Correlation Coefficient between Replications ("Cross-correlation" on Smart-EP)

Note: the following is intended only as a guideline. Use of these measures is still under development.
Decisions regarding response presence/absence are best made through visual observation of appropriately
replicated waveforms by experienced/skilled clinicians. Clinicians are solely responsible for any use of these
"objective" measures.

- A unique feature of the Smart-EP is that when recording and you are viewing the average waveform, it
  is actually recording into two buffers (A & B). It then uses these two buffers to calculate a "SNR".
Importantly, you have the ability to "Split Buffers", to see the average waveform divided into TWO
REPLICATIONS (each with half the number of trials of the overall average). This allows you to
always have replications a ("sub averages") available – even if you only got one at an
intensity/condition before a baby wakes up.

  Caveat: If you are recording in "alternating" stimulus mode (typically done for tone-ABR), one buffer ("sub average") will be rarefaction onset and the other buffer will be condensation. You may not be able to always compare the sub averages, especially if
there is a large stimulus artifact. (However, this can be a bonus for "Neurological ABR"
where one could record click-ABRs with alternating (obtain at least two reps) then split
buffer to get rare and cond click responses.)

- IHS Smart-EP (USB version only) provides three objective measures; two of these (RN and SNR) are
determined "online" while the third (correlation) is determined after the recording is completed. None
of these measures identify any specific wave (e.g., it does not specifically measure wave I or wave V).
The split buffers are used for the SNR and RN calculations.

- The new Smart-EP RN measure is an online measure of how noisy a waveform is – this is an excellent
addition to the software! For software date August 8, 2005 or later, the Smart-EP RN is the standard
deviation of the points in the noise estimate and is a better (more consistent) measure than the previous
RN measure.* Note: the Smart-EP "+/-" response noise estimate is 2X the size of that suggested by
Picton et al and earlier workers.

- The RN may be used several ways.
  1. NOTE: Your windows must be set correctly before testing, using a 10-ms
     window around wave V (see below).
  2. Stop averaging if you clearly see a response (perhaps before RN reaches the
criterion) or when RN meets criterion. If you do not see a response present,
then recordings must have RN values below some criterion to be able to say "no
response". If no replicable response present and RN is higher, you cannot
interpret waves. Note that this requires clinician to know what they are looking
for/at. An overall/final (after averaging all replications) criterion requiring
the RN to be less than 0.08 μV (or lower) seems currently appropriate.*
Note, even lower RN values would be better.
3. Perhaps the best way, albeit more conservative and longer, is to always record to a specific RN level that is quiet enough to be confident that IF a response were present, you would be able to see it because you recorded a quiet wave. Using the post-August 8th software, we recommend that a “final” residual noise (i.e., after averaging all replications together) should be no more than 0.08 μV. IF two replications are obtained, then recording each to a RN value of 0.11 μV or lower is reasonably quiet, though not always (IHS recommends even lower – perhaps 0.07 μV per rep). If the RN is not below the criterion (such as 0.11 μV for each of two reps or 0.08 μV for average of all reps), one cannot say "no response".

*Caveat*: If significant stimulus artifact is present in the sub averages (split buffers) within the "SNR region" (see "windows" below), the RN (and SNR) values are likely not valid. This is really only a problem for high-level 500-Hz (90-100dBnHL air-conduction or 30-45 dBnHL bone-conduction) tones, as the windows for higher frequencies are far enough away from the stimulus artifact.

- The **SNR measure** is also obtained online, and is a measure of response signal-to-noise ratio. The SNR can be used as a guide as to whether a response is present (assuming SNR Region set correctly). The larger the SNR, the more likely a response is present (see *caveat* above). The IHS smart-EP “SNR” is equivalent to the Picton et al. (1983) Standard Deviation Ratio (SDR) divided by two. Statistically, a 95% criterion for SNR would be 1.2 to 1.5. Waves with SNRs of less than approximately 0.80 are unlikely to be response present. Waves with SNRs of 1.5 or higher are highly likely to be a response present. I am still "calibrating" this measure, and have seen clear responses with SNRs of approx. 1.2. *(It seems that around SNR=1 - 1.2 may be a cutoff for response present.)* This is very helpful, but clinicians should still use visual observation of replications to determine response presence. (However, if you have an SNR of, say, 1.50 with first replication, it is likely to be a replicable response if you do a "split buffer".)

