The caloric examination is usually the most informative subset of the electromyography (EMG) test battery because caloric test results can be used to validate a tentative diagnosis of asymmetric function in the peripheral vestibular system.

The principle advantage of the caloric test lies in the ability of an investigator to evaluate selectively the physiologic integrity of a patient's left or right horizontal semicircular canal. By irrigating the external ear canal with cool or warm water it is possible to affect changes in the movement of endolymph of the ipsilateral horizontal semicircular canal, and thereby alter the level of afferent neural activity emanating from the ipsilateral vestibular end organ. From the background material presented by de Souza Honrubia and Hoffman in Chapter 2 we know that the caloric stimulus is nonphysiologic in that normal everyday movements of the head and of the head and body are accompanied by simultaneous movements of the motion transducers (the otoliths and cupula) of both the left and right end organ systems.

There are three primary disadvantages of caloric testing. First, although we are infusing the external ear canal with warm or cool water (with reference to body temperature) or air that is controlled thermostatically, the actual level of stimulation at the end organ level may vary greatly depending on the heat-transmitting capacities of the surrounding bone and air in the middle ear space. Second, the auditory system, the vestibular system responds to natural head (or head and body) movements that cover a wide frequency range (for example, from approximately 0.01 to 8 Hz). Caloric stimulation is analogous to head rotation at a frequency of 0.003 Hz. Thus, conducting a caloric examination in isolation without rotational testing is analogous to conducting pure-tone threshold audiometry at 125 Hz and inferring from these data the hearing sensitivity over the rest of the frequency range of hearing (and the integrity of the entire auditory end organ). Third, in caloric testing we have adopted the misleading practice of making inferences about the physiologic health of the entire membranous labyrinth (three semicircular canals, utricle, and saccule) based on testing that is capable only of evaluating the horizontal semicircular canal over an extremely narrow portion of its operating range. This can be a dangerous and inaccurate assumption.

The importance of the caloric test as an integral component of the site of lesion vestibular test battery makes the
accurate performance of this test essen-
tial. The purposes of the present chapter
are: (1) to present the historical develop-
ment of caloric test procedures; (2) to
describe conventional methodologies and unconventional permutations of the
alternating binarial bithermal (ABB)
caloric test, and to describe conven-
tional measurement techniques; (3) to
describe methods of calibrating caloric
systems; and (4) to discuss those vari-
ableS that may affect the caloric re-
sponse.
It is interesting that since the ABB ca-
loric test was first described in 1942 by
Fitzgerald and Hallpike,39 the original
methodology has remained unchanged
with few exceptions over the subsequent
50 years. These exceptions have in-
cluded the following:

1. Addition of electro-oculographic
instrumentation (also called elect-
roungiography, or ENG), and
photovoltic nystagmographic
recording techniques (PEG),
which have permitted the exam-
iner a method of quantifying accu-
rately vestibular system function;

2. Inclusion of fixation suppression
testing;

3. Appreciation of the effects of cer-
tain variables on the caloric re-
sponse; and

4. The recent advent of computerized
data collection and analysis tech-
niques.

The clinical significance of various types
of caloric test results will be discussed in
Chapter 9.

HISTORICAL PERSPECTIVE

Background
Caloric testing began in 1888 when
Schlitzederkam observed that nystag-
mus could be elicited by irrigating the
ears with water.746,208 However, it was
not until 1906 that Barany and
Mittawer25 were the first to develop the use of
the EOG as a means of providing a perma-
nent record of nystagmus. Finally, Efen-
rickson20 and Stickel20 were the first to
comment that caloric nystagmus be-
came reduced or absent in the presence
of visual fixation. Prior to this time
caloric testing was conducted routinely
with the subject's eyes open and fix-
atcd on a stationary point.

It was Robert Barany who formu-
lated the hypothesis that thermal con-
vection currents set up within the mea-
trabrous labyrinth were the origin of
caloric nystagmus.4,48 Barany observed
that when water cooler than body tem-
perature was infused into the ear canal
of a patient sitting upright, a nystagmus
was elicited, with a fast phase directed
toward the opposite ear. Alternatively,
when water warmer than body tempera-
ture was infused into the ear canal a
nystagmus was elicited with a fast
phase directed toward the same side.
Additionally, the nystagmus could be
made to reverse direction if the patient's
head was directed downward such that
the crown of the head was pointed to-
ward the floor.

