Hearing aids with external receivers: Can they offer power *and* cosmetics?

By Michael Hoen and David Fabry

The design of hearing solutions for people with moderate to severe hearing loss (HL) traditionally encounters the trade-off between form and function, appearance and performance. That is, patients typically must sacrifice cosmetics and/or ease of use to obtain devices that can provide them with adequate gain and output. Conversely, larger hearing aid (HA) styles may provide sufficient gain, yet reduce patient satisfaction along a number of other variables.

In fact, compared with patients with milder losses, persons with moderate to severe sensorineural HL are less satisfied with their hearing aids along a number of dimensions,[1] including:

(1) feedback: 11% less satisfied (than users with milder HL)
(2) overall clarity of sound: 6% less satisfied
(3) naturalness of sound: 10% less satisfied
(4) cell phone (14%) or telephone use: 6% less satisfied
(5) localization of sound: 12% less satisfied
(6) speech understanding in noise: 10% less satisfied

As far as cosmetic or ergonomic aspects are concerned, power users also typically miss the benefits of smaller, "invisible" device styles. Higher amplification levels are still limited to behind-the-ear (BTE) or full-shell in-the-ear (ITE) devices, causing people with more severe HL to miss the everyday advantages of smaller completely-in-the-canal (CIC) or mini/micro BTE device styles that have gained popularity in recent years. In fact, although open-fit devices for use with reduced-diameter tubing, large vents, and mini/micro BTEs now comprise over 15% of the US market, they do not provide an adequate gain/output solution for patients with moderate-to-severe hearing losses.

This paper will address a number of technical issues related to hearing aid development for users who have higher gain expectancies but don't want to compromise with esthetics: The questions we will address include:

(1) What are the technical reasons related to lower satisfaction and benefit from hearing aid use by patients with moderate to severe sensorineural hearing loss?

(2) What devices have external receivers and what are the purposes of that design?

(3) Do patients prefer and/or perform better with these types of devices than with existing technology?

ITES VS. BTES: A CHOICE BETWEEN APPEARANCE AND PERFORMANCE?

From a consumer's point of view, the selection of an intra-instrument (a hearing aid worn in the ear or in the ear canal) is mainly a matter of cosmetics. Intra-instruments are perceived as being cosmetically superior because they are small, and thus can be at least partially hidden inside the ear canal. However, from the fitter's point of view, ITEs can provide other advantages, such as an improved high-frequency response[2] and/or a potential reduction in the occlusion effect (see below).

But, intra-devices also have a disadvantage: They are small. Small size is associated with an increased susceptibility to feedback effects, because the maximal distance between microphone and receiver is limited and because the relative spatial arrangement of those two components is constrained by the spatial configuration of the earmold. Also, the small size of the ITE housing doesn't allow the use of larger receivers or larger battery sizes that are better adapted to generating higher gain levels and to handling numerous signal processing algorithms, such as feedback cancelers or anti-reverberant systems that are mostly needed in power instruments.

These disadvantages appear to be associated with the recent appearance on the market of BTEs with micro-housings that allow for significant cosmetic improvements. These instruments are a major cause of the steady increase in BTE sales in recent years.[3,4] But again, due to lack of space in micro-housings, these instruments are rarely suitable for customers with moderate-to-severe HL.

So do consumers with moderate to severe HL really have to choose between cosmetics and performance? And why does achieving gain actually require space?

NATURAL LIMITS OF AMPLIFICATION

The main limit to amplification is imposed by the electromechanical properties of receivers. Receivers contain a moving metallic armature that translates alternating electrical bursts into mechanical air pressure vibrations. This process admits a limit imposed by the maximal amplitude of the armature's movement and receivers will peak-clip as the amplitude of the sound to generate gets too high. In order to push this limit, one must use larger receivers and/or rely on greater power consumption, which requires the use of a larger battery size. Either approach runs into the same final space limitation issue.

Space restrictions limit the use of internal instruments in place of traditional BTE devices if gain is the more important consideration. Moreover, in a BTE design, the sound has to be conducted via tubing from the receiver to the ear canal, which creates resonance effects in the output sound and adds peaks to the frequency response. These peaks in the gain-frequency response alter sound quality as well as speech comprehension,[5] and also increase the likelihood of the hearing instruments to generate feedback whistles. Thus, lack of space, which results from addressing the cosmetics issue, has direct implications for the quality of sound and the susceptibility of these instruments to feedback effects.

