

# HOW TO USE PROBE MICROPHONE MEASURES WITH FREQUENCY-LOWERING HEARING AIDS

by Joshua M. Alexander, Ph.D., CCC-A.

**If** you have started reading this article, then the chances are good that you already believe in the value of probe microphone measures for verifying that the hearing aid output provided to the patient sufficiently meets the targets of a validated prescriptive rationale (NAL or DSL). In that we ultimately seek to make speech information at each frequency that reaches the patient's cochlea both audible and comfortable over a range of levels spanning from soft to loud, the goals for amplifying with frequency-lowering hearing aids are no different from those for amplifying with conventional hearing aids. Therefore, it is reasonable to assume that the best outcomes with a frequency-lowering hearing aid will also be achieved when the real-ear aided output after lowering meets prescriptive targets *over the widest bandwidth possible* (not to be confused with input bandwidth). It is important that we think in terms of output and not gain since the prescriptive targets for gain account for the fact that the input speech spectrum progressively decreases as frequency increases. Because the high-frequency speech energy (the **source band**) that is moved may have a lower intensity than the speech that would normally occupy the lower-frequency region where it is moved to (the **destination band**), the gain necessary for audibility may be higher than the prescribed gain. However, there is no evidence that it should be different from a standard fitting when expressed in terms of output.

What makes frequency-lowering amplification different from conventional amplification is the content of the information that reaches the cochlea. While there is no hard evidence as to what this content should be, Alexander (2013a, 2013b; see also Mueller *et al.*, 2013) provides some general suggestions for different audiometric configurations. Scollie (2013) also makes some specific suggestions for using calibrated recordings of /s/ and /ʃ/ as input stimuli for making decisions about choosing frequency-lowering settings that move /s/ into a region of audibility while simultaneously maintaining a spectral distinction with /ʃ/. Both suggestions emphasize that the frequency-lowered content should both be audible and usable (does not introduce new confusions between speech sounds). While probe microphone measures can help verify audibility, usability will depend on the manufacturer-specific method used for frequency lowering. Despite differences between techniques, there are a few general guidelines for using probe microphone measures to help minimize the risk-benefit ratio associated with their use.

## PRIMARY GOALS FOR PROBE MICROPHONE MEASURES WITH FREQUENCY-LOWERING HEARING AIDS

1. The audible bandwidth after frequency lowering is activated should not be less than it was before it was activated. In other words, frequency lowering should not restrict the existing audible bandwidth.
2. The lowered information should be audible.
3. The 'weakest' frequency lowering setting should be used to accomplish your objective.
  - a. Generally, settings become weaker as the destination band is moved higher in the audible bandwidth, as indicated by a higher **start frequency** (sometimes called,  $F_{\min}$  or **cutoff frequency**).
  - b. For techniques that use **frequency compression**, weaker settings have lower **compression ratios**.

The first goal will be reviewed in more detail. How to accomplish the second and third goals is less obvious because probe microphone measures only show the signal after lowering, and do not provide information about where the signal originated. To help in this regard, the author has developed a set of online tools, the *Frequency Lowering Fitting Assistants* ([www.tinyURL.com/FLassist](http://www.tinyURL.com/FLassist)), which can be used with a desktop computer or mobile device. For most of the manufacturers who implement frequency lowering, these tools display the **frequency input-output functions**, and for a given output frequency (namely, the **maximum audible output frequency or MAOF**) they calculate the approximate input frequency. These estimates are based on thousands, or in some cases, tens of thousands, frequency-specific measurements for each technique (about 100 per setting). Clinicians can then plot these functions for the different settings to see what consequence they will have on the content of the audible signal after lowering.

