White Paper:
Frequency Compression

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Abstract:
This paper describes the patient-specific frequency compression newly introduced in Siemens latest platform. This feature is unique in its aim of ensuring benefit for all patients. The candidacy procedure of Octiv frequency compression indicates who is most likely to benefit from it and its fitting strategy prescribes the optimal parameters for these patients.

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I Introduction and background

The idea behind frequency compression is far from new – its algorithmic implementation belongs to a group of frequency lowering techniques which have been around for several decades (see for example Mazor et al., 1977). These techniques were developed to compensate for the hearing loss in high frequencies: the gradual deterioration of the human hearing system with age affects higher frequencies first while residual hearing of low-frequencies is preserved. The temptation then, has been to manipulate those parts of the signal that would fall onto the malfunctioning high-frequency specific cochlear region so as to fall in the frequency region processed by presumably healthy, residual part of the cochlea. From the algorithmic point of view, the bandwidth of the processed signal is thereby substantially reduced.

Does it work?

“A fundamental problem in all such systems is that in order to reduce the bandwidth of the speech signal, some information must necessarily be lost” (Mazor et al., 1977) The high-frequency part of the speech signal may still contain formants which are important for both vowel and consonant recognition (Harrington, 2010) and spectral cues needed for the identification of consonants (fricatives in particular, Jongman et al., 2000). It is also worth remembering that the spectral cues thought to govern speech recognition are rarely absolute in value, they exist in certain more and less flexible ratios and are context dependent. Bandwidth reduction caused by frequency lowering will result in the absence or degradation of many of the speech spectral cues in the signal. Any frequency lowering algorithm will try to “make up” for this loss of information by adding the lost information somewhere else in the bandwidth-reduced signal. The difficulties involved can be shown by comparing two of the currently available frequency lowering hearing aid strategies:

1) Non-linear frequency compression

2) Linear Frequency transposition

Non-linear frequency compression results in a compressed and thereby lowered high-frequency region (see figure 1). It does not allow the compressed information to fall below some frequency (Fmin). Thus, the information below Fmin will be perfectly preserved whereas the information above Fmin will be compressed and lowered. The speech relevant spectral cues ratios above Fmin will be changed through the compression of the signal.

![Fig 1. Nonlinear frequency compression: As an example, the highest peaks from the source region are chosen here (for details regarding scale and peak picking methods see Timms, 2003). Note that only the most important spectral information is lowered (red peaks). Channel representation was chosen arbitrarily so as to enable comparison between Figure 1 and 2.](image-url)
**Linear frequency transposition** lowers the signal content from a high-frequency region onto a lower target region (see figure 2). Since the spectral content is only lowered (transposed) and not compressed, one could argue that the relationships between speech relevant spectral cues are preserved after the transposition. However, the lowered spectral content is mixed with the original spectral content thereby changing the speech cues in the resulting mixture.

![Fig 2. Linear Frequency Transposition](image)

Both of these frequency lowering strategies completely remove the high-frequency part of the signal. This has the advantage that the resulting excitation will do no harm for those patients where high-frequency region stimulation is thought to be detrimental (Vickers *et al*., 2001; Baer *et al*., 2002; Gordo and Iorio, 2007; but see also Preminger *et al*., 2005; Cox *et al*., 2012). However, frequency lowering strategies come at the expense of reducing the bandwidth of the signal and/or contaminating parts of the remaining signal so that the now audible content of the processed signal differs from what the patient is used to hearing (e.g. speech spectral cues).

**What is the alternative?**

The alternative to frequency lowering is the standard amplification provided by hearing aids through gain prescription and amplitude compression strategies. This is the most common approach, because if it works, it more or less restores the spectral cues to their pre-hearing loss state. But does it always work?

Unfortunately, amplification of a high-frequency signal via hearing aid amplification also has some limitations. The most common are due to

1. discomfort due to perceived excessive loudness and/or unacceptable sound quality,
2. loss of frequency discrimination even when audibility is present,
3. insufficient gain due to the constraints of the hearing aid,
4. acoustic feedback of the hearing aid.

