**Clinical application of a new objective test of semicircular canal dynamic function – the video head impulse test (vHIT).**

**A safe, simple and fast clinical vestibular test.**

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### Preface

If you want to test hearing in the left ear, then you present a sound to the left ear to stimulate the auditory system and measure the response – for example whether a patient can hear the sound or whether there is a measurable physiological response to the sound. If you want to measure vision in the left eye, you present a visual stimulus to the left eye and ask the patient what they saw. Similarly if you want to test the semicircular canal function in the left ear you turn the person’s head to the left to stimulate the semicircular canal in the left ear, and you measure the eye movement response while the patient tries to keep looking at a stationary target straight ahead. That is the response - just how well they can keep looking at the target. That head turn activates the receptors in the left horizontal semicircular canal which transmits the information to the brain and results in the eye movement response, which corrects for the head turn so that in healthy subjects the eyes stay looking at the target. So in the case of the semicircular canals, the response is that both eyes turn to correct for, or compensate, for the head turn - to keep looking at the target as the head is turned, so the person’s gaze is stable during the head turn. The eye movement response is a tool to probe of the function of the semicircular canals of the inner ear. Of course to test the semicircular canals on the right you turn the patients head to the right.

What happens if the patient has no semicircular canal function in one ear? Now turn the head to that affected side but since the canal is not working, the eyes do not correct for the head movement. Instead of the eyes turning to correct for the head turn, the eyes move with the head. So at the end of the head movement the patient must make a saccade back to the target. That saccade tells the clinician that the semicircular canal is not working properly – the response is just not adequate, so there is probably a deficit in the semicircular canal on that side. In most patients it is easy to see the corrective saccade at the end of the head turn and so we call it an overt saccade. For example if, at the end of a head turn to the left, the clinician sees the patient has to make an overt saccade to get back to the target, then the semicircular canals on the left side are deficient.

This figure shows the difference between the responses of a healthy subject (top row) and a patient with a vestibular loss (bottom row), at comparable moments before, during and after the head rotation.
How can we objectively measure the adequacy of the semicircular canal response? One way is to measure the speed of the eye rotation and compare it to the speed of the head rotation. Eye velocity should be about equal and opposite head velocity and the ratio of the two velocities is called the vestibulo-ocular response (VOR) gain and in healthy subjects it is usually around 1.0. Or we can measure the saccades – whether they are there or not. The following explains how to do this test in real life.

**The Head Impulse Test**
The clinician stands before the patient, holding the patient’s head in his hands, and the patient, who is looking straight at the clinician, is asked to keep staring at the earth-fixed target (the clinician’s nose). If the clinician now turns the patient’s head abruptly and unpredictably to the left or right, through a small angle (only 10-20 degrees - not a large angle), that head turn is what we call the head impulse. If the patient has a functioning vestibulo-ocular response they will be able to maintain gaze on the target because the vestibulo-ocular response drives the eyes to rotate to exactly compensate for head rotation and so maintain fixation. However if the patient’s vestibulo-ocular response is inadequate then their eyes will be taken off target during the head rotation, because their eyes will not rotate at the correct speed to exactly compensate for head rotation. So an inadequate VOR means that the eyes go with the head during the passive unpredictable head turn and will be taken off target by the head turn, so that at the end of the head turn the patient must make a corrective saccade back to the clinician’s nose. To the clinician watching the patient’s eyes, this saccade is usually very clear, and we have termed it an overt saccade. It is the tell-tale sign of inadequate semicircular canal function on the side to which the head was rotated. So an overt saccade after a leftwards head rotation means the left semicircular canal has a deficit. If there is any doubt, the clinician just repeats the head impulses until they are satisfied.