Feedback effect

The feedback effect (FE) is a sound oscillation created by leakage of amplified sounds at the receiver level back into the microphone. This sound gets re-amplified in an endless loop, resulting in a particularly strong and annoying whistle in the HA.[6] Among the factors that can modulate the establishment of a feedback loop, figure gain and distance are the most important.

Gain plays a crucial role in the appearance of FE because as gain increases so does the sound pressure level (SPL) in the ear canal. As a result, more sound can potentially feed back into the microphone and get into the endless loop. This is why feedback is such an important issue in instruments that must provide high levels of amplification.

The second factor influencing FE is the spatial separation between microphone and receiver. In order for sound leaking at the level of the receiver or tubing to feed back into the microphone and get re-amplified, the distance between the receiver and microphone must be sufficiently short. Unluckily, this is always the case in traditional hearing instruments designs (See Figures 1 and 2).

One way to remove FE would be to hermetically seal the tubing to the receiver and the earmold to the ear canal so that absolutely no sound could leak from the tubing or earmold. However, this would lead to dramatic occlusion effects.

The occlusion effect

The occlusion effect (OE) results from improved audibility of the bone-conducted (BC) compounds of sounds, particularly in the low frequencies (LF), when the external ear canal is occluded. This causes listeners to be dissatisfied with the quality of self-generated sounds such as chewing, yawning, and, most importantly, their own voice.[7]

The importance of the OE was observed to decrease with the deepness of insertion of earmolds.[7,8] This is related to the preferential direction that BC sounds take inside the ear canal. If insertion remains close to the canal's entrance, BC sounds will travel preferentially in the canal to the cochlea, and will be perceived. But if the insertion is deeper, BC sounds will travel mostly toward the end of the canal and so will have less effect on perceived sounds.[9]

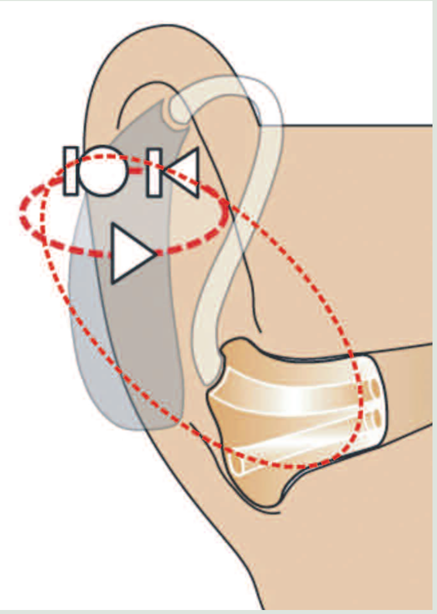

Figure 1. *Small and multiple feedback loops in a BTE design.*

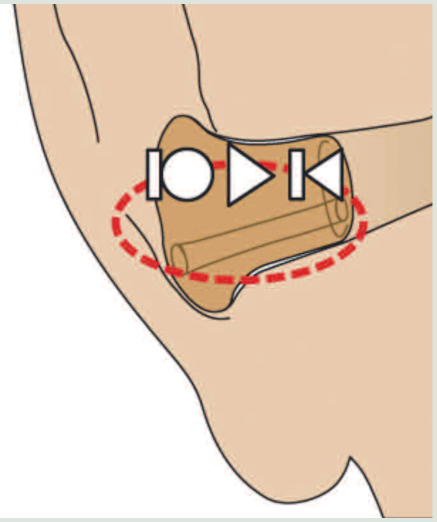

Figure 2. *The small feedback path in an ITE design.*

Venting

The relationship between the occlusion and feedback effects is dictated by the size of the vent used in the earmolds.[7,10-13] Indeed, one way to reduce the OE is to increase the size of the vent in the earmold. However, this also increases the sound impedance of the vent, causing increased LF leakage and decreased maximum gain before feedback, particularly in the high frequencies (HF). Thus, one would have to compensate for an increase in vent size by a decreased gain in the HF.

Diminishing the OE by increasing the size of the vent in traditional ITEs or BTEs might therefore end up reducing the availability of relevant HF cues and thus hinder speech comprehension. For many patients, the decrease in the OE is limited by the acceptable loss of intelligibility accompanying the increase of vent diameter. This represents a compromise that HA wearers usually have to make. However, the consequences are especially serious for users who require high gain.

