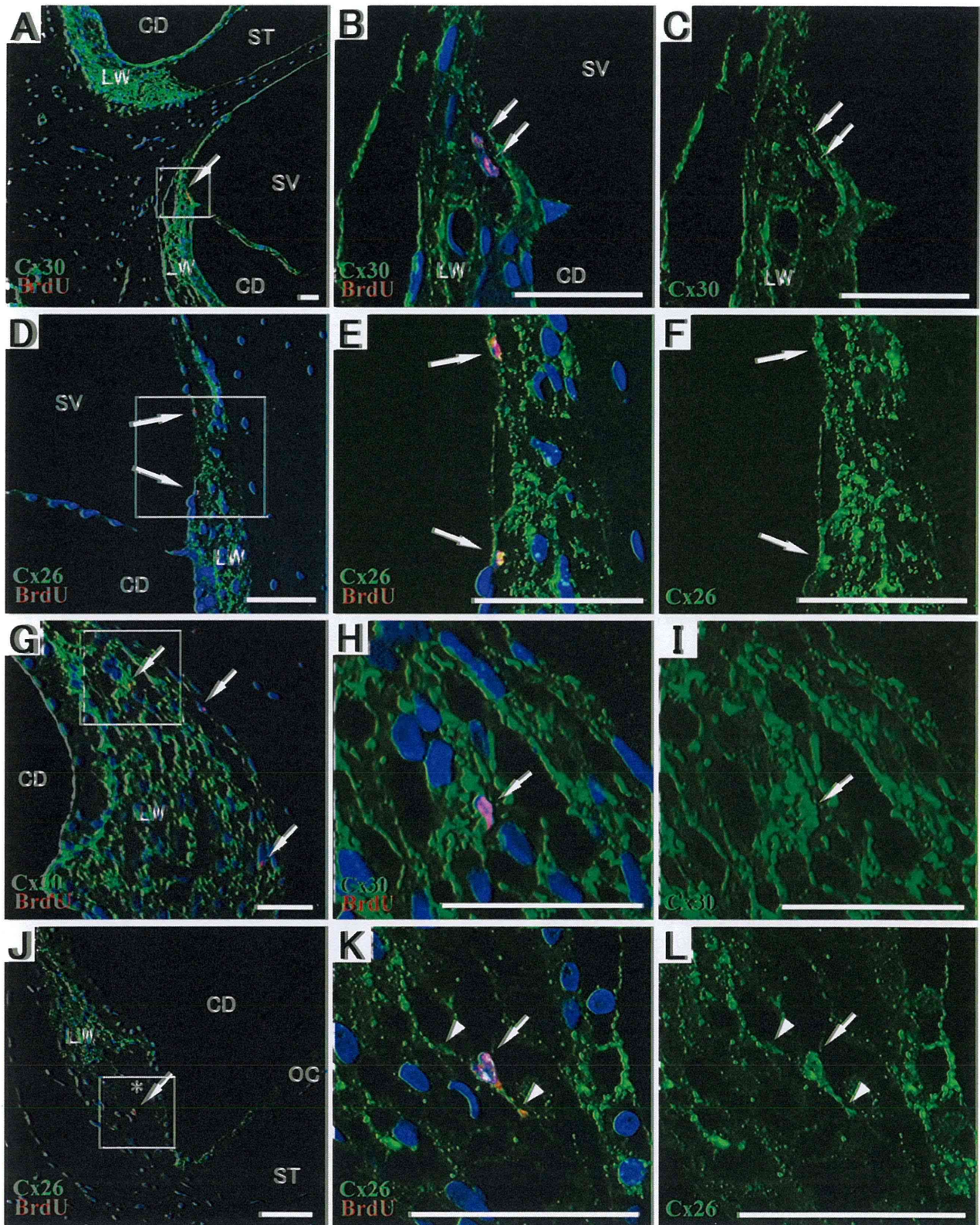
3NP + MSC, rats in which MSC transplantation was performed 3 days after administration of 3NP; MSC only, control rats into which MSCs were transplanted without previous 3NP administration; MSC survival, the number of rats in which surviving MSCs were detected within the cochlea; and invasion into lateral wall indicates the number of rats showing MSC invasion into the lateral wall.