The method of caloric transduction
described by Barany is illustrated in
Figure 8–1. When warm water is in-
fluenced in the external auditory meatus
the skin of the ear canal is heated, re-
sulting in a temperature change which
is transmitted to the horizontal semicir-
cular canal. Additionally, heat transfer is
carried to the vestibule through the
air in the middle ear space.44 The
dendolymph closest to the canal wall is
heated, causing it to become relatively
less dense than the surrounding
endolymph. Because less dense fluids rise,
and more dense fluids fall, the heated
endolymph rises and is replaced by
more dense endolymph, which is in turn
heated and in turn rises. The fluid move-
ment that results from the heating of the
endolymph is called a "convection cur-
rent." Warm water irrigations for the

**Horizontal Semicircular Canal**

**Utricular movement of cupula**

**Ampulla**

**Middle Ear Space**

**Crista**

**Auricula**

**External Auditory Meatus**

**Utricular movement of cupula**

**Ampulla**

**Middle Ear Space**

**Crista**

**Auricula**

**External Auditory Meatus**

---

**FIG 9-1.**

Horizontal semicircular canal result in utriculocapital movement (toward the utricle) of the horizontal semicircular canal cupula. Utricular movement of the right cupula is analogous to the movement induced in the right horizontal semicircular canal by a rightward head turn. The resulting effect in the right cristae is a depolarization of the dendrites at the base of the hair cells. This creates a net increase in electrical activity over the resting spontaneous activity. The activity travels through the medial longitudinal sacculus results in a slow deviation of the eye to the opposite direction (leftward in the present example) and a fast correcting saccade toward the same side as the caloric stimula- tion (toward the right in the present example).

It has been demonstrated that the convective current associated with a massive 10°C change in endolymphatic temperature results in only a 1.5- to 2.6-μm cupular deflection. The nystagmus direction (determined by the direction of the fast phase of the nystagmus burst) reverses if the patient’s head is inverted. This is illustrated in Figure 8-2. In the current example, if the head position is reversed such that the face is pointing downward (subject prone), the irrigation of the ear canal with warm water results in a deflection of the cupula away from the utricle, resulting in a hyperpolarization of the end organ, which creates a decrease in the resting discharge rate. This is analogous to what occurs in the right semicircular canal following a head turn toward the left. The result is a slow deviation of the eye toward the right and a fast correcting saccade toward the left. Under normal testing conditions, cool water irrigations result in slow-phase eye movements toward the ear stimulated and fast-phase eye movements away from the stimulated ear. Alternately, warm water irrigations result in slow-phase eye movements away from the ear stimulated and fast phases toward the stimulated ear (the movement is “COWS”; cold opposite, warm same). This phenomenon is depicted in Figure 8-3. Barany received the Nobel Prize in 1914 for his observations of thermal stimulation of the vestibular system.

It is now believed that thermal convection currents are the primary but not the sole mode of transduction within the horizontal semicircular canal system during caloric testing. Recent experiments conducted under weightless conditions aboard the Spacelab scientific space laboratory have demonstrated that caloric nystagmus can be elicited in the absence of the gravitational field that is required for convection currents to exist. (See “Cortical Testing in Caloric Testing” at the end of this chapter.)
Attempts to Evaluate Vestibular System Function Through Caloric Testing

