Functional Description of the AHAAH Model

The AHAAH model is a 'first principles' model of the human ear; that is, it is an electro-acoustic analog of the ear. Consequently, it has elements within it that represent the various anatomical components of the ear's structure. The present description is a non-mathematical presentation of the model for the user who would like to have a deeper understanding of the model that would promote its full and proper use; but for whom the equations of motion can be accepted on faith.

The model was designed with the aim of predicting hearing loss to 'very intense' sounds, i.e. those sounds with peak pressures above 130-140 dB. For such sounds the loss mechanism is understood to be mechanical stress within the structures inside the cochlea. The level at which this happens is a complex function of frequency and intensity; but the rule of thumb would be that for sound pressures above 130-140 dB, the AHAAH model should be used to predict hazard. At lower pressures the ear acts as though it is being 'tired out'; but at high pressures it acts as though it is being 'torn up.'

The challenge for the model is to predict displacements in the inner ear in response to sounds in the free field, at the ear canal entrance, or at the ear drum position. And, of course, the predictions should be validated with hearing loss data from the human ear.

For pressure histories measured in the free field, the model assumes a 'worst case' angle of incidence (sound arriving straight down the ear canal) and then calculates the pressure history at the eardrum (all linear processes). The energy is then propagated across the middle ear to the stapes, which is the input to the inner ear or cochlea. At this point, the transfer function from the free field to the stapes looks very much like the A-weighting curve or the threshold of hearing. This makes sense because the acoustics of the head and middle ear shape the energy that arrives at the cochlea and is available for the nervous system to process.

If the acoustic waveform were recorded at the ear canal entrance or at the ear drum, then input to the calculational process begins at the proper element in the circuit diagram/ear with the result that the proper pressure history arrives at the inner ear.

The middle ear introduces several complexities in the form of non-linearities, in addition to the frequency weighting: a peak-limiting nonlinearity and a time and frequency varying attenuator. Consider each in turn.

The middle ear is linear at most sound pressure levels people experience; but above 130-140 dB, it becomes non-linear. Because the annular ligament that holds the stapes in position in the oval window has a finite width and is very tough, it stops the stapes from displacing more than a few tens of microns. Were the middle ear linear, at very high SPLs it would try to displace 1000 microns or more. So at high SPLs the annular ligament represents a strong peak-limiting element in the ear.

The middle ear also contains a pair of muscles attached to the bones of the middle ear. When they contract, they attenuate on the order of 20 dB at frequencies below about 1.0 kHz and progressively less at higher frequencies. The middle ear muscles can contract reflexively in response to intense sounds, which means that the contractions have a latency of about 10 msec and a rise in their effect. Thus, for an impulse like a rifle shot, the latency is sufficiently long that the muscles would have no effect on the transmission of the middle ear. On the other hand, if the 'owner of the ear' knows that the shot is going off, or if the impulse is one of a series (as in a machine gun), the muscles might be contracted at the time the impulse arrives. The AHAAH model allows the user to decide whether to evaluate the response to the impulse as though it were an evoked response (latency and onset of contraction appear at the proper time) or as though the impulse were one of a series or one whose arrival is anticipated (contraction in place before the start of the impulse).

Given the stapes displacement as an input, the model then calculates the displacements of the basilar membrane, on which sits the Organ of Corti, the site of damage. The organ of Corti, which is about 30 mm long in the human ear, acts as a frequency analyzer in which the high frequencies appear near the stapes and the lower frequencies are spread progressively along it in a wave-like motion. The model finds the peak displacements of the waves (in microns) at 23 locations (about 1/3 octave spacing). As each peak passes, it squares the size of the displacement and accumulates the total at each of the 23 locations. The 23 doses are in units called Auditory Hazard Units (AHUs).

Experiments with the cat ear established that the relationship between ARUs and hearing loss could be expressed by the formula:

Threshold shift (in dB) = 26.6 x Ln (AHU) -140.1

Furthermore, the correlation between this formula and the actual threshold shift was 0.94. This relationship is presumed to be true for mammalian cochleae, or at least for the cat and human cochleae.

As it turns out, 500 ARUs result in about 25 dB of threshold shift measured right away, a change in sensitivity that recovers within 24 hours. Thus 500 ARUs represents a safe dose for at least occasional exposure.

One final concern was the prediction of threshold shift based on susceptibility of the ear. Most auditory qualities e.g. threshold, have a standard deviation of about 6 dB. The model assumes that a susceptible ear is like a normal ear that is being driven harder. Thus, a 95%ile ear (1.64 standard deviations) is like a normal ear being driven at a 10 dB higher pressure.

In Summary:

The AHAAH model begins with a digitized waveform recorded at one of 3 locations - free field, ear canal entrance, or ear drum - and propagates the energy through the middle ear and its non-linearities to arrive at a stapes displacement that drives the inner ear. The cochlea frequency analyzes the input from the stapes and accumulates the dose at 23 locations within the inner ear. The dose in the exposure is in ARUs, for which 500 or less are considered safe.