histological analysis, and thus were most likely to experience recovery of hearing, were selected for ABR data collection. At 14 days after 3NP administration, the ABR thresholds both of rats receiving MSC transplantation after 3NP treatment (3NP + MSC,  $n = 12$  for 8 and 20 kHz and  $n = 7$  for 40 kHz) and of 3NP-treated rats that demonstrated MSC invasion of the lateral wall (3NP + MSC/LW,  $n = 6$  for 8 and 20 kHz and  $n = 3$  for 40 kHz) selected from 3NP + MSC in the following histochemical analysis were lower than those of 3NP-treated rats without MSC transplantation (Figure 7, A–C) for 8, 20, and 40 kHz. A remarkable decrease in the ABR threshold at 40 kHz was detected in 3NP-treated rats with MSC invasion of the lateral wall compared with the 3NP-treated group lacking transplantation at 14 days, although little difference had been seen at 7 days (Figure 7C). This result suggests that an even greater effect on the ABR threshold by MSC transplantation may be expected with a longer observation period. The 3NP-treated rats with MSC transplantation also had higher recovery ratios than the 3NP-treated rats without MSC transplantation at all tested frequencies 14 days after 3NP administration (Figure 7D). Moreover, the rats with lateral wall invasion of MSCs tended to show a higher recovery ratio than the other two groups. The difference between the 3NP-treated rats showing invasion of MSC into the lateral wall and 3NP-treated rats without transplantation was greater for higher frequencies: at 40 kHz, the recovery ratio was significantly higher ( $\sim 23\%$ ,  $P = 0.036$ ) for the rats with lateral wall invasion of MSCs. To examine the effect of surgical manipulation, an equal volume of vehicle (D-PBS) was also injected into the semicircular canal of 3NP-treated rats as control. These control experiments showed that the vehicle injection did not change the time course of ABR thresholds at 8 kHz but aggravated the ABR thresholds at 20 kHz at 7 days after 3NP administration and aggravated the ABR thresholds at 40 kHz at least at 7 and 14 days after 3NP administration in comparison with 3NP-treated rats with or without MSC transplantation.

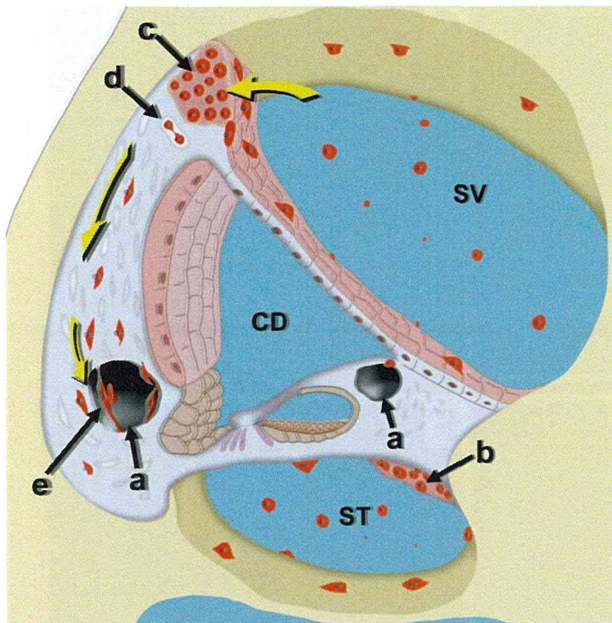
## Discussion

### Apoptosis and Regeneration of Cochlear Fibrocytes in 3NP-Treated Rats

In this study, we demonstrated that acute hearing loss in rats treated with the mitochondrial toxin 3NP corre-



**Figure 5.** Expression of gap junction proteins Cx30 and Cx26 in transplanted MSCs. MSCs prelabeled with BrdU (red) are shown in the apical part (A–F) and middle part (G–L) of the lateral wall. Middle and right columns show high-magnification images of the squared area of the panels in the left column. In the right column, only Cx30 or Cx26 expression (green) is shown. **A–C:** In the apical part, weak expression of Cx30 was frequently detected in the BrdU-positive cells (arrows) as well as in neighboring fibrocytes. **D–F:** Cx26 expression was also observed in BrdU-positive cells in this area (arrows), but spots of immunostaining at cell attachment sites with neighboring fibrocytes were not visible. **G–I:** In the middle part of the lateral wall, strong expression of Cx30 was detected in the transplanted MSCs (arrows) as well as in neighboring fibrocytes. In this area, expression of Cx26 was observed in the MSCs even in the severely injured area (J–L, arrow). These MSCs appeared to have formed new gap junction connections (arrowheads) with neighboring fibrocytes. Nuclei were stained with 4,6-diamidino-2-phenylindole (blue). SV, scala vestibuli; CD, cochlear duct; ST, scala tympani; LW, lateral wall; OC, organ of Corti. Scale bars = 50  $\mu$ m.