These limitations can make high-frequency gain compensation inefficient, and in some cases even harmful (e.g. Ching *et al*., 1998; Hornsby and Ricketts, 2006).

In short, both classical high-frequency amplification and frequency lowering strategies have their limits in terms of the bandwidth and the spectral information they provide. Additionally, while with frequency lowering an acclimatization to changed spectral cues is needed (Smith and Faulkner, 2006; Kuk *et al*., 2010; Glista *et al*., 2012), in the case of standard amplification, acclimatization to changed loudness cues may also be required (Vestergaard, 2004). The advantages and disadvantages of frequency lowering strategies thus have to be weighed carefully so as to achieve the greatest benefit for the individual user. Siemens Octiv products
therefore offer a non-linear **Frequency Compression (FCo)** feature but with individually chosen effective parameters.

**II FCo feature description**

The Siemens FCo feature belongs to the class of non-linear frequency compression strategies. The algorithm leaves the lower part of the frequency spectrum untouched. This is crucial since the information contained in the speech signal up to approximately 1500 Hz allows us to extract speech information such as fundamental frequency (crucial for e.g. male vs. female voice distinction, meaning in tonal languages, prosody changes) and 1st and 2nd formant information (crucial for e.g. vowel and voiced consonant recognition). Contaminating this information would dramatically reduce speech intelligibility (SI) and sound quality for the patient.

Three terms which we will use to describe the FCo feature (figure 3) are:
- **Fmin**: represents both
  - the lower boundary of the target high-frequency region that needs to be compressed,
  - the lower boundary of the compressed region.
- **Fmax**: the upper boundary of the compressed region. Ideally, this should fall at or near the last (highest) potentially audible frequency of the patient.
- **Fend**: the end frequency of the signal bandwidth of a hearing aid.

The lowest Fmin that one can choose is 1500 Hz. The remaining part of the spectrum (from Fmin up to Fend) is non-linearly compressed into a narrower frequency range. For the same Fmin, moving Fmax towards Fmin (and further away from Fend) will increase the strength of the compression.

Research has shown that SI benefit through the use of frequency compression depends heavily on the correct choice of parameters and on the facilitation of the learning process (Simpson et al., 2005; Simpson et al., 2006; Smith and Faulkner, 2006; Alexander, 2009; Scollie et al., 2010; Glista et al., 2012). Given the difficulties involved in the choice of parameters, one simple approach would be to propose a very weak frequency compression with the mildest parameter settings, with the rationale that it will not do any harm apart from limiting the output of the device at high frequencies. On the plus side, this approach would result in reducing the possibility of feedback and sound distortions, thus compensating for the reduced signal.

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bandwidth of conventional hearing aids. This is the common default approach with previously available frequency compression techniques.

In reality, one must be aware that weak frequency compression does not necessarily allow for a better speech recognition, yet still heavily reduces the signal bandwidth and thus deprives the user of the potential SI benefit and full sound experience (Moore and Tan, 2003; Hornsby and Ricketts, 2006; Ricketts et al. 2008; Sjolander and Holmberg, 2009). Octiv hearing aid devices provide a signal bandwidth of 12 kHz so as to allow direct high-frequency amplification where appropriate, plus a highly effective feedback cancellation system. Consequently, the Siemens fitting algorithm does not activate FCo for all patients.

Who is a candidate for FCo?

The FCo feature candidacy takes into account the hearing loss and the prescribed gain for the chosen amplification strategy. This information defines the last (highest) audible frequency for each patient. On the basis of the last audible frequency and the choice of the acoustical coupling, the decision is made as to the activation of the feature for the specific patient. Thus, our candidacy strategy is audiogram and fitting formula specific as well as taking into account the acoustical coupling effects. The above candidacy procedure results in the following rules for feature activation:

- For those patients where it can be predicted that conventional high-frequency amplification will be effective, FCo is not activated, so as to provide full auditory stimulation and preserve all the nuances of real life sounds.
- For those patients where we expect FCo to be more beneficial than the conventional amplification strategy, FCo is activated with the most effective, individually calculated parameters.