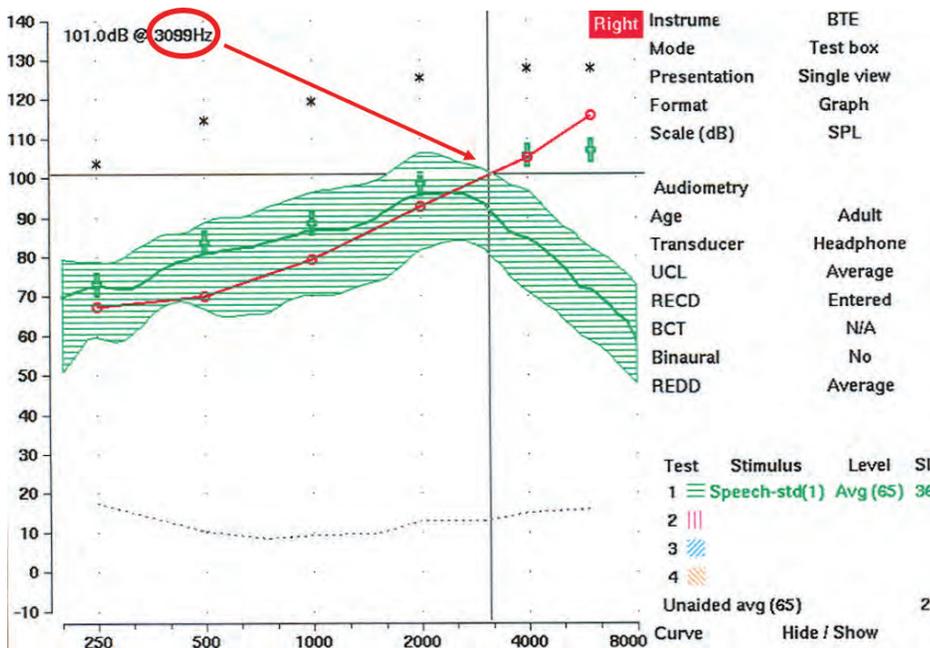
The Frequency Lowering Fitting Assistants are ideally suited for providing information about how much of the amplified speech falls within the audible bandwidth after lowering. While not necessarily recommended, they can also help maximize the audible input frequency if that is the objective in Step 3. More than likely, the objective will be less clearly defined and may involve an outcome measure, or a general desire to improve the detection or identification of **fricative** while maintaining perception of the speech sounds the patient can hear more normally using conventional amplification. Achieving these general objectives is akin to a balancing act in that the clinician is trying to provide enough new

high-frequency information without ruining the ‘old’ low-frequency information (see Alexander 2013a for a more in depth discussion about these tradeoffs and specific suggestions for some of the techniques). The Frequency Lowering Fitting Assistants and a little bit of background knowledge on speech acoustics can *empower clinicians* (and researchers!) by allowing them to make *informed decisions* about which speech cues in the existing audible bandwidth will be affected and about which cues will be made audible with the different settings.

With these goals in mind, the general protocol for using probe microphone measures with frequency-lowering hearing aids is as follows.

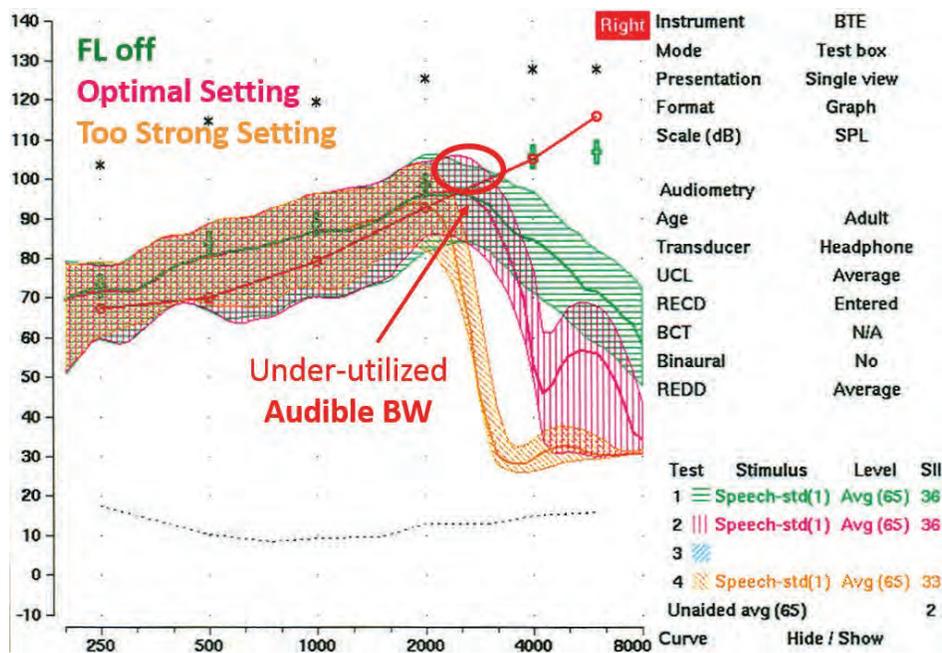
## PROTOCOL FOR USING PROBE MICROPHONE MEASURES WITH FREQUENCY-LOWERING HEARING AIDS