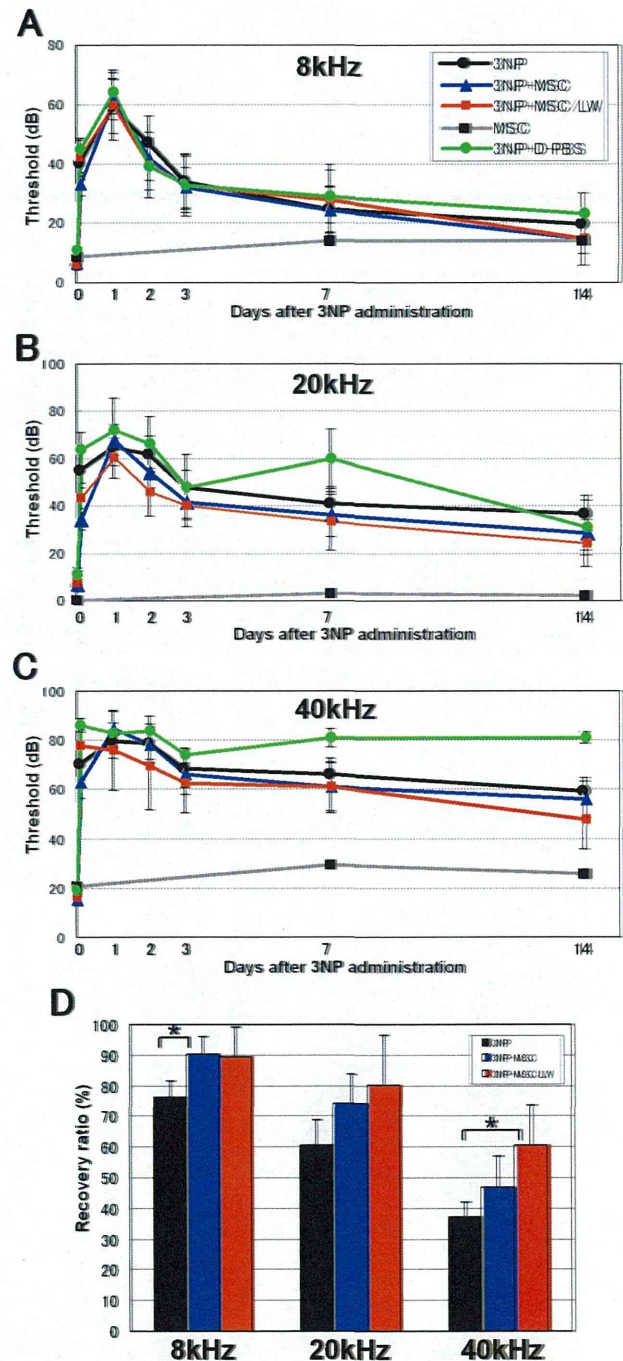


**Figure 6.** A summary of the histological observations shown in Figures 2, 4, and 5 and our hypothesis for the movements of the transplanted MSCs. The transplanted MSCs are represented in red. **Yellow arrows** indicate the hypothetical route of MSC migration to the injured area (**a**). Some MSCs (**b**) formed a cell mass around the scala tympani. A number of MSCs (**c**) successfully invaded the lateral wall. The invading MSCs (**d**) proliferated in the lateral wall. The MSCs that reached the injured area (**e**) continued to proliferate and repaired the disconnected gap junction network. SV, scala vestibuli; CD, cochlear duct; ST, scala tympani.