What solution could address all these issues together. Is there a way to provide power users with the best of two worlds, cosmetic and comfort advantages along with sufficient gain and satisfying sound quality?

A TECHNICAL SOLUTION: TAKING THE RECEIVER OUT

What if we take the receiver out of the housing of a BTE to gain space at this level and insert it directly in the ear canal? The idea of designing devices with external receivers is far from new. The first instruments with external receivers in the ear canal were built in the late 1970s in Australia. But today, in this age of mini, micro- or even nanoturization and advanced digital technology, how great might be the benefits of this "good old" idea?

A quick market overview shows that a significant number of manufacturers have recently introduced new devices using the external receiver technology (see Table 1). What can also be seen is that this trend was actually pushed by the objective of fitting mild to moderate HL, mainly with open fits. Thus, the main purpose of these devices is to provide high cosmetic appeal as well as easy, user-friendly fittings (open, soft domes) that result in increased spontaneous satisfaction. At the time this manuscript was written, only one manufacturer (Phonak, highlighted in Table 1) was using the advantages of this design both for cosmetic and amplification interests.

Table 1. *Main technical specifications of hearing instruments based on the external receiver design currently available on the market. (Based on public data, not necessarily exhaustive).*

Manufacturer *Product (Line)*	SeboTek *720 PAC*	Hansaton *Leonardo Natural*	Oticon *Delta 8000*	Interton *Bionic Shape Twin*	Vivatone *Entré*	Phonak *microPower*
Market Introduction	2003	Jan. 2005	Feb. 2006	2006	Apr. 2006	Apr. 2006
Channels number	4	16	6 or 7 *	32	2 to 4 **	16
Frequency Range (Hz)	<200 to >8000	250 - 8800	200 - 8000	200 - 8000	500 - 4000	100 - 7000
Suggested Fitting	Open or Closed Domes	Open Domes	Open or Closed Domes	Open Domes	Open Domes	Custom Shells
Soft Domes Custom Shell	Yes No	Yes No	Yes No	Yes Yes	Yes No	Yes *** Yes
Target HL range Low frequencies High frequencies	mild-to-moderate 80 dB HL 90 dB HL	mild-to-moderate 40 dB HL 75 dB HL	mild-to-moderate 30-70 dB HL 70-80 dB HL	mild-to-moderate 70-80 dB HL 80-100 dB HL	mild-to-moderate 50-70 dB HL 80-90 dB HL	moderate-to-severe 100 dB HL 110 dB HL
Directionality	Programmable Polar Response	Automatic and Adaptive	Automatic and Adaptive	Automatic and Adaptive	Automatic	Automatic and Adaptive
Noise Canceller Operating channels	None -	Yes 4	Yes 6 to 7 *	None -	Yes 2 to 4 **	Yes 16
Feedback Canceller	Notch filter	Phase Canceller	Phase Canceller	Phase Canceller	Phase Canceller	Phase Canceller
Data Logging	No	No	Yes	No	No	Yes
Automatic Telephone Program	No	Yes	No	No	No	Yes

* Depending on selected dome ** Depending on model *** Only for demonstration purpose

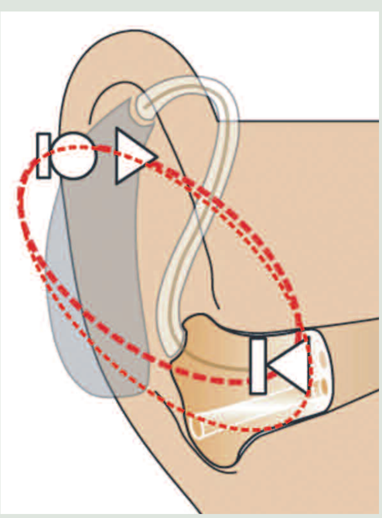

Figure 3. *The diameter of the feedback loop is naturally increased in the CRT design.*

Instruments with external receivers: What they are

In instruments with external receivers, the core components of the HA are left in a standard BTE housing while the receiver is mounted on a soft dome or a custom shell inserted in the ear canal (see Figure 3). Using an external receiver saves space in the main housing of the instrument, so the BTE part can be dramatically reduced in size. The BTE part of an instrument with an external receiver can be reduced to a 2-gram micro-housing that in most wearers disappears behind the pinna.