**Covert saccades**
Does the absence of an overt saccade mean that the canal is normal? No. Because our measures with scleral search coils (Weber et al 2008) showed that some patients with a semicircular canal deficit on one side could manage to generate small corrective saccades actually during the head movement, so that at the end of the head turn to their affected side hardly any overt saccades were necessary to bring the eyes back on target. These small hidden saccades during the head rotation had concealed their inadequate VOR. We have called these hidden saccades covert saccades. It is important to realize that covert saccades can entirely obscure or conceal even a complete, total loss of canal function. These covert saccades are very fast and they occur during the head rotation and they are almost impossible to detect by the naked eye. It was only by using scleral search coils, the “gold standard” of eye movement measurement, during patient testing that we found them (Weber et al 2008), but clearly clinicians want to be able to detect them so they can accurately diagnose whether the patient has a vestibular loss or not and our new vHIT tests does just that. (Examples of recordings of overt and covert saccades are shown in the “Understanding vHIT Data” section)

The video Head Impulse Test (vHIT)

The simplest clinical indicator of a semicircular canal deficit is what I have just described - the head impulse test (also called the head thrust test, or the Halmagyi-Curthoys test, or the Halmagyi test). But detecting that saccade is subjective and relies on the clinician seeing the small corrective saccade after an abrupt head movement. The new indicator we describe below - the vHIT test uses a video camera to measure the eye movement and so it is objective and provides hard copy of the patient’s performance. But first we will describe the test procedure and its logic.

This head impulse sign was described by Halmagyi and Curthoys in 1988, and from that time to the present, the clinical use of the head impulse test has been to indicate deficient canal function by virtue of the clinician (subjectively) observing whether there was an overt saccade or not at the end of the head turn. However some vestibular-deficient patients were missed by the head impulse test, even by expert clinicians, probably because of covert saccades. Clearly the ideal would be to have objective measure of both the head movement stimulus and the eye movement response using a system fast enough and accurate enough to detect covert saccades. The scleral search coil method of measuring eye movement achieves this aim, but it is clinically unrealistic, because of its huge expense, the high cost of each coil, the complexity of processing the data and the fact that patients do not like having a contact lens placed on their eye. However we have developed a new lightweight video system procedure – which we have called the video head impulse test (vHIT) – which does measure eye velocity and does detect covert saccades and is non-invasive and practical in clinics. Most importantly we have shown by direct comparisons that the accuracy of vHIT matches the accuracy of the “gold standard” search coil technique. vHIT has been validated by direct measures of VOR performance in healthy subjects and patients by two independent methods – search coils and vHIT. At exactly the same time: the same subject, the same eye movement responses were measured independently by these two methods and compared and found they both give essentially the same answer.
How does the video head impulse test (vHIT) work?
The procedure is as described above, except that the patient wears a pair of lightweight, tightly-fitting goggles on which is mounted a very small, very light, very fast, fire-wire video camera and a half silvered mirror. This transparent mirror reflects the image of the patient’s eye into the camera. The eye is illuminated by a low-level infra-red light emitting diode which is not visible to the patients. A small sensor on the goggles measures the head movement. The whole goggle system is lightweight (only about 60g) but it must be secured tightly to the head to minimize goggle slippage, because any slippage of the goggles will move the camera relative to the eye and so be registered as a movement of the eye and so generate artifactual data.

In testing, the clinician first conducts a quick calibration procedure, in which the patient is required to look between two laser spots projected from the goggles onto the wall. Then the clinician asks the patient to keep staring at an earth-fixed target, and gives the patient brief, abrupt, horizontal head rotations through a small angle (about 10-20 degrees), unpredictably turning to the left or right on each trial.

**Stimulus**

Displacement = 10° to 20°

Peak Head Velocity = 100°/s to 250°/s

Peak Head Acceleration = 1000°/s² to 2500°/s²
The clinician’s hands must be well away from the goggles and the goggle-strap to minimize the chance of any artifactual camera movement.

The head movement speed is measured by the gyroscopes in the goggles, and the image of the eye is captured by the high-speed firewire camera (250Hz) and processed by very fast software to yield eye velocity. At the end of each head turn the head velocity stimulus and eye velocity response are displayed simultaneously on the screen (figures below) so the clinician can see, just how good the stimulus and response were. In a full test usually around 20 impulses are delivered randomly in each direction and it may take 4 or 5 minutes to do that. At the end of the full test all the head velocity stimuli and eye velocity responses are superimposed and displayed on the computer screen, together with a graph of the calculated VOR gain for every head rotation as shown below in (Fig. 4). VOR gain is the ratio of eye velocity to head velocity, and so it should be ideally be about 1.0 for constant gaze during the head rotation.