lated with a severe foci of apoptotic cochlear fibrocytes in the lateral wall and spiral limbus, both of which are indispensable to the potassium recycling system of the cochlea. The active uptake and passive conductance of  $K^+$  by Na,K-ATPase and the gap junctions, respectively, maintain the endocochlear potential of the endolymph to generate acoustic depolarization of cochlear hair cells through a mechanically gated cation channel.<sup>28</sup> Furthermore, Na,K-ATPase is highly expressed in type II fibrocytes located lateral to the spiral prominence epithelium and suprastrial region.<sup>29</sup> In the case of a cochlear energy shortage induced by 3NP, it is assumed that the active uptake of  $K^+$  by Na,K-ATPase would not continue but the passive conductance of  $K^+$  via gap junctions would be maintained, resulting in an overall decrease of cytosolic  $[K^+]$  in a part of the lateral wall and spiral limbus. Because potassium deprivation is a well-known cause of apoptosis,<sup>30</sup> the apoptosis of the cochlear fibrocytes we observed is likely because of low cytosolic  $[K^+]$ .

In the BrdU incorporation assay, active regeneration of the fibrocytes was observed near the apoptotic area in the lateral wall, suggesting that reconstruction of the potassium recycling route by cellular regeneration led to normalization of endocochlear potential and hearing recovery. Thus, regeneration of cochlear fibrocytes may be an essential process for hearing recovery after acute cochlear energy shortage (such as sudden hearing loss attributable to inner ear ischemia). These spontaneously regenerated cells are thought to be mainly generated by the mitosis of cochlear fibrocytes around the injured area.

However, the recent report suggests that bone marrow cells also have the capacity to migrate into the lateral wall and differentiate into the cochlear fibrocytes.<sup>22</sup>



**Figure 7.** Hearing recovery after MSC transplantation. Thresholds of ABR for 8 (A), 20 (B), and 40 kHz (C) were recorded at 2 hours, 1 day, 2 days, 3 days, 7 days, and 14 days after 3NP administration. **A-C:** ABR thresholds are shown for rats with 3NP administration only (3NP, **black circle**), rats with MSC transplantation at 3 days after 3NP administration (3NP + MSC, **blue triangle**), rats with MSC transplantation at 3 days after 3NP administration and after histological confirmation of MSC invasion into the lateral wall (3NP + MSC/LW, **red square**), rats with MSC transplantation without 3NP administration (MSC, **black square**), and rats with vehicle injection (3NP + D-PBS, **green circle**). **D:** Hearing recovery ratios were calculated from ABR recovery thresholds at 2 weeks. The recovery ratios of 3NP + MSC rats (blue) and 3NP + MSC/LW rats (red) were higher than 3NP rats (black) at all frequencies. \* $P < 0.05$ .

### *Transplantation of MSCs Accelerated Hearing Recovery*

The 3NP-treated rats showed complete hearing recovery at low frequencies; however, there remained a residual hearing loss at higher frequencies. Considering that the cochlear fibrocytes that were injured in this model are mesenchymal in origin, we transplanted rat MSCs into the cochlea to attempt to rescue the residual hearing loss. We used MSCs, which we previously established and demonstrated their potential as MSCs, and we further confirmed the surface antigen expression of the cells used for transplantation in flow cytometry, which showed similar expression pattern to human and murine MSCs. This suggests that the cells maintained the capacity as rat MSCs at the moment of transplantation. Because there is no barrier in the inner ear perilymph between the cochlear and vestibular compartments, cells delivered from the lateral semicircular canal by perilymphatic perfusion are considered to have reached the cochlea. Within the perilymph of the cochlea, these cells presumably spread through the scala vestibuli toward the apical turn of the cochlea, and then, after passing through the helicotrema where the scala vestibuli communicates with the scala tympani, kept moving through the scala tympani toward the basal turn. There is no other way in which MSCs can spread within the cochlear perilymph.

Our study clearly demonstrates that rat MSCs were successfully transplanted into the inner ear of 3NP-treated rats by perilymphatic perfusion from the lateral semicircular canal. A number of MSCs were detected on the surface of the ampullary crest facing the perilymph and some of them were detected within the tissue of the ampullary crest, indicating that MSCs survived at least for 11 days after the perfusion and had maintained their ability to invade and migrate into the inner ear tissue. A small number of MSCs appeared to have been rejected by the host tissue in the ampullary crest. This may be attributable to differences between the F344 and Sprague-Dawley rat strains used. In the cochlea, a number of MSCs formed cell masses on the surface of the scala tympani, where the majority of the surrounding tissue is bone tissue, suggesting that these MSCs did not invade the cochlear tissue. In the scala vestibuli, a small number of MSCs were also found attached to the surface of the bone and the Reissner membrane. However, in the apical part of the lateral wall, a number of MSCs were observed within the tissue, suggesting that MSCs had successfully invaded the lateral wall from the perilymph. This area may be an optimum site for MSC invasion.