The ITE part containing the receiver can be inserted deeply in the ear canal. A very slim tube containing wires serves to connect the BTE and ITE parts. In power applications, custom shells can allow for individualized fitting, while still offering enough space for a large receiver (i.e., larger than in micro-BTEs), with the device remaining extremely discreet. Thus, the cosmetic aspect of the appearance vs. performance dilemma seems to potentially disappear behind these advantages.

However, the list of advantages that external receivers can provide doesn't stop here. They can also break the sound barrier!

Less feedback and occlusion with more gain

Devices that rely on canal receiver technology (CRT) disrupt the usual relationship among occlusion, feedback, gain, and venting. First, the placement of the receiver in the canal increases the distance between microphone and receiver (Figure 3); CRT devices thus exhibit a natural improvement in resistance to feedback. Moreover, the use of a wired connector eliminates the risk of sound leaking out at the tubing level, which also helps increase feedback resistance.

Second, the occlusion effect can be reduced by placing the earmold deep enough that bone-conducted sounds are directed out of the ear canal. This can increase spontaneous acceptance and wearing comfort, while also providing more natural self-generated sounds (e.g., the wearer's voice).

Third, placement of the receiver in the canal reduces the residual volume of the canal, thus naturally increasing the sound pressure level in the canal compared with other standard fittings. This allows for outstanding amplification opportunities even when larger vents are used. Figure 4 presents modeling data of achievable gain levels depending on the distance between receiver and microphone and the diameter of the vent. These data clearly show that for a certain target gain to be achieved (here the red 60-dB curve), the vent size can be almost twice as big in a CRT device as in a classic ITE instrument, thus allowing for increased comfort. So, while achieving sufficient gain, CRT devices have a naturally improved resistance to feedback effects and allow the occlusion effect to be reduced by the use of larger vents for improved sounding and fitting comfort.

Improved sound quality

Figure 5 shows the frequency response curve of a CRT device recently introduced by Phonak. It shows a very broad frequency range with limited peaks compared to classic BTEs. The smoothness of the frequency response curve is thought to ensure improved sound quality.[14-17] Output increases, especially in the high frequencies, which allows for a very reliable restoration of speech cues. This smoothness of the frequency response occurs in part because the sound is transmitted through a wired connector, not an air-filled tube.

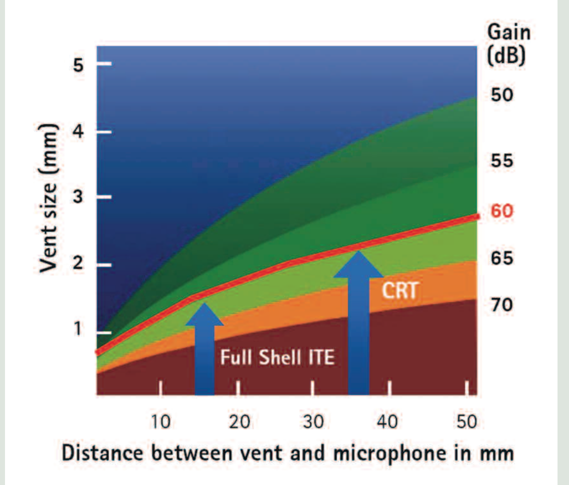

Figure 4. *Relation between vent size (y-axis), distance between vent and microphone (x-axis), and gain. Modeling data for a target gain of 60 dB (red curve).*

TESTING OF CRT DEVICES

To determine the sound quality levels that can be achieved in CRT devices we ran a study that included subjective rating of sound quality as well as objective measurements of performance on a speech-in-noise comprehension test, the OLSA.[18] In this experiment, we compared three commercially available devices. The goal of the study was to compare the performance of CRT devices with that of a traditional but efficient BTE instrument. The traditional hearing aid was a 311 BTE instrument (Phonak Eleva), while the two CRT devices were the Phonak microPower, an instrument with an external receiver designed for patients with moderate-to-severe HL, and another CRT device, selected to theoretically exhibit performances close to those of microPower (hereinafter designated as "x-Receiver Device").

