FREQUENCY COMPOSITION™: A NEW APPROACH TO FREQUENCY-LOWERING

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Frequency-lowering has come a long way. Over time, the technique has evolved from a controversial feature to one that is gaining more and more acceptance. The evolution of frequency-lowering is one topic of this white paper. Other topics are its applicability in the case of cochlear dead regions and its potential for wider use. The discussion not only addresses the technical effect, but focuses as well on the audiological benefit. This paper also describes, in detail, Bernafon's new frequency-lowering system and its success in internal tests.

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Frequency-lowering shows new promise for overcoming high-frequency hearing loss.

New Potential for Success

Advances in technology have revived the old concept of "frequency-lowering". In the last few years, the number of frequency-lowering hearing instruments has indeed seen a sharp increase. This trend appears to reflect a change in the perception of the benefit.

In the past, frequency-lowering techniques were mainly seen as relevant for severe to profound hearing impairment. Currently, frequency-lowering seems suitable for wider use, extending to hearing aid users "who have less severe losses" (McDermott, 2010, para. 1). The reason is that frequency-lowering increases the patient's perceived bandwidth.

The idea of frequency-lowering is actually old, as Bentler (2010) confirmed: "The concept is not new – but the potential for success is" (para. 1). She bases her hope on new digital processing techniques. With their ready availability, frequency-lowering shows new promise for overcoming high-frequency hearing loss.

An Alternative in the Case of Cochlear Dead Regions

Bentler (2010) further noted that "The high-frequency sounds that hold much of the discrimination and clarity in speech sounds are often the least audible for persons with hearing loss" (para. 2). Normally, it is possible to restore audibility with the use of a hearing instrument. In some cases, however, high-frequency amplification provides only limited benefit. This phenomenon was the subject of a study from which Vickers, Moore, and Baer (2001) concluded, "Our data suggests that the key factor is the presence or absence of a dead region at high frequencies" (p. 1172).

The term "dead region" dates back to a publication by Moore, Glasberg, and Vickers (1996). It designates a region of the basilar membrane where the inner hair cells and/or neurons are no longer functioning. With respect to dead regions, Vickers et al. (2001) detail their findings, "Patients without a dead region at high frequencies will generally benefit from amplification of high frequencies, whereas patients with a dead region will generally not benefit" (p. 1172).

Dead regions thus have a great impact. Not only do they cause the loss of essential information and make it difficult to understand speech and hear some environmental sounds, but they also compromise the benefit of hearing instrument amplification. In this situation, the hope rests on the alternative approach: frequency-lowering.

The Evolution of Frequency-Lowering

Researchers realized early on that frequency-lowering might solve the problem associated with dead regions. The approach actually makes sense. Take high-frequency sounds that a patient fails to hear and relocate them to a lower frequency region where the patient's hearing is still intact. In this way, the sounds become audible again.

First attempts to implement a useful system date from the 1960s. At that time, however, the state of the technology prevented success. In a review monograph, Braida et al. (1979) concluded, "With only minor exceptions, the results of previous research on frequency-lowering have been negative" (p. 108).

A few decades later, the transition from analog to digital hearing aids generated a new wave of interest. For the first time, it became possible to offer frequency-lowering in a commercially available BTE hearing instrument. As a result, research efforts increased, producing implementations of frequency-lowering in several variants.

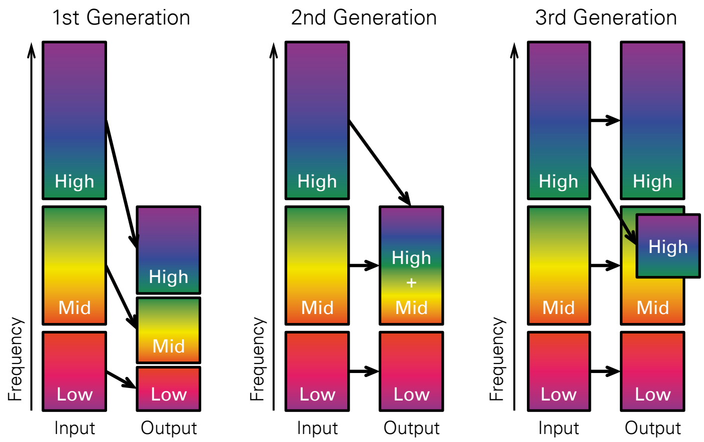

Figure 1: Variants of frequency-lowering – one example per generation

Variants of the third generation preserve the high-frequency signal components at the source location.

As shown schematically in Fig. 1, these variants trace three steps in the evolution:

1. Variants of the first generation (1990s) reduce the frequency of all signal components, across the entire frequency range: low, mid, and high. Typical designation: linear frequency compression.
2. Variants of the second generation (2000s) share two properties:
   - I. They reduce the frequency of signal components only in the mid and high frequencies.
   - II. They leave a void in the high-frequency range.

   Typical designation: non-linear frequency compression.
3. Variants of the third generation (2010s) feature three properties:
   - I. They reduce the frequency of signal components only in the high frequencies.
   - II. They preserve the high-frequency signal components at the source location.
   - III. They superpose the relocated signal components on those in the target location.