Furthermore, some of MSCs within the tissue appeared to be undergoing mitosis and forming cell clusters, suggesting that MSCs can proliferate in the injured lateral wall to substitute for the fibrocytes lost through injury. It is likely that the MSCs that invaded the tissue from the apical part of the lateral wall migrated to the injured area in the middle part of the lateral wall. Invasion of MSCs into the lateral wall was observed in half of the rats that had 3NP treatment and MSC transplantation but in only one of seven rats that underwent only MSC transplantation,

demonstrating that rats with injury in the lateral wall had a higher rate of MSC invasion than those without injury. The approximate number of BrdU-positive cells in the whole lateral wall with 3NP treatment and MSC transplantation estimated from the immunostained cross sections is 3000 to 5000 cells in single cochlea, and it is 3 to 5% of total cells transplanted by the cell perfusion. It is known that transplanted stem cells are recruited to injury sites by chemokines.<sup>31</sup> Recently, we performed DNA microarray analysis of the cochlear lateral wall RNAs in 3NP-treated rats and found a significant increase in the expression of the small inducible cytokine A2 gene encoding monocyte chemoattractant protein 1 (MCP1, data not shown), which has been reported as a chemokine that induces migration of neural stem cells.<sup>32</sup> This may suggest that the MSC migration to the injured area of the lateral wall in this study may also be induced by chemokines because most MSCs were observed in the lateral wall in basal turn, which had a prominent damage, but not in the apical turn.

One of the most important roles of the cochlear fibrocytes is potassium ion transport for the potassium recycling system within the cochlea, and the gap junction network is essential for ion movement in this system. Thus, we analyzed the expression and distribution of the gap junction proteins Cx30 and Cx26 after MSC transplantation and found that some MSCs within the tissue in the middle part of the lateral wall showed a distribution of Cx30 and Cx26 similar to that of normal cochlear fibrocytes in the same part of the lateral wall. We also observed that MSCs that had invaded the injured area had processes that protruded toward neighboring fibrocytes with condensed Cx26 expression at the tips of the processes, suggesting that these cells invaded the injured area and reconstructed a new gap junction network with the remaining fibrocytes in the area. Moreover, these cells occasionally showed a morphology of dividing cells, suggesting that invading MSCs in the injured area could still proliferate. On the other hand, MSCs observed in the apical part of the lateral wall, which probably represented newly invading MSCs, did not show gap junction connections with their neighboring fibrocytes. The MSCs forming a cell cluster in this region had a round shape without attachments to other fibrocytes, suggesting that these MSCs may still have had stem cell potential and migratory abilities and did not contribute to ion transport. Nuclear expression of connexins in MSCs may indicate that such MSCs were not completely differentiated as cochlear fibrocytes. Nuclear expression of other connexins has been reported in the other types of cells.<sup>33-35</sup> Although functional significance of nuclear expression of connexins is primarily unknown, a recent study reported that nuclear expression of connexins might exert effects on gene expression and cell growth.<sup>36</sup> In this study, invasion of the injured lateral wall by MSCs was histologically confirmed in only 50% of the treated rats, but the rate of MSC invasion of the target area could be improved by using isogenic or autologous transplantation. Otherwise, the addition of appropriate growth factors or continuous transplantation of MSCs may also improve the rates of MSC invasion.

A recent study reported that BrdU could be transferred from prelabeled grafted bone marrow cells to host neuronal precursors and glia.<sup>37</sup> Because BrdU was used to label MSCs in this study, the origin of BrdU-positive cells detected in the cochlea after MSC transplantation needs to be addressed. In the 3NP-treated rats without MSC transplantation, regenerating fibrocytes were confined around the area of apoptosis, which was clearly demarcated in the center of cochlear lateral wall. On the other hand, in the 3NP-treated rats with MSC transplantation, BrdU-positive cells were dispersed from the apical part to the central part within the lateral wall. Furthermore, morphology of BrdU-positive cells was different from neighboring fibrocytes of host tissue in both the apical part and the central part (especially in apical part as shown in Figure 4F). These findings indicate that most of BrdU-positive cells detected within the lateral wall were MSC-derived cells. However, there remains a possibility that a part of BrdU-positive cells around the area of apoptosis may be regenerating fibrocytes taking up BrdU from grafted MSCs. This question will be answered by future studies using MSCs with stable expression of green fluorescent protein by transfection of lentivirus-green fluorescent protein as donor cells.