In practice normal healthy subjects typically have VOR gains less than 1.0 (around 0.8 - 0.9). But with vHIT any deficient response or VOR response asymmetry is easily seen. So in the space of about 5 minutes the clinician has an objective measure of the VOR response for both directions of rotation. The 250Hz video is fast enough that covert saccades can be detected and these are easily visible on the superimposed records (see below)
Examples of results from vHIT

1. Normal healthy subject

These and the following figures show superimposed records of eye velocity responses (black traces) to brief unpredictable horizontal head rotations (red traces) to the left and right. The first column shows the plot of the gain of the VOR for all of these (closed circles are for leftwards and open circles are for rightward impulses), as a function of peak head velocity. The average VOR gain is shown graphically and given numerically beneath the graph, together with the standard deviation and the number of impulses in each direction. Here the eye velocity matches head velocity so the head velocity traces and eye velocity traces are almost exactly superimposed showing that the eye velocity closely matches the head velocity. (We have inverted the eye velocity traces in these figures so you can more easily compare the eye velocity with head velocity.). Corresponding to that, the VOR gain values are good 1.08 for left and 0.94 for right. These VOR gain values are in the normal range and there is no asymmetry.

2. A patient with bilateral vestibular loss.

Comparable records from a patient with bilateral vestibular loss. Now the black traces (eye velocity) records do not follow the red (head velocity) records. The patient’s VOR is clearly inadequate as the gain graph shows: the average VOR gain is 0.30 for left and 0.39 for right and both of these are significantly outside the normal range. In addition, there are large

overt saccades
saccades at the end of most head impulses and these are overt saccades and would be easily seen by the clinician at the end of the head turn.

3. A patient with a unilateral vestibular loss

In this patient, eye velocity matches head velocity reasonably well for rightward head rotations, but not for leftwards head rotations (towards the patients affected side). Not only is the eye velocity insufficient, but there are many saccades which occur during the head impulse (covert saccades) and also some saccades which occur after the head impulse (overt saccades). The covert saccades would be very difficult for the clinician to detect by visual observation. The numerical values show the clear VOR gain difference for the two sides: to the right (healthy side) the average gain is 0.79 (in the normal range), whereas to the left (affected side) the average gain is only 0.39, significantly below the normal range. So this person has a severe left sided horizontal canal deficit.
**The Graded series of head velocities**
Instead of just giving one value of head velocity over and over again, as in the above examples, it is possible to give a graded series of increasing head velocities, which allows us to show the data in a 3-d format. Each line is a separate head impulse and they have been sorted so that the head velocity progressively increases from very small to large.

![Head Velocity](image)

Head Velocity
250 Hz Accelerometer
On Video Goggles

![Eye Velocity](image)

Eye Velocity
250 Hz Video

![Normal Subject](image)

Normal Subject
The figure above shows that as these head velocities increase, in a healthy subject there is a corresponding increasing series of matching eye velocities. (The small “stalagmites” are small saccades.) In fact it is usually sufficient just to show the graded series of eye velocity responses:

In the following examples a red surface has been fitted over the eye velocity responses (this example and the other “red surface figures” shown below have been recorded with search coils). Even in healthy subjects the VOR gain is not exactly 1.0, so even some healthy people occasionally make some very small overt or covert saccades. These are usually so small the clinician does not see them but the coils and video methods are so sensitive that they pick these up.

Now the saccades appear as small stalagmites, after the eye velocity response. This graded series method is especially good at showing the difference between overt saccades (panel C) and covert saccades (panel B).

Below are the results of a patient who made many covert saccades during the head impulses to his affected ear, whereas his VOR gain for head rotations to his (right) healthy side are only slightly reduced compared to healthy subjects. The VOR gain shows the very clear, consistent difference in VOR gain for the two sides.
The objective measures of the eye movement response by vHIT allows the objective measurement of whether there is recovery of vestibular function after acute vestibular neuritis. Below is data from a patient who was measured at the acute stage of unilateral vestibular neuritis (with many overt saccades and a low VOR gain (open circles)). However when measured again at testing some weeks later (Recovered) there is clear objective evidence that the VOR gain has increased substantially (closed circles) and there are very few saccades.