   Typical designation: spectral feature translation.

Experience with frequency-lowering systems has broadened the insight into their subtleties, but there are still open questions. For instance, efficacy was the main focus in the past, whereas the preservation of sound quality gained in importance over the years. In fact, systems of the first generation failed because they affected the low frequencies and thus overly degraded the quality of sound.

Another issue is the question of how to deal with the high-frequency signal components. For instance, Vickers et al. (2001) wrote, "For a patient with a dead region at high frequencies, there may be several benefits of reducing the gain at high frequencies" (p. 1174). In contrast, Cox, Johnson, and Alexander (2012) "recommend against limiting high-frequency gain prescription solely because a patient has DRs in one or two high-frequency regions" (p. 14).

The debate reflects the existence of two opposing risks: adverse effects in the case of dead regions vs. loss of cues in the case of remaining hearing. The debate also explains the step from second to third generation systems, i.e., removing vs. preserving high-frequency signal components. Currently, it seems best to offer a flexible solution in the fitting software. Such an option allows you, as a hearing care professional, to adjust the system according to your patients' needs.

Technical Effect and Audiological Benefit

The technical effect of frequency-lowering is easy to verify, but it is not so easy to verify the audiological benefit. Current measurement equipment, e.g. Audioscan Verifit, does indeed allow you to measure the improved audibility of high-frequency sounds in an objective way, at the patient's ear. Improved audibility, however, does not necessarily mean better speech understanding. The acoustic signal may actually sound strange, due to the relocated signal components. These signal components may as well distort or mask speech information in lower frequencies. So, in contrast to the intended benefit, it is also possible that frequency-lowering does harm.

Numerous studies confirmed the technique's potential to improve the intelligibility of speech.

The audiological benefit of frequency-lowering techniques has been the subject of numerous studies. To some extent, the studies produced inconsistent results. Overall, however, they confirmed the technique's potential to improve the intelligibility of speech in quiet. This improvement is mainly due to a better recognition of fricatives and affricates (Simpson, Hersbach, and McDermott, 2005; Robinson, Baer, and Moore, 2007; Glista et al., 2009). In a subsequent study, Bohnert, Nyffeler, and Keilmann (2010) found frequency-lowering beneficial even to speech in noise.

The studies raise some recurrent issues:

- The benefit of frequency-lowering varies: some patients benefit a lot, others not at all.
- Frequency-lowering requires a trade-off between improvement of speech intelligibility and acceptable degradation of sound quality.
- With respect to speech intelligibility, frequency-lowering exhibits contrasting properties: useful to unvoiced sounds, but potentially harmful to voiced sounds.
- The modified sound of a frequency-lowered signal calls for acclimatization.

The last two aspects interrelate with a system's mode of operation: fixed or adaptive. The objective of an adaptive mode is to operate on unvoiced sounds only, while leaving voiced sounds untouched. In this way, the adaptive mode attempts to avoid sound degradations. Due to its continual changes, however, the adaptive mode may be more difficult to acclimatize to than a fixed mode.

In short, when looking for a frequency-lowering system, consider the following points:

- To preserve sound quality, signal components below 1.5 kHz should remain unchanged;
- Gain in the high frequencies should remain unchanged – unless a patient benefits from attenuation;
- In contrast to an adaptive mode of operation, a fixed mode supports acclimatization;
- Speech tests reveal the extent to which a patient benefits from and acclimatizes to frequency-lowering.

Frequency Composition™ – a Third-Generation Approach

Frequency Composition™ is Bernafon's approach to frequency-lowering. As a third-generation approach, Frequency Composition™ preserves the high-frequency signal components at the source location and superposes the relocated signal components on those in the target location. With the preservation of high-frequency sounds, Frequency Composition™ maintains the hearing aid's 10 kHz bandwidth, which contributes to sound quality.

Frequency Composition™ is backed up in the fitting software Oasis. Oasis provides flexibility in configuring Frequency Composition™. In contrast to the default setting, Oasis allows you to reduce high-frequency gain if needed. Oasis also allows you to reduce the intensity of the relocated signal components, and thus to decrease or increase the effect of frequency-lowering gradually.

In a first step, Oasis analyzes the patients' audiograms and determines candidates for Frequency Composition™. Next, it determines individual choices of source and target frequency ranges. The procedure for selecting candidates is based on established principles (Baer, Moore, and Kluk, 2002; Vinay and Moore, 2007; Salorio-Corbetto, Baer, and Moore, 2012). For those not selected, Oasis still allows you to activate Frequency Composition™ manually.

Frequency Composition™ achieves substantial energy of fricative sounds to appear in the target location, while minimizing adverse effects on vowels.

The selection of the source frequency range also takes signal properties into account. In particular, Frequency Composition™ exploits the differences in spectral shape of fricatives (rising spectrum) vs. vowels (falling spectrum). Frequency Composition™ thus achieves substantial energy of fricative sounds to appear in the target location, while minimizing adverse effects on vowels. In this way, Frequency Composition™ preserves sound quality and, together with a fixed mode of operation, also supports acclimatization.