1. Deactivate frequency lowering and fit the hearing aid to prescriptive targets using probe microphone measures as you would normally do for a conventional hearing aid. *See Figure 1.*
  - a. Find the maximum audible output frequency, MAOF, which is the highest frequency in the real-ear aided output that exceeds threshold on the SPL-o-gram (Speechmap®). This point can be defined somewhere between the average and peaks of the amplified speech range; the exact point is subject to debate so consistency between measures is most important.
2. Activate frequency lowering and use the Frequency Lowering Fitting Assistants to position the lowered speech within the audible bandwidth (MAOF) while not reducing it further. *See Figure 2.*
  - a. Most of the source region should be audible.
  - b. Avoid too much lowering, which will unnecessarily restrict the bandwidth you had to start with and reduce intelligibility.
3. With the chosen settings activated, verify that the MAOF is reasonably close to what it was when it was deactivated in Step 1. *See Figure 3.* Sometimes it may be slightly higher, which is O.K. If it is unacceptably lower, try increasing gain in the channels near the MAOF. Rarely, a weaker setting will have to be chosen in order to maintain the audible bandwidth. If a better estimate of the maximum audible input frequency is desired, the value for MAOF from this step should be entered into the Frequency Lowering Fitting Assistants.

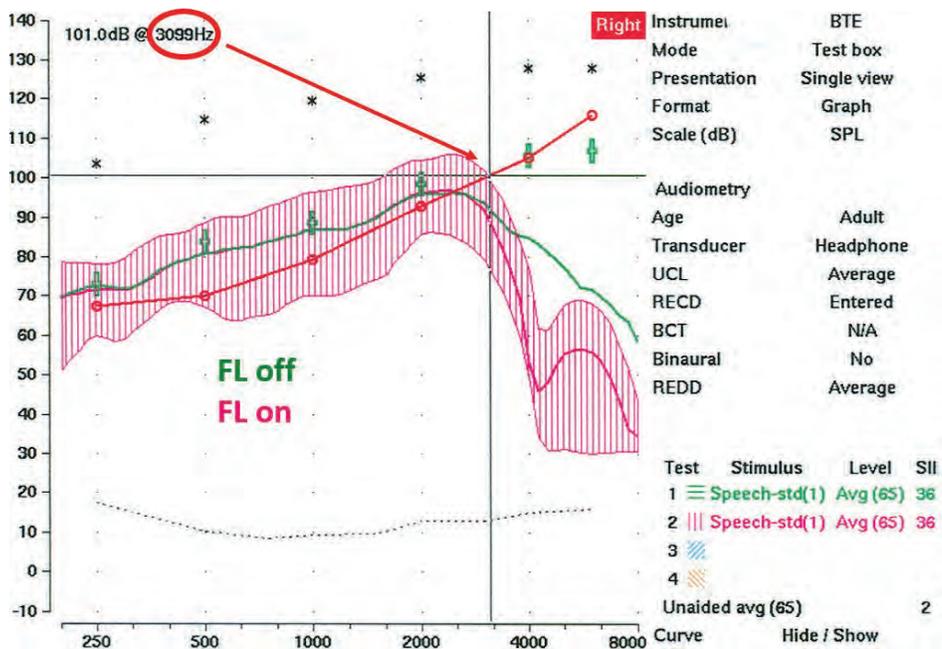


**Figure 1.** SPL-o-gram showing the first step in the protocol for using probe microphone measures with frequency-lowering hearing aids, in which frequency lowering is deactivated. Thresholds in dB SPL are represented by the red line and circles. The amplified long-term average speech spectrum or real-ear aided response (REAR) is represented by the green region, with the thick line and crosses corresponding to the average, and with the line