The following examples are search coil recordings of three different patients with varying degrees of progressive loss of vestibular function following systemic gentamicin toxicity, showing the decreased eye velocity response and the overt saccades after the head impulse.
In the final case of severe gentamicin vestibulotoxicity there is almost no corrective eye movement during the head movement, so the VOR gain is close to zero, but there are many overt saccades after the end of the impulse.
Validation of vHIT

It is important to emphasize that the accuracy of the vHIT method has been carefully checked by simultaneous measures of eye movements during head rotations by two entirely independent systems (search coils and vHIT) measuring the stimuli and response of healthy subject and patients. This was done for 8 healthy subjects and 8 patients with various known vestibular losses. This is the way the simultaneous search coil and video measures were done (clinician Konrad Weber; subject Hamish MacDougall).

The evidence of this direct comparison was published in a peer-reviewed very high ranking journal in the field (Neurology -- MacDougall et al 2009) and it shows that the VHIT method and search coils gave very closely similar results – there were no significant differences in VOR gain, and the similarity of the eye velocity responses, as measured by the concordance correlation coefficient between the eye-velocity records for vHIT and for search coils was very high – meaning they both gave the same answer. The figure shows just how similar the measurements with search coils and video are.
Contraindications and Challenges  vHIT cannot be used on everyone. Some people have very stiff necks or cannot relax their neck muscles sufficiently for the clinician to give them an unpredictable head rotation. In individuals who have previous neck trauma it is not advisable to carry out this rapid head turn. Blinks can be a problem – the patient must be asked to keep their eyes wide open during each head turn, and to try to keep looking at the fixation target. The patient must understand the instructions and attempt to maintain fixation. The goggles must be tightly fixed to the head, and the clinician’s hands must be well away from the goggles and the goggle strap.

Why does vHIT detect semicircular canal loss?  In a healthy subject a head rotation to the left activates receptors in the left horizontal semicircular canal, so the nerve fibres from the left canal generate nerve impulses which cause both eyes to rotate smoothly so that both eyes exactly compensate, or correct for, the head movement. So both eyes stay looking at the target during the passive unpredictable head movement. But if the person has a loss or deficiency in the left horizontal canal system, then the neural drive to the eyes will not be enough to drive the eyes to correct perfectly for a leftward head movement. So the eyes will move with the head and the result will be that at the end of the head movement the eyes will have been dragged off target and the patient will have to make a corrective saccade to get back onto the target. That is the overt saccade which the clinician sees. Obviously a right side canal deficit will cause a loss for rightward head movements. If just one side is affected and the other side is healthy then the corrective saccade will only occur for head rotations towards the affected side. That patient has a unilateral vestibular loss. This is the most frequent kind of deficit. When both sides are affected, the patient makes corrective saccades for both directions of head rotation – they have bilateral vestibular loss.

Summary of video HIT Advantages  The vHIT method has now been in use for 18months by Dr Leonardo Manzari in the MSA Clinic at Cassino, Italy, as well as at two other locations (Sydney and Zurich), and the results show how extremely useful it is. The vHIT method provides objective measures of the eye-velocity response to the head-velocity stimulus, and shows the VOR gain for the two directions of rotation. It shows the presence of both overt
and covert saccades and has the very large advantage of being objective – these records of the eye movement responses and the VOR gain provide the hard objective evidence about the adequacy of semicircular canal function which clinicians require.

Q & A

- **Why is it necessary for the clinician to move the patients head? Why can’t we just get the patient to turn their own head while they are looking at the target spot?**
  
  Firstly that sounds a very easy thing to do but it isn’t. Some people, even very intelligent people, just cannot do that task at all, try as they may! But more importantly, if the patient moves their own head they can voluntarily generate a corrective eye movement at the same time as they cause their head to move. Just as they can voluntarily control their own head movement, so they can voluntarily control their own eye movements. Active voluntary control of head movement and eye movement by the patient just does not provide the probe of the inner ear function which we get so well if the patient’s head is turned in unpredictable directions by the clinician. We have found that patients doing the head impulse voluntarily (by actively turning their head) quickly learn to make an early saccade during the active head movement which is very very hard to detect – another version of the covert saccade. So the clinician cannot see any saccade even though the vestibular system may be non-functional.

- **Why measure eye movements to test inner ear balance function? The patient’s problem is in their ear so why not measure ear function rather than eye function?**
  
  The answer is because the eye movement response to a head turn is a very sensitive indicator or tool or probe of just how well the balance mechanism of the inner ear is functioning. There are very strong fast neural projections from the inner ear to the eye muscles.