What matters at the end of the day is how the properties translate into benefits. In this respect, frequency-lowering raises three questions:

1. Does a system improve the discrimination of high-frequency phonemes?
2. Does it maintain the quality of sound?
3. Does the selection of candidates work reliably?

For Frequency Composition™, the answer to all three questions is yes. The results of in-house tests are shown in Fig. 2.

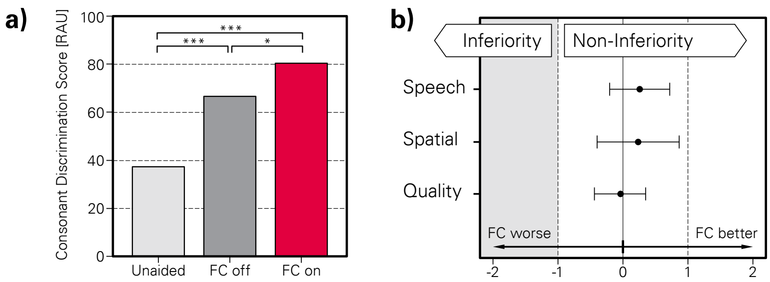

Figure 2: Test results on Frequency Composition™ (FC); a) consonant discrimination test, b) SSQ ratings

Improvement of High-Frequency Phoneme Discrimination
Fig. 2a shows the results of a consonant discrimination test, based on logatoms. Logatoms have a vowel-consonant-vowel (VCV) structure. The consonants used in this test were the voiceless fricatives /s/, /f/, and /ʃ/ as well as the affricate /ts/. The combination of the four consonants with the three vowels /a/, /u/, and /i/ produced twelve different logatoms. They, in turn, generated a list of 24 test units when pronounced by a male and a female speaker.

The scores in Fig. 2 were given by 13 hearing-impaired subjects suffering from sensorineural hearing loss. Their average high-frequency loss amounted to 81.1 ± 9.1 dB HL. With this degree of hearing loss, all test subjects were candidates for using Frequency Composition™, as determined by the fitting software Oasis.

There were three conditions under which the test was conducted: unaided, aided with Frequency Composition™ off, and aided with Frequency Composition™ on. The objective of the test was to gather raw data in terms of percent-correct scores. These scores were then subjected to the rationalized arcsine transform (RAU), a method that makes proportionate data suitable for inferential statistics (Studebaker, 1985).

Frequency Composition™ improves the discrimination of high-frequency phonemes.

As Fig. 2a shows, the discrimination scores increase from the unaided to the aided condition – and again from Frequency Composition™ off to on. Additionally, statistical analysis reveals that the increase from the unaided to the aided condition is statistically significant, and so is the increase from Frequency Composition™ off to on. From these results, the conclusion is that Frequency Composition™ improves the discrimination of high-frequency phonemes.

Maintenance of Sound Quality
Fig. 2b shows the results of a survey, using the "Speech, Spatial, and Qualities of Hearing" (SSQ) questionnaire (Gatehouse and Noble, 2004). The survey included 14 respondents, half of whom also participated in the discrimination test. Hence these respondents were candidates for Frequency Composition™, as determined by Oasis. In contrast, the rest of the respondents were non-candidates because of less severe high-frequency hearing losses.

The survey proceeded as a single blinded cross-over trial. Randomly allocated to two groups, half of the respondents first used a RITE hearing instrument with Frequency Composition™ off, the other half with Frequency Composition™ on. After three weeks, they all completed an SSQ questionnaire. Then the groups received the opposite treatment for another three weeks. After the second trial period, the respondents again completed an SSQ questionnaire. The difference in ratings is shown in Fig. 2b.

Frequency Composition™ maintains the quality of sound.

Fig. 2b shows the average differences with respect to the aspects speech, spatial, and quality. The differences are all close to zero and the 95 % confidence intervals within ±1 scale unit. Compared to the ten scale units used by the SSQ test, the non-inferiority analysis yields a significant result: Frequency Composition™ maintains the quality of sound.

Reliability of Candidate Selection
What remains at this point is to establish the reliability of the candidate selection. For a selection procedure to be reliable, it needs to distinguish between patients who are more apt to benefit and those who are less, i.e., between candidates and non-candidates. As seen before, candidates achieved a significant improvement in the high-frequency phoneme discrimination test. When non-candidates attended the same test, they also achieved higher scores, but not to the extent that candidates did. This result backs up the conclusion: the selection of candidates works reliably.

Frequency Composition™ – Ready for You to Use

Time and technology have made frequency-lowering a useful system to overcome severe high-frequency hearing losses. In particular, the Frequency Composition™ system has shown its capability for selecting the right patients and providing them with a significant advantage. At the same time, Frequency Composition™ has also been shown to maintain sound quality. Thus whenever faced with potential candidates, consider using Frequency Composition™ available with Bernafon Acriva 9|7 hearing systems.

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