Minimal, Maximal, and Directional Preponderance Tests

A number of caloric examinations were developed in the beginning of the twentieth century. Most of these examinations were developed in Germany and are referred to as minimal, maximal, or directional preponderance tests. The minimal tests, for example, those of Demetriades-Mayer, Veits-German, and Türek, employed small amounts (5–10 mL) of cold water as a stimulus to the labyrinth obviating the discomfort associated with caloric testing using larger volumes of water (thus, the term “minimal test” is used). The patient's head was placed in a "neutral" position (not optimal for stimulation of the labyrinth), and the ear irrigated with the water over a period of 5 to 10 seconds. Following the interval of 30 to 60 seconds required for the heat transfer to take place, the patient's head would be placed in an optimal position for labyrinthine stimulation and the patient would be instructed to open his or her eyes. The latency, duration, and/or frequency of the nystagmus was measured and compared following stimulation of each ear. The minimal tests were used to determine the physiologic threshold for a response from the labyrinth. The maximal tests, for example, those of Barany, employed larger volumes of water (50 to 250 mL).
delivered over longer time periods (20 to 40 seconds). These tests were used to investigate the function of patients (1) who had little or no response to minimal stimulation, (2) who had a pre-existing spontaneous nystagmus that contaminated the minimal tests, or (3) who had a pre-existing gaze nystagmus of central nervous system origin. The directional preponderance tests include the cold-warm contrast test and the ABB test. These examinations were used to detect the phenomenon of the propensity for the eyes to demonstrate a nystagmus fast phase that beat stronger in one direction rather than the other following cool and warm water irrigations. This phenomenon, observed with the subject's eyes open, was first reported by Fitzgerald and Hallpike in patients with temporal lobe disease. This observation might be referred in present-day vernacular as directional preponderance of fixation suppression ability (see Chapter 9).
Alternate Binaural Bithermal Caloric Test
In 1942, Fitzgerald and Hallpike reported the use of a bithermal water caloric test. For this test the patient was placed in a supine position with the head elevated 30°. Tanks of water were placed on raised shelves above the patient’s head. One tank contained water heated to 44°C (110°F) and a second tank contained water heated to 30°C (87°F). Because these temperatures were 7°C above and below body temperature, they were referred to as warm and cool caloric stimuli, respectively. A hose from the cool tank was placed in the patient’s ear, and the gravitational pull created by the weight of the water caused the water to flow out of the tube. The ear was irrigated with 250 ml of cool water over a period of 40 seconds. The patient’s eyes remained open during this test, and the magnitude of the induced caloric nystagmus was quantified according to its duration. Following this phase of the test, a time interval was provided in which the temperature of the ear canal, middle ear, and surrounding bone was allowed to normalize. Then the three other irrigations were conducted. In conjunction with Parry’s observation the warm water irrigation produced a nystagmus with a fast phase directed toward the stimulated ear, whereas the cool water irrigation produced a nystagmus with a fast phase directed toward the unstimulated ear.

Instrumentation for Caloric Testing
A number of different caloric irrigators are now available for use. They differ in their ability to deliver a precise volume of stimulus to the ear drum. They differ in the type of media that is controlled by the irrigator. The two major types of irrigators deliver either air or a liquid at the same time. Air and water caloric irrigators. The third type delivers a water caloric stimulus through an expandable rubber receptacle that is placed in the patient’s ear canal. This device was designed by Kenneth Brooker and is called the Brooker-Gram’s “closed-loop” system. These caloric stimuli circulate the cool or warm water continuously throughout the system so that the temperature is maintained at a preset level at any particular instant. This is to be compared with those water caloric systems that must be “purged” prior to irrigation to bring the water temperature up to the proper level. (See Appendix.)

Air Irrigator
An air irrigator system consists of an air flow regulator, a heater, and a thermistor. Air is supplied to the air caloric irrigator from either an external air pump or air supplied from the wall sources that are located in most hospitals. The air is heated with a Peltier thermoelectric device. This device heats air in proportion to the amount of current flowing through a feedback circuit. This feedback circuit includes a thermistor which measures the temperature of the air (Fig. 8-4-B). The thermistor is located at the tip of the delivery system because air is a poor conductor of heat. Thus, the placement of the thermistor at the tip of the irrigator makes it possible to measure the temperature of the air at the last possible moment prior to when the air leaves the delivery system. The advantage of the latter delivery system is that the tympanic membrane can be visualized during the irrigation. The chief advantage of the air caloric system is that of convenience. There is no water to recover as it runs out of the ear canal, and an ear with a tympanic membrane perforation can be irrigated without concern of infection from the use of nonsterile water.
Conventional Water Irrigator

The water irrigator is the conventional caloric irrigation system. The stimulator contains two "baths" containing 30°C and 44°C water, respectively (Fig. 8-5). A temperature-sensing device submerged in each bath is connected to a thermostat that will heat the water when the water temperature decreases beyond a preset level. This level is normally slightly greater than 30° or 44°C due to the decrease in temperature that occurs as the water travels from the baths to the irrigation tip (see Appendix). A highly sensitive thermostat is important for the maintenance of correct water temperature. An undue amount of time will be required to bring the bath back to the correct temperature if the water temperature must decrease too far before the thermostat recognizes the change. Thus, it is important for the thermostat to be capable of detecting small variations in water temperature and to cause corrections for these deviations to occur quickly.