Eighteen experienced HA users, aged 39 to 80 years (mean = 65.2 +/- 11.4 years) and with moderate-to-severe high-frequency sensorineural HL, took part in the study. All subjects performed the different tests randomly fitted with the three devices on three separate testing days. For the speech-in-noise adaptive test, both omnidirectional and directional microphone modes were tested.

Subjective rating of sound quality

The hearing-impaired volunteers were asked to judge the sound of soft classical music as a general indicator of the sound quality of the devices in the study. We selected a situation in which the hearing aid wearers would demand a high level of sound quality. The subjects were asked to judge the sound as being either "Echoic," "Dull," "Hollow," "Sharp," or "Natural."

As shown in Figure 6, the three tested devices received few negative ratings, and most participants judged the classical music as sounding natural. The best results were obtained for the microPower device; 88% of the responses rated its sound as natural. Next came the 311 BTE (72% natural) and then the x-Receiver Device (60%). Statistical assessment of these observations using a chi-square test did not reveal any significant difference among the three tested devices. Thus, it appears, devices with external receivers can reach subjective sound naturalness levels very similar to those observed with a 311 BTE.

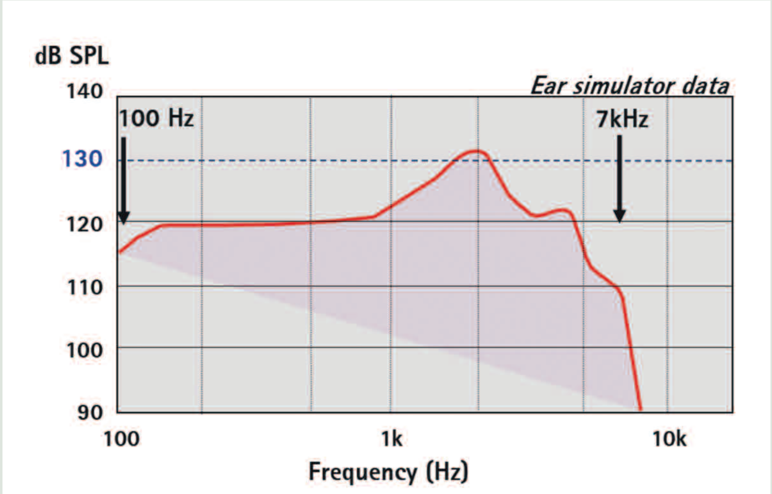

Figure 5. *MPO shape of the Phonak microPower CRT device. Smooth high output levels can be achieved over a broad frequency band.*

Objective measurement

Along with collecting subjective observations, we conducted objective behavioral measurements in a challenging situation by having the volunteers take an adaptive speech-in-noise comprehension test. Subjects were asked to repeat sentences delivered together with a concurrent noise at a variable signal-to-noise ratio (SNR). The test adapts the SNR according to subjects' online behavior. The SNR progressively stabilizes around the speech reception threshold (SRT) of the participant, defined as the SNR at which subjects have a comprehension score of 50%.

Observations and statistical analyses (repeated-measures ANOVA – $\alpha = 0.05$) of results (Figure 7) showed that all three devices behaved globally quite well. For each hearing aid, the speech-in-noise results were better in aided conditions (omni- or directional) than in the unaided condition. But the results for the individual types of device differed somewhat. We observed a significant main effect of device type ($F[2, 24] = 13.09$; $p<0.001$), with the 311 BTE device globally showing the best results with an average over microphone conditions SRT of -3.6 dB. Next came the microPower (SRT = -3.3 dB) followed by the x-Receiver Device (SRT = -1.5 dB).

Statistical post-hoc tests (LSD test, $\alpha = .05$) performed on the main effect showed that the difference between the 311 BTE and microPower was not significant ($p = 0.55$), but that the x-Receiver Device did perform statistically significantly worse than the 311 BTE ($p<0.001$) and