top and bottom lines corresponding to the peaks and valleys, respectively. The highest amplified frequency (somewhere between the average and peaks) that crosses the threshold line is denoted the Maximum Audible Output Frequency (MAOF). In this example, the MAOF as indicated by the red arrow and black crosshairs is about 3099 Hz.

There is at least one caveat related to differences between the classes of frequency-lowering techniques. With **frequency compression** techniques, which simply ‘squeeze’ the bandwidth of the source, there is, more or less, a one-to-one relationship between input and output frequencies so that if the relationship is known, the clinician can infer the levels of the input speech spectrum by looking at the amplified output and using a tool like the Frequency Lowering Fitting Assistants. However, with **frequency transposition** techniques, which mix the lowered and un-lowered speech signals, even if the relationship is known, the clinician cannot tell what the contribution to the overall speech levels is from each signal alone. For example, if the energy for /s/ is transposed to a region dominated by



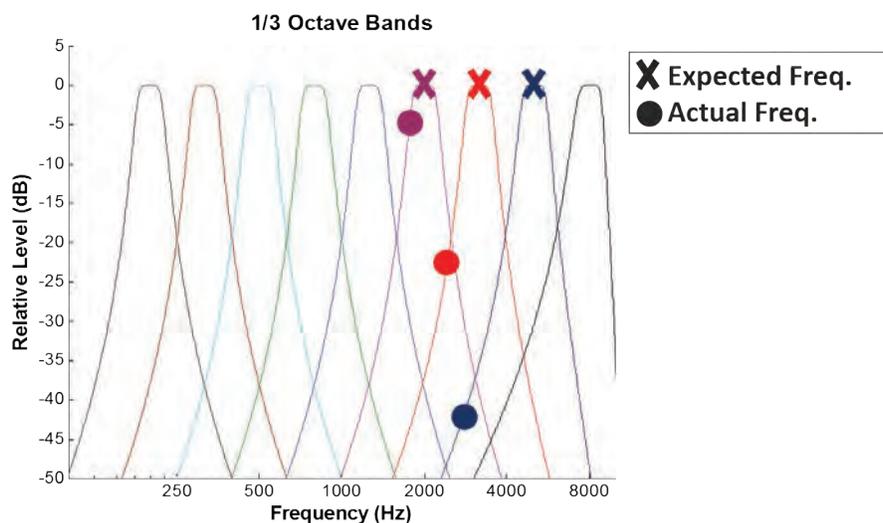
**Figure 2.** SPL-o-gram showing the second step in the protocol for using probe microphone measures with frequency-lowering hearing aids. Frequency lowering (FL) is activated and different candidate settings are explored. The REAR from Step 1 (Figure 1) without frequency lowering is displayed in green for purposes of comparison. An example of a frequency-lowering setting that is too strong and unnecessarily restricts the audible bandwidth from Step 1 is shown by the orange REAR. This setting results in a range of under-utilized audible bandwidth as indicated by the area circled in red. An example of a setting that might be considered 'optimal' from a finite set made available to the clinician by the programming software is shown by the magenta REAR.