There is usually a foot pedal connected to the irrigator that opens and closes a solenoid switch that gates the flow of water. An internal timer is used to establish the duration of the water flow (usually 30 to 40 seconds). The solenoid switch controls when the flow of
water stops. The volume of water per unit time (flow rate) may be controlled by one of two methods. First, a control is present that regulates the water pump. When the control is increased, the water pump will push water more quickly through the delivery tube. Second, the flow rate may be controlled by varying systematically the internal diameter of the delivery tip. For this method the internal diameter of the delivery tip is designed to be small at the point of exit of the water and large at the base of the base of the tip. To increase water flow the plastic tip is sharpened until an internal diameter is reached that permits the appropriate volume of water to be delivered over a 40-second period (for example, 250 mL).

There are variations in the design of the water irrigators. These differences usually involve how water is delivered to the ear. It is preferable that the basin be insulated so that the decrease in water temperature is limited as the water flows from the bath to the irrigation tip. Also (as noted earlier), there are irrigators that circulate precisely heated water through the entire tube continuously, so that no purging needs to be performed prior to initiation of irrigation. Also, the design of the irrigation tip differs from manufacturer to manufacturer. Some delivery tips are simply "tipped," while others consist of large handles that have a delivery tip projecting out of them.

Two final issues deserve mentioning with respect to water caloric irrigators. Most clinical centers use tap water for caloric irrigations. The alternative is to use distilled water. The advantage of distilled water is that, unlike tap water, it does not contain organic material, and thus, will not contain sediment or promote the growth of algae. All water irrigators require routine maintenance. This routine maintenance includes calibration but also includes cleaning of the holding tanks and tubing.

Finally, electrical safety must be assured for all patients tested in the ENG laboratory. During the caloric irrigation there is a direct connection between the patient and the irrigator and ENG recorder. Therefore, if the ENG recorder, the caloric irrigator, or the patient are not properly grounded it is possible for current to pass from one machine to the other with the patient as the bridge between the two. The result can be a dangerous electrical shock. Therefore, as required in all medical centers the electrical safety of ENG equipment (such as current leakage and grounding) should be evaluated on a regular basis.

Closed-Loop Water Irrigation System

The inconveniences associated with the need to purge the water caloric system as well as with recovery of the water media have been eliminated with the advent of the "closed-loop" irrigation system. This system consists of the two standard bilateral baths and thermostatic control of temperature (Fig 8-6). However, water flow through the system is constant (to obviate the need for purging the system), and a silicone balloon is connected to the tip of the

FIG 8-6. Photograph of Brockenbrough-Graham closed-loop water caloric irrigator. Note separate delivery tubes for cool and warm water. Also note that within each irrigator tube (for example, for warm and cool irrigations) is a delivery and removal valve. This permits the continuous circulation of water when the system is not being used (Photograph courtesy of Life-Tech, Inc., Austin, Texas.).
METHOD FOR CONDUCTING CALORIC TESTS (AIR AND WATER)

Alternating Binaural Bithermal Test

Figures 8–7A–D. Illustrate the sequence of activities involved in performing the alternate binaural bithermal caloric test. Prior to the beginning of each caloric irrigation, a set of 10° sacadic recalibrations should be conducted to ensure that 10 mm of paper movement represents 10° of eye movement (Fig. 8–7C). The caloric test is usually administered with the patient in the supine (face-up) position with the head elevated slightly to a 30° angle. Alternatively, the patient may have the examination performed while seated with the head flexed backward 60°. Both maneuvers are designed to bring the horizontal semicircular canal cupula into a near-vertical position where the forces of the convective current can detect it optimally. It has been our experience that the test is best tolerated when the patient is supine. This is a more comfortable, natural position for the patient to be in for the somewhat long duration of this test (generally 30 to 45 minutes).