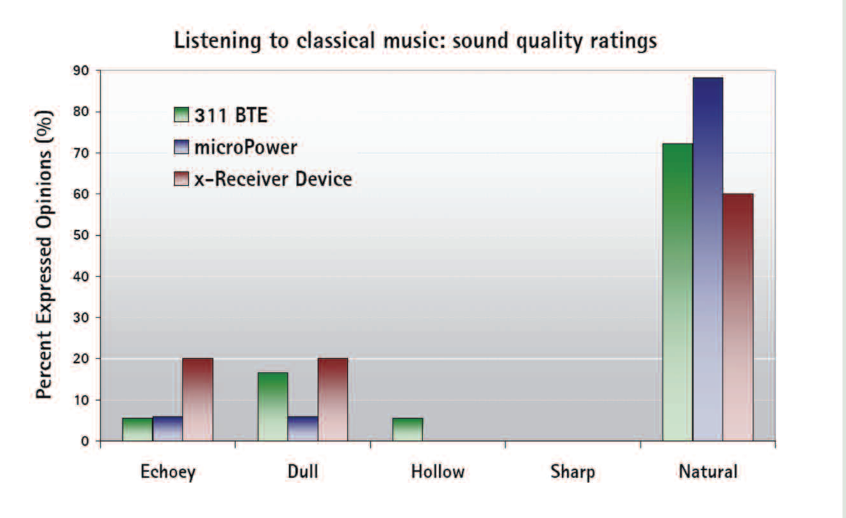

Figure 6. *Subjective quality ratings given by subjects listening to soft classical music with a 311 BTE, microPower, or the x-Receiver Device.*

the microPower device (p<0.001) together.

This final result demonstrates that very high levels of sound quality and high-fidelity amplification of high frequencies speech cues can be achieved in CRT devices. This was true in both the omnidirectional and the directional mode (second-level interaction non-significant, ($F [2, 24] = 0.008$; $p = .99$), showing that external receiver technology can also account for the expectations of patients with severe-to-profound hearing loss regarding directional microphones.[19,20]

DISCUSSION AND CONCLUSIONS

It should be noted that not every instrument with an external receiver can match the speech-in-noise capabilities of 311 devices. Also, note that the x-Receiver Device used in this study operates on only four channels, whereas the two Phonak devices, the benchmark 311 BTE and microPower, operate on 16 channels. That allows for better restoration of speech cues and better high-frequency fine-tuning of the broadband response. Among other factors including device-specific signal processing strategies as well as different additional signal processing algorithms, this may account for the global difference observed here.

In this paper, we have shown that it is possible for devices with external receivers in the canal to offer the best of two different worlds to consumers with moderate-to-severe HL. This is because these types of devices can offer the cosmetic and comfort advantages of intra- or micro-devices while also providing sufficient gain and maintaining very high sound quality that ensures auditory compensation for these users that is just as good as what an excellent 311 BTE device can offer.

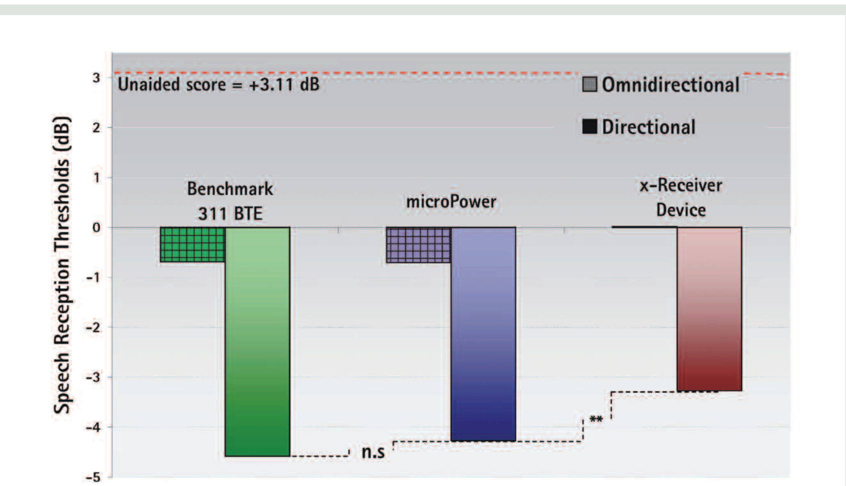

Figure 7. *Results obtained on an adaptive threshold speech comprehension in noise test with the three compared devices.*

Michel Hoen, PhD, is Coordinator of International Field Studies in the Audiology and Training Competence Center at Phonak AG headquarters in, Stafa, Switzerland. **David Fabry**, PhD, is Vice-President, Professional Relations and Education, Phonak Hearing Systems, Warrenville, IL. Readers may contact Dr. Hoen at Michel.Hoen@phonak.com.

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