How do we define the most effective FCo parameters?

There are several constraints that need to be kept in mind when defining the FCo parameters:

1. The choice of Fmin:
   a. Fmin defines the lower boundary of the target high-frequency region we want compressed (the upper boundary is defined by Fend). The rationale is to leave as much of the low-frequency signal content untouched, so as to preserve low frequency speech cues that are known to govern vowel and voicing perception as well as gender and prosody cues important for preserving as natural sound as possible. Therefore, if Fmin is set too low, important speech cues are compressed unnecessarily and the sound quality suffers.
   b. Fmin also defines the lower boundary of the resulting compressed region. From this point of view, if Fmin is set too high, we run the risk that the compressed signal will not be audible any more, and/or that the compression will be too strong.

2. The choice of Fmax:
   Fmax defines the upper boundary of the compressed region. If Fmax is set too high, there is a risk of the compressed signal falling into the high-frequency region where it may not be audible, where there may be dead regions present or where the prescribed amount of gain will result in an unpleasant sound. If Fmax is set too low (for the same Fmin) the compression may be too strong.

3. Defining the strength of the FCo compression:
   a. The strength of the compression depends on the distance between Fmin and Fmax: the closer the distance the stronger the compression. In other words, for the same Fmin, the lower the Fmax, the stronger the compression will be. If the compression is too weak, there will be no SI benefit due to the processed signal not falling into the audible region. If the compression is too strong, there will be no SI benefit, a decrease in sound quality due to the contamination of the original signal and a dramatic reduction of spectral information.
Taking into account all of the constraints outlined above, FCo fitting strategy is designed so as to achieve optimal balance between SI and sound quality. An individual FCo compressed region is calculated through a weighted combination of the following rules:

1. The highest audible frequency calculated for a given hearing loss and the selected gain prescription,
2. The probability of a dead region as calculated for the given audiogram,
3. Placement of speech cues respective to the HA frequency channels:
   - For a given input signal, minimal audible difference between /s/ and /sh/ fricatives should be preserved (Jongman et al., 2000; Scollie et al., 2011)
   - For a given input signal, minimal audible difference between the average 2nd and 3rd formants in /i/ and /e/ vowels should be preserved (Alexander, 2009)

III FCo feature and fitting validation

Several studies were conducted during the development of the FCo algorithm. The Octiv FCo fitting approach was investigated in a study at Hörzentrum Oldenburg. The goal of the study was to assess our fitting strategy for severe and moderate hearing losses with the goal of achieving optimal balance between speech intelligibility and sound quality, based on patients’ perception of the low and high frequency speech cues. All patients were fitted with two different fittings:

**FCo fitting 1**: The last audible frequency was calculated on the basis of the NAL-NL2 fitting formula. Additionally, a TEN test was conducted in order to determine if a dead region was present (Moore et al., 2000; Hornsby and Dundas, 2009). If a dead region was present and the suspected lower boundary of the dead region fell below the last audible frequency for that patient, then the lower boundary was used as the last audible frequency. Taking this last audible frequency into account, Fmax and Fmin were adjusted so as to ensure the mapping of /s/ and /sh/ and the higher formants of /i/ and /e/ vowels into separate frequency channels. In other words, Fitting 1 has as its focus the optimisation of speech cues audibility for a specific hearing loss.

**FCo fitting 2**: The parameters from the Fitting 1 were changed by shifting Fmin and Fmax into a higher frequency region for approximately 1 critical bandwidth (specific to the audiogram in question). Fitting 2 thus has at its focus an improved sound quality due to the preserved original low-frequency speech cues for the respective patient.