The ears should be inspected visually with an otoscope prior to the caloric irrigation. In particular, the ear canal should be examined for the presence of large amounts of cerumen that could impede the flow of water or air to the eardrum. Also important to note is the condition of the eardrum. This may be done during the otoscopic evaluation (Fig. 8–7B) but may also be done through tympanometric testing (Fig. 8–7A) prior to the caloric irrigations. If there are signs that the eardrum is perforated, measures should be taken to avoid passing water into the middle ear cavity. There may be occasions when it is necessary to conduct a caloric test in the presence of unilateral or bilateral tympanic membrane perforations. In these situations, calculations of symmetry of vestibular system responsiveness will be impossible because the heat-transmitting properties of the middle ear space will be different for the ear or ears with tympanic perforation. The diagnostic question in these situations is usually whether peripheral vestibular system function exists at all.

Following the visual inspection of the ear canal a catch basin is placed under the patient's ear (Fig. 8–7D). We have found it useful to place towels beneath the basin so that the basin is placed directly beneath the auricle. This produces two benefits. First, there is little possibility that water will leak out from the space beneath the ear and the basin and saturate the patient. Second, this leaves both hands of the examiner free to open the ear canal and insert the irrigation tip properly. Then, the water irrigation system is purged. If one were to begin irrigating directly from the water tank, the first 10 to 15 seconds of the irrigation (roughly 25% to 50% of the irrigation duration) would consist of water that had been cooling in the irrigation hose. Therefore, it has become the practice of clinicians to purge the water in the hose prior to the irrigation. From a practical standpoint, purging consists of

"An alternative to water caloric testing is to conduct the examination using an air caloric stimulator. In the absence of an air caloric stimulator, a finger cot may be placed deeply in the ear canal, and water may be inhaled into the finger cot."

"Electromyography"
running one full irrigation cycle into a sink or receptacle. When the cycle is completed and the water flow is terminated, the water at the irrigation tip should be close to the calibrated temperature. It is important to begin irrigating immediately following this procedure.

It is critically important that the caloric examination be discussed with the patient in detail prior to the initiation of the test. In particular, telling the patient that they will, or may, become "dizzy" or "nauseous," or that "they may vomit" will gain one little and in general will "program" the patient to expect these unpleasant reactions. The patient should be told that they will be feeling cool (or warm) water in the ear and that it will be present for 40 seconds. The
physiology of alerting is not completely understood. It is clear, however, that the cortex exerts some control over the brain stem vestibular centers. When the cortex is occupied with cognitive tasks this control is potentiated and the brain stem reflex is unimpeaded. Alerting tasks have traditionally involved serial additions or subtractions. However, these tasks are not particularly interesting and only serve to make the examination more difficult for some patients to tolerate (especially those who are poor at arithmetic).

There is good evidence in fact that simple conversation is more effective than serial arithmetic for releasing induced mystagmus.97 One final observation is that many patients will have a combination of vestibular and auditory system disease. These patients will have great difficulty engaging in conversation when their better ear (if they have a better ear) is being irrigated. For these circumstances it is best to establish a signal (such as a pat on the shoulder) that can be administered when the patient should begin the alerting exercises. On this rare occasion it is necessary to have patients do some repetitive task. These tasks can be made interesting without being prohibitively difficult. Examples of these tasks include the serial naming of letters or digits, or describing rooms in their home.

Occasionally, one caloric irrigation will be substantially smaller than the other three. When this occurs it is the responsibility of the examiner to determine why this unlikely event has occurred. In most instances the sources of a single small response are poor irrigation technique or inadequate alerting of the patient. Therefore, in all instances this irrigation must be repeated. Also, as stated earlier, it is essential that eye movement calibration be conducted prior to each caloric irrigation. Proctor et al.98 found that corneoretinal potentials showed a systematic change over
Caloric nystagmus records elicited from two normal patients (top and bottom, respectively) during periods of time when patients were not adequately alerted (areas between arrows).

**Technique for Fixation Suppression Testing**

Following the caloric irrigation, and in the midst of the alerting tasks, the nystagmus response will appear to reach a peak (evaluated visually by the steepness of the slopes of the slow component of the nystagmus response). It is at this point that the fixation suppression (FS) test should be administered. It cannot be overemphasized that it is important to evaluate patients for FS at the peak of the caloric response when the eye velocity is greatest. This will make the determination of FS unambiguous. Also, Kato et al. have demonstrated that FS measures derived from a strong stimulus are more informative than those derived from a weak stimulus.