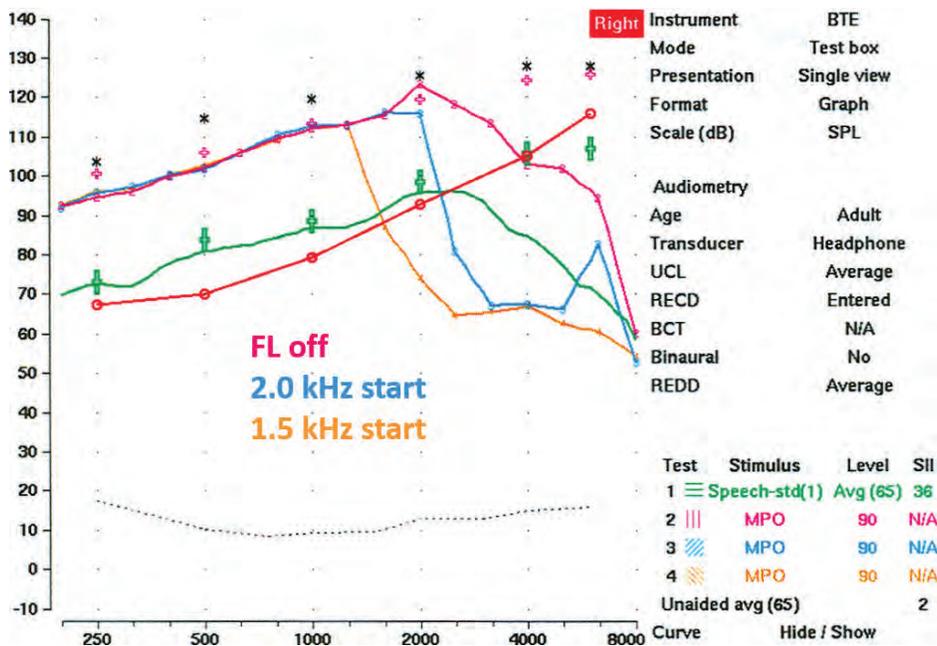
**Figure 3.** SPL-o-gram showing the third step in the protocol for using probe microphone measures with frequency-lowering hearing aids. The average amplified speech spectrum from Step 1 (Figure 1) without frequency lowering is represented by the green line for purposes of comparison. With the chosen frequency-lowering setting activated (magenta REAR, same as in Figure 2), the MAOF is 'verified' or checked to be sure that it is reasonably close to what it was when it was deactivated in Step 1. In this example, the MAOF (about 3099 Hz) as indicated by the red arrow and black crosshairs is unchanged between the first and last steps.

vowel energy, the long-term output levels measured at the lower frequencies might mostly reflect the contributions from the vowel, while the transposed /s/ might be completely inaudible. Even if the two were at the same level, this would only result in an increase of 3 dB, which would hardly be visually noticeable on most probe microphone system displays. Therefore, while the Frequency Lowering Fitting Assistants can indicate whether the transposed speech has been moved to a region where aided audibility is possible, they cannot specifically verify that the transposed signal is audible. To do this, the Audioscan® Veri-fit® by Etymonic Design Incorporated has designed special speech signals which contain the normal low-frequency information through 1000 Hz and then a single 1/3 octave band centered at one of four frequencies from 3150 to 6300 Hz. The basic idea is to remove the low frequency destination band and to isolate a limited number of high-frequency bands so that the observed low-frequency levels can be safely assumed to originate from the transposed source. While the frequency specificity and testable input bandwidth are limited with these signals, the clinician is encouraged to use them to the extent possible whenever a transposition-based technique is activated (see Alexander 2013a,b for a list of manufacturers that use transposition).

Finally, as with all hearing aids, maximum power output (MPO) needs to be verified for frequency-lowering hearing aids. However, with the current probe microphone systems, this requires a



**Figure 4.** Schematic showing the problem experienced when measuring MPO with frequency lowering activated. 1/3-octave analysis filters centered on the frequencies of different test tones in the MPO sweep are represented in different colors. The X's indicate the frequencies the probe microphone system expects to see for three input test frequencies above a hypothetical start frequency of 1500 Hz. The filled circles indicate the actual frequency for each of the three inputs after frequency lowering. The actual frequencies fall on the skirts of the analysis filters, therefore, output levels recorded by the probe microphone system become increasingly smaller for inputs above the start frequency.