- "Cross correlation" ("Process"). Using same windows as "SNR Region", but setup differently (you must set up the "cursors" under "Show") and measured after recording finished. The Smart-EP has the easiest method to (quickly) calculate correlations between waves that I've seen on any equipment. Simply click on one waveform, then hold down ctrl key and click on second waveform (circle at 0 ms will turn grey) then go to "Process" and "Cross-correlate". *(Note: only be two waves at a time.)* In general, a correlation of 0.46 or higher is strongly suggestive of a response present. *(As with SNR, however, visual observation of replicated waveforms by a experience/skilled clinician is the standard/accepted method.)*

*For SMART-EP software dated before August, 2005, the RN is the largest peak-to-peak amplitude present in the noise estimate (the "+/-" response is used as the noise estimate) – as such it is somewhat conservative, overestimating the noise present in the response. You should contact IHS to arrange for an up-to-date version of the Smart-EP software. Also, non-USB versions of the Smart-EP do not (and will not) have these online response measures.*
Windows (or "SNR Regions") must be set-up prior to any recordings to use RN and/or SNR. (Windows for correlations can be set and re-set, using cursors, after recordings obtained.) SNR region is set under "System", and can be saved as part of the "settings". Windows are typically 10-ms in length, as follows:

**REVISED January, 26, 2007** (later windows based on review of infant results)

<table>
<thead>
<tr>
<th>STIMULUS</th>
<th>RN, SNR &amp; CORRELATION (CCR) WINDOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC/BC Clicks</td>
<td>1.8-11.8 ms on Smart-EP</td>
</tr>
<tr>
<td>AC 500-Hz tones</td>
<td>10.5 - 20.5 ms (Caveat: RN and SNR with 90-100dBnHL AC stimuli)</td>
</tr>
</tbody>
</table>
| BC 500-Hz tones           | 20dBnHL stimulus: 10.5 - 20.5ms  
30-45dBnHL stimuli: due to stim artifact: 14-24ms (only RN valid)  
(Note: higher BC is later because of stim.artifact)  
(Caveat: SNR region must not include stimulus artifact) |
| AC 1000-Hz tones          | 7.5-17.5 ms (Caveat: RN and SNR with 30-50dBnHL BC stimuli) |
| AC/BC 2000-Hz tones       | 6.5-16.5 ms                          |
| AC/BC 4000-Hz tones       | 5-15 ms                              |

Note: New IHS Smart-EP software (post August 8, 2005) allows one to re-calculate (offline) RN and SNR values using different SNR regions (for example, if you used wrong SNR regions). Simply set the new/correct region, then “split buffer” and then “add”.

**CCR and Multiple Replications**

Normally, one must have an even number of waveforms to average to then obtain a single CCR. With current Smart-EP software (post August 8, 2005), it is possible to “add” all the replications and then obtain CCR for the “split buffer”.

Otherwise, one can use the following:

2 replications: between replication #1 and #2: Response present if $r \geq 0.46$

3 replications: between 1 & 2, 1 & 3, and 2 & 3: Response present if $r \geq 0.46$ for 1 or more comparisons.

4 replications: 2 choices
(i) PREFERRED: Average offline 1&3 and 2&4 to double number of trials in each replication; then calculate CCR between new waveforms: 13 & 24: Response present if $r \geq 0.46$

(ii) CCR between 1&2, 1&3, 1&4, 2&3, 2&4, 3&4: Response present if $r \geq 0.46$ for 3 or more comparisons