The patient is instructed to open his/her eyes and fixate his/her vision on a stationary target placed at central gaze at least 1 m from the head. This target may be a light-emitting diode that is mounted on the ceiling or the examin-
er's finger held at least 1 m from the patient at central gaze (Fig 8–9). Within 1 to 2 seconds (to permit the patient to fix their gaze on the point source) the caloric nystagmus should attenuate markedly. This phenomenon is known as "fixation suppression" or as "vestibular-ocular reflex cancellation." The absence of this reduction of nystagmus following fixation has been referred to as paradoxical caloric response.""5 optical fixation reversal phenomenon,""5 and failure of FS,""5 which is the term that will be used within this text. Calculations of FS will be described later in this chapter.

It should be noted that Bell's phenomenon may complicate the determination of FS ability (discussed later). Bell's phenomenon refers to the averting (rolling up) and adducting (moving toward midline) of the eye that occurs upon eye closure. There is tremendous intersubject variability in the magnitude of Bell's phenomenon. Thus, for some patients it is possible for caloric nystagmus to be absent or periodically suppressed if the eyes are rolling behind closed lids. Hood and Korves"" reported that the entire caloric response could be suppressed by Bell's phenomenon. Therefore, a patient with a particularly strong Bell's phenomenon may show what appears to be a complete absence of caloric response with eyes closed but will show a response with eyes opened."

**Fig 8–9.** Examiner conducting fixation suppression test. The patient is being asked to fixate her gaze on the examiner's finger. This test is being performed just following the peak of the caloric response.

**Fig 8–10.** Air caloric irrigation. The speculum is inserted into the patient's ear, and attempts are made to visualize the tympanic membrane during the irrigation.

The air caloric stimulator has the advantage of being able to be used in the presence of tympanic membrane perforations. It has also been reported that the technique is better tolerated by pediatric and adult patients than is water caloric testing. Lastly, the use of the air stimulator obviates the need to contend with the retrieval and disposal of water following water caloric irrigations.

The procedures for conducting binaural air caloric testing are identical to those for conducting binaural water caloric testing. The difference lies in the care that one must take in the placement of the irrigating tip in the external auditory canal. The optimal delivery system for air caloric stimulation is a delivery tube running through the handle and head of an otoscope. With this system the tympanic membrane may be visualized throughout the irrigation (Fig 8–10). Because air is a poor conductor of heat it is critical that the delivery port be placed as deeply as possible in the ear canal. The air stream should be directed toward the tympanic membrane. The patient should be pre-
pared by the examiner for the noise as-
associated with the air caloric stimulus.
The effectiveness of air as a caloric medium has been a subject of discussion over the past 17 years. Capps et al.72 in-
roduced the air caloric stimulator as a substi-
tute for the conventional water cal-
oric stimulator. The investigators dem-
strated that the irrigation of an ear with 0° C water (5 mL) or air (60 sec-
onds) yielded the same magnitude of nystagmus slow-phase eye velocity, am-
plitude, and frequency. The water me-
dia resulted in a longer response dura-
tion than the air stimuli. The investigators observed that 24° C and 50° C air temperature (air flow, 8 L/min) resulted in nystagmus velocities that were identical to those obtained following water irrigation using 30° C and 44° C water for cool and warm irrigations, respectively.

Some investigators have demon-
strated a lesser nystagmus intensity and larger intersubject variability for air cal-
oric stimulation when water stimula-
tion was used as a "gold standard."29, 50 Coats et al.28 demonstrated that when the air irrigation tip was moved from an optimal depth outward 7 mm toward the external auditory meatus the nys-
tagmus slow-phase velocity (SPV) de-
creased 40% and 20% for the warm and cool irrigations, respectively. For these reasons and in an attempt to decrease the intersubject variability the investiga-
tors recommended that the tempera-
tures of 27.5° C and 45.5° C be used for cool and warm air caloric irrigations. Additionally, the authors recommended that an irrigation duration of 100 sec-
onds be used and that the flow rate be increased 13 L/min.