**Figure 5.** SPL-o-gram showing the resultant MPO curves for different frequency lowering settings for the same example in Figures 1–3. The average amplified speech spectrum from Step 1 (Figure 1) without frequency lowering is again represented by the green line for purposes of comparison. The magenta curve is the MPO curve when frequency lowering is deactivated. This curve should be used when verifying MPO since the MPO curves generated with frequency lowering activated will begin to deviate from the actual output for frequencies above the start frequency as indicated by the examples shown in blue (2.0 kHz start) and orange (1.5 kHz start).

little bit of faith. The reason for this is that narrow filters centered at each MPO test frequency are used to measure the output from the hearing aid (Figure 4). Therefore, as test frequencies increase above the start frequency and become increasingly shifted by the hearing aid, they progressively fall outside the passband of the analysis filters. Consequently, MPO with frequency lowering activated will not be accurate since the output frequencies fall on the skirts of the filters, resulting in significantly decreased output levels as measured by the probe microphone system (Figure 5). Therefore, the best-recommended procedure for verifying MPO is to deactivate frequency lowering and then run the MPO pure tone sweep. We then have to assume that the output-limiting compression circuits used to manage MPO in the hearing aid behave the same way regardless of whether the input signal has been shifted in frequency or not. To date, there has been no evidence or reported clinical anecdotes to indicate otherwise. ■

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## GLOSSARY

**Compression Ratio:** With respect to frequency compression techniques, the parameter that determines the relationship between input and output frequencies, hence, the exact amount of frequency shifting and subsequent reduction in the source bandwidth. Higher ratios correspond to greater frequency shifts and lower output bandwidths. It is very important to note that nominal compression ratios are not comparable across manufacturers. For some manufacturers, the relationship between input and output frequencies as defined by the compression ratio can be expressed using a linear equation, for others it can be expressed using a nonlinear equation, and for others the relationship is indeterminate.

**Cutoff Frequency:** See “start frequency.”

**Destination Band:** The frequency range where information is *moved to* after lowering. It is sometimes also referred to as the ‘target band.’

$F_{\min}$ : See “start frequency.”

**Frequency Compression:** A class of frequency-lowering techniques whereby the source band is reduced in bandwidth as if it were squeezed so that the destination band is contained entirely within the source band. The ‘start frequency’ is like an anchor that does not shift. If the start frequency is non-zero, such that the input spectrum is divided into a lower region that does not experience frequency alteration and an upper region that is subjected to frequency lowering, the technique is often referred to as ‘nonlinear frequency compression’ or ‘NFC.’

**Frequency Input-Output Function:** A plot that shows where frequencies in the input signal (abscissa) are moved to in the output signal (ordinate).

**Frequency Lowering Fitting Assistants:** A set of online tools ([www.tinyURL.com/FLassist](http://www.tinyURL.com/FLassist)) that plots the frequency input-output functions for a wide range of manufacturer-specific frequency-lowering techniques. They are used to help visualize how information in the output signal is altered by the selection of different frequency-lowering parameters.

**Frequency Transposition:** A class of frequency-lowering techniques in which only a segment of the higher-frequency source band is resynthesized in the lower-frequency destination band, thereby allowing the information from the two bands to potentially mix in the final output. Compared to ‘frequency compression’ techniques, there is little to no overlap between the source and destination bands and the start frequency is subject to lowering.

**Frication:** Speech feature characterized by a high-frequency noisy spectrum that is produced by turbulence as air escapes through an incomplete closure somewhere along the vocal tract. While frication defines an entire class of sounds, the fricatives, it is also an important feature for the affricate and stop consonant speech classes.

**Maximum Audible Output Frequency (MAOF):** The highest frequency in the amplified speech signal that is audible. It is often used interchangeably with the term ‘audible bandwidth’ and may be defined by the average or peak levels in the speech dynamic range or somewhere in between.

**Source Band:** The frequency range where information is *moved from* before lowering.

**SPL-o-gram:** Plot used to display audiometric thresholds, loudness discomfort levels, the real-ear response for different speech levels and maximum power output, and prescriptive target levels all on a common scale (estimated dB SPL at the tympanic membrane).

**Start Frequency:** The lowest frequency in the source region.

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