Seventeen patients with an average age of 69 years and experience in wearing hearing aids participated in the study. Their average audiogram is shown in figure 4. The test battery comprised the TEN test, a sound acceptance questionnaire, a speech in quiet test (closed, nonsense syllable test so called logatome test; see Bellanova et al., 2010) and a speech in noise test (OLSa, adaptive speech test; Wagener et al., 1999). Each patient was tested with both fitting approaches (cross-design) as well as without frequency compression. One training session was performed with a speech training software adjusted specifically for FCo training (Serman, 2012).
Results
The overall results suggest that the last audible frequency is the most important factor in the audiogram and gain prescription dependent FCo parametrisation. The results also point towards the importance of preserving uncompressed low frequency speech cues for patients where these cues can still be made audible through gain prescription only.

Fig 5. SI results for 65 dB S0N0 OLSa, FCo. Plot ordinate shows the difference between speech reception thresholds for FCo ON and OFF (the more negative SRT implies more benefit through FCo). Linear regression was fitted across individual data for both fittings, as an indicator of trend only.

In particular, the results for the OLSa test show a trend of SI benefit for individuals with lower hearing losses benefited more from Fitting 2 (Figure 5). Observe for example that patients with higher last audible frequency have less benefit (smaller SRT) from strong settings (Fitting 1) than from moderately strong settings (Fitting 2). Note also that the benefit trend for both Fittings decreases with an increase in last audible frequency last audible frequency (indicating a severe hearing loss) with FCo Fitting 1, whereas moderate, thus highlighting the importance of preserving as much uncompressed spectral cues as possible.

Providing strong parameters (Fitting 1) to patients with higher last audible frequencies not only resulted in minimal SI benefit, it also slightly decreased their perceived sound quality (see figure 6). Here it is clear that the stronger parametrisation (Fitting 1) results in a slightly reduced subjective sound quality. The same trend regarding the connection between the last audible frequency and the stronger and more moderate fitting emerged for the nonsense syllable test in quiet.
Fig 6. Comparison of subjective Sound Quality for two different Fittings based on the questionnaire targeting spontaneous acceptance and perceived sound quality. Shown are mean values based on answers to 7 questions per each speech category. Judgments were made on a 4 point scale.

The results for speech in noise are of particular interest because they show benefit for speech in noise for adult patients, a known difficult situation for frequency lowering methods (Glista et al., 2009; Kuk et al., 2009) and this occurred after only a minimal period of training. In figure 7, the speech in noise results are shown in terms of the last audible frequency as an indicator of the hearing loss.

Fig 7. Speech intelligibility results for 65 dB S0N0 OLSa. Plot ordinate shows the difference between speech reception thresholds for FCo ON and OFF (the more negative SRT implies more benefit through FCo). The results are split according to the last audible frequency (strong HL< 4000 Hz, mild HL > 4000 Hz).

IV FCo parameters in Connexx

Connex offers FCo parameters based on the above unified fitting approach for all patients. The feature is enabled by default only for those patients where speech intelligibility benefit is expected. However, the feature can be activated for all audiograms and all acoustical parameters, in which case the optimal FCo parameters will be suggested by Connex.

Another unique aspect of the Connexx implementation is that the FCo feature allows for independent adjustment of frequency compression parameters. This approach allows the hearing care professional to adjust FCo strength differently according to the patient’s need for speech intelligibility benefit or the improvement in sound quality. Such high flexibility is particularly helpful when fitting patients which are used to different frequency lowering parameters.
V Summary

Frequency lowering methods are currently the only hearing aid features available that enable hearing loss compensation for patients whose high frequency hearing loss is too severe to obtain audibility from standard amplification methods. Since high frequency gain is crucial for speech understanding in adults and both speech understanding and speech development in children, not having access to it will greatly reduce patient’s benefit and satisfaction with hearing aids.

Frequency compression strategies allow for utilization of residual low-frequency hearing without contaminating the low frequency signal areas known to be of extreme importance for natural speech perception and speech understanding. Research has shown that, depending on the user’s hearing loss, too mild compression will not have any real benefit for speech recognition whereas if the parameters are too aggressive, this will lead to deterioration of speech intelligibility and sound quality and consequent rejection of the feature. The new Octiv FCo feature is unique in its aim of ensuring benefit for all patients: its candidacy procedure indicates who is most likely to benefit from it and its fitting strategy prescribes the optimal parameters for these patients.

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References


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