Benitez et al.13 reported that the maximum nystagmus SPV to cool and warm air caloric stimulation (27.4° C and 45° C, respectively, 6 L/min, 60 sec-
onds) was 33% and 20% of that follow-
ing conventional bithermal water cal-
oric stimulation. Greven et al.40 also demonstrated that the nystagmus evoked by air caloric stimulation was less intense than that elicited by water caloric stimulation. However, Ford and Stockwell53 demonstrated equivalent nystagmus velocity when comparing air and water caloric stimulation (24° C 50° C for cool and warm air caloric irriga-
tions, 8 L/min, 60 seconds). The equiva-
leney of air and water caloric stimuli have been reported by other investiga-
tors (for example, Tole49). Equivalent re-
sponses from air and water stimulation in clinical populations was observed by Suter et al.41 Most investigators have observed that nystagmus duration is in-
creased for water compared with air stimula-
tion techniques.

In the hands of a meticulous, experi-
enced clinician it is possible to obtain equivalent responses following air and water caloric stimulation. Factors of depth of insertion of the delivery tip and the orientation of the delivery tip in the ear canal are important in the ensured of this equivalency.7, 28, 36 It is clear that air caloric testing is more techni-
cally demanding than water caloric test-
ing, and for these reasons the present authors continue to favor water caloric stimulation techniques over air tech-
niques in the absence of tympanic perfor-
ations. (See "Problems, Pitfalls, and Ar-
tifacts" for caloric inversion following air caloric irrigations in the presence of medium or large tympanic perfora-
tions.)

Simultaneous Binaural Bithermal Test

Although Riceco-McClure30 de-
scribed a simultaneous binaural bither-
mal caloric test in 1904 (using 15° C or 48° C water), it was Brookler19, 20, 42 who is credited with popularizing this test in recent years. Brookler described a standardized method for conducting a bithermal caloric examination that has been referred to as the simultaneous bithermal test (SBT). For this examina-
tion, instead of alternately irrigating
each ear with cool and then warm calorific stimuli, the ears are simulta-
neously irrigated first with cool water, then following a 2-minute interval they are irrigated simultaneously with warm water. The water is delivered through a ¾” tube to both ears. The total water flow is 250 mL, and the temperatures are the same as required for the ABB test (30°C and 44°C). Conventional ENG instrumentation is used to record the induced nystagmus. There are no quantitative measurements for this test. Only the presence or absence of nystag-
um is observed as well as the direction of the induced nystagmus following each of the caloric irrigations. The SBT test was offered not as a replacement but as an adjunct to the ABB test.

Monothermal Caloric Tests

For these examinations only two warm caloric irrigations or two cool cal-
oric irrigations are conducted. Percent differences in the magnitude of the re-
sponses obtained from each ear are cal-
culated. For the most part, these exami-
nations are used as screening tests (if the ENG examination up to the caloric test is normal) or are considered adjunctive tests (the Torok Monothermal Dif-
ferential Caloric Test).

Monothermal Warm

Several investigators have attempted to decrease the amount of time required to conduct the ABB caloric test by con-
ducting the examination at one temper-

ature (monothermal caloric testing). Both monothermal cool and monother-
mal warm calorific screening tests have been proposed, although the monother-
mal warm caloric test has been the most popular of the two. The technique of the monothermal test is to administer only two of the four caloric irrigations that are used in the bithermal test. The aver-
age SPV obtained following the two irri-
gations is placed in a symmetry for-
mula:

\[
\text{LW} - \frac{\text{RW}}{2} \times 100
\]

where LW = left warm and RW = right warm.

If the percent difference between the sides exceeds a critical value (which varies from published report-to-report but usually is between 25% and 29%), the monothermal test is called abnor-
mal. It is important to understand that some investigators have suggested that the monothermal warm test be used as a replacement for the alternate binaural bithermal caloric test. Other investiga-
tors (including the present authors) sug-
gest that the monothermal warm test be used as a "screening" test (hence the name monothermal warm screening test (MWST)). It is understood that the MWST can be performed only if no ab-
normalities have been identified during the ENG up to the caloric test part of the ENG test battery. Also, the MWST calculations can be performed only if the SPV derived from each of the two warm irrigations exceeds 117/sec. It should be understood that the ABB cal-onic test must be performed if the dif-
ference between sides exceeds the criti-
cal upper limit. The reason for this is that the critical value is exceeded. It will not be possible to determine whether a pa-

tient is demonstrating a unilateral weakness or a directional preponder-
ance based on two warm irrigations. Fi-
nally, the FS test is conducted during each of the warm irrigations. The MWST is described in greater detail in Chapter 9.