In this study, we demonstrated that MSC transplantation into cochlea damaged by an acute energy shortage caused a significant improvement in hearing. In particular, the recovery ratio of the ABR threshold at 40 kHz was ~23% higher in the 3NP-treated rats that showed invasion of the lateral wall by MSCs than in 3NP-treated rats without MSC transplantation. This hearing recovery is thought to be caused by the supplement of fibrocytes differentiated from transplanted MSCs in the lateral wall in the basal and middle turn of cochlea. There may be an alternative possibility that the invaded MSCs induced the fibrocellular regeneration in the injured area in lateral wall. In the cochlea, the apical turn receives low-frequency sound and basal turn receives high-frequency sound such as ultrasound at least 80 kHz in rat. The cochlear region, which receives 40 kHz sound, in rat is thought to be around middle to basal turn. In this study, a number of BrdU-positive cells were found in the basal turn including the hook region, as shown in Figure 4, and this might result in the higher recovery ratio shown in 40 kHz. Without therapeutic intervention, the ABR thresholds for 40 kHz showed no improvement between 14 and 42 days after 3NP administration, suggesting that hearing loss for high-frequency sound was permanent. Thus, the MSC transplantation proved to be an effective therapy for this permanent hearing loss.

Because the vehicle injection instead of MSC suspension aggravated ABR thresholds at high frequencies, accelerated hearing recovery by MSC transplantation was considered to be induced by the effect of transplanted MSCs but not by the effect of surgical manipulation. We assume that the aggravated ABR thresholds at high frequencies may be caused by washout of secreted growth factors within the perilymph. The difference in the effects on ABR thresholds at high and low frequencies may be explained by the distinct distances from the semicircular canals where perilymphatic perfusion was

conducted. It is likely that the washout effect of perilymphatic perfusion was bigger in the high frequency area than in the low-frequency area because the high-frequency area is located closer to the semicircular canals.

Recently, stem cell transplantation directly into the inner ear has been reported in several animal experiments<sup>38,39</sup>; however, data demonstrating successful improvement of hearing after these transplantations have not been reported. In addition, few reports have shown any convincing evidence that transplanted cells have invaded the injured region and repaired the structure and function. The failure to improve hearing in the previous studies may be related to the surgical methods used to deliver stem cells into the cochlea. In this study, we transplanted MSCs by cell perfusion from the lateral semicircular canal with drainage to the posterior semicircular canal to minimize the surgical effects on the cochlea. This method is similar to a recently reported technique that demonstrated the integrity of hearing function after delivery of stem cells to the inner ear<sup>40</sup> and confirmed that the operation produced no significant hearing defects in normal control rats.

Bone marrow MSCs have greater advantages for clinical use in human patients than other multipotential stem cells, such as embryonic stem cells because MSCs can be collected from the patient's own bone marrow for an autologous transplantation with little physical risk, no rejection risk, and few ethical problems. In the present transplantation, many MSCs were confirmed to have invaded the lateral wall and to have contributed to recovery of hearing loss despite transplantation between different rat strains. Therefore, we expect that autologous transplantation of bone marrow MSCs would be even more effective in treating hearing loss caused by injuries to the cochlear fibrocytes. In addition, significant improvement of hearing by MSC transplantation between different rat strains indicates a possibility of allogenic transplant. Even temporary effects by allogenic transplant may cause difference in the final outcome of hearing recovery by promoting regeneration or viability of host fibrocytes during acute period of injury.

This is the first report demonstrating that MSC transplantation improves incomplete hearing recovery with evidence that transplanted MSCs actually invaded the injured area and contributed to the structural reorganization of the injured cochlea. Cell therapy targeting regeneration of the cochlear fibrocytes may therefore be a powerful strategy to cure sensorineural hearing loss that cannot be reversed by current therapies.

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