- **Can we give the stimuli regularly (using a metronome)? and why is it necessary to randomize the direction of head turn?**
  
  If each impulse is given in a very regular fashion (e.g. 3 seconds between each impulse and always alternating directions) the patient can quickly learn to either blink just at the start of the head turn, or generate a covert saccade, so the clinician misses seeing any deficit. The test should not be given at regular intervals – the timing when each head turn is delivered should be random. Unpredictable directions and unpredictable intervals minimize the chance of learning affecting the test results.

- **How many impulses?**
  
  We normally aim to get about 20 impulses for each direction. Although the very first impulses usually tell the whole story and the rest just confirm that story and give the clinician greater confidence in the results. In some patients it is difficult to deliver 20 impulses in each direction – the patient may have a stiff neck or not be able to totally relax their neck muscles. There is no absolute minimum, it really depends on the quality of the responses on each trial. If there is any doubt the stimulus and measurement is very easy and takes only an extra few minutes to give more. With a small number of impulses the calculation of VOR gain becomes less reliable because there are so few values.
• **How big should the head movement be? (insert video into this section)** Even very small head turns can be very valuable in showing a loss of function. The important thing is not how large the head turn is but **how abruptly it starts**. It should be an abrupt start, not through a big angle, but it should start abruptly. If the head is turned through a small angle, slowly, then there is no need for the patient to make any corrective eye movement at all and so they don’t and the clinician does not detect the deficit which may be there.

• **Why do we have this vestibulo-ocular response?** The corrective eye movement response is used to provide stable vision during the head movements of walking, running, driving and all the normal activities we get up to. This very simple eye movement response is an indicator of the function of one part of the balance system of the inner ear.

• **Can we suppress this response?** Healthy people can almost totally override the vestibulo-ocular response. For example if you are reading a book on a bus going around a corner - you want to keep your eyes on the text rather than having them being driven off the page by the vestibular input automatically correcting for the angular turn. It is abilities like that overriding (also called VOR suppression) which are an unnoticed but essential part of everyday living which make clinical testing of vestibular function more complex than testing hearing. In hearing there is such a simple output – do you hear that sound? and sounds cannot be suppressed or “shut out” in any way analogous to the way the vestibular information can be. But by restricting our measurements to just the start of these brief unpredictable head turns we can selectively probe the function of the semicircular canals since it takes a little time for that VOR suppression to work.

• **Is the patient’s understanding of the instructions important?** It is **VITAL** that the patient understand the instructions – that the patient has to keep looking at the fixed target – to try to keep their gaze stable and not to blink during this unpredictable movement. They **must not** try to “help” the clinician by looking ahead, or looking where their head is going - they must not turn their eyes with their head.

• **Why has it taken so long to develop this system?** Because we need very fast cameras which were very small and lightweight which can be comfortably be fitted to the head in goggles which have minimal slip.

• **What is the worst kind of error with this system?** Slip of the goggles. If the camera slips on the head then it appears as if the eye has moved relative to the camera. A real eye movement and the movement of the camera relative to a fixed eye both generate the same effect at the camera - the image of the pupil of the eye moves across the camera sensor plane. This is the worst artifact. We want to measure real eye movements relative to a fixed camera, not artifactual eye movements. To avoid camera slippage, the camera should be tightly fitted to the head (the test only takes about 5 minutes so it will not cause discomfort for too long). But if it is not tight enough you might as well not do the test. The operator’s hands must be well away from the goggles and the goggle strap.
• **How do we maintain control over the stimulus?**

In clinical testing of hearing, precisely controlled stimuli are presented through calibrated headphones and the patient’s responses are measured. In clinical testing of the vestibular system, this kind of presentation of controlled stimuli is just not feasible. Instead we present vestibular stimuli which are not well controlled – a head turn by a clinician can vary enormously from one trial to the next – but we rely on the fact that *we measure the stimulus exactly each time and relate each response to that stimulus*. In some respects this is an improvement over testing of hearing since we actually measure what the stimulus is on each and every trial, rather than assuming that a calibration check taken a few weeks before guarantees the stimulus value.

**Conclusion**

This has been a simple introduction. I have focused on the behaviour – the head turn stimulus and the eye movement response. But of course we would like to know about just how the head turn is detected by the receptors in the semicircular canals and how it is transformed into neural signals and how those neural signals result in the eye movement response, and how something like VOR suppression can occur. Those matters are taken up in the companion chapters.

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