It is noteworthy that attempts have been made to develop a monothermal cool screening test (for example, see Becker11); however, cool stimuli have been associated with a larger number of false-negative predictions than warm stimuli. The reason monothermal warm caloric testing is associated with a smaller number of false-negative results than monothermal cool testing is un-
clear. It may be that the identification of
abnormality to a pathologic vestibular system is associated with attempts at challenging the system to operate at levels above its resting discharge rate, rather than by evaluating the system with stimuli that are designed to decrease the spontaneous activity of the peripheral system close to its lower limit of function.

**Monothermal Differential Caloric Test**

This examination as described originally by Tokuy93, 95 is a two-part test designed to identify the presence of vestibular recruitment and vestibular de-recruitment. Vestibular recruitment refers to the unusually rapid growth in the responsiveness of the vestibular system to increases in the intensity of the (caloric) stimulus. Vestibular de-recruitment refers to the observation of no increase or a decrease in the responsiveness of the vestibular system to increases in stimulus intensity. The stimulus is made more intense by increasing the volume of the caloric stimulus (from 10 mL to 100 mL of water). It has been the contention of the authors that vestibular recruitment (like loudness recruitment in the auditory system) is observed in the presence of peripheral vestibular system disease, such as end organ disease,96 whereas de-recruitment phenomena are observed in the presence of central vestibular system disease (eighth cranial nerve and central vestibular pathways).97,98

In the first part of the test the patient's ear is infused with 10 mL of 30°C water over a 5-second period. The patient is initially seated upright with the head pitched forward 30°. This position is designed to take the horizontal semi-circular canal out of the plane of maximal stimulation (the cupula is oriented approximately parallel to the ground). After 1 minute, when the thermal changes are uniform, the patient's head is brought back 90° from the original position (60° degrees backward from vertical). This position is designed to bring the horizontal canal into a plane of maximal stimulation (the cupula is vertical). The PENG recording techniques developed by Tokuy et al.96 are utilized to record the induced nystagmus.

The second (more intense) irrigation is conducted using 100 mL of water at the same temperature (20°C). The irrigation is performed with the patient's head tipped back 60° from vertical (optimal position for horizontal canal stimulation). The irrigation occurs over a 20-second period. The variable used to quantify nystagmus intensity is called culmination frequency, (see the section "Measurement of Caloric Data" for a description of culmination frequency.)

**Indications and Technique for Ice Water Caloric Testing**

In the absence of caloric responses to standard bithermal stimulii it is important to conduct ice water irrigations to verify the absence of any residual function. The ice water test is conducted with very cold water (10°C) either obtained from a drinking fountain or by filling a cup with water and ice. The patient turns the head so that the test ear faces upward (Fig 8–11A). Two milliliters of water are drawn up into a syringe and infused into the ear canal. The patient maintains this head position for 20 seconds with the water in place, at which time the head is turned so that the water can run out of the ear canal. The patient's head is brought into the optimal position for caloric testing (30° up from supine, as illustrated in Fig 8–11B), and the nystagmus is recorded. Some have stated that because of the discomfort of the test, the ice water irrigation may "release" a latent spontaneous nystagmus. A latent spontaneous nystagmus can be differentiated from caloric nystagmus by placing the patient in the prone position after the nystagmus has been observed in the supine position. The probability of latent spon-
taneous nystagmus is good if the nystagmus direction does not reverse when the patient is inverted from the supine to the prone position.

MEASUREMENT OF CALORIC DATA

There are a number of different measurement issues in caloric testing. First, it is important to find a measurement variable that shows a small coefficient of variation (that is, small variation within a group of subjects). Additionally, it is important to develop methods for using this variable or these variables to differentiate normal from abnormal vestibular systems.

Measurement Variables

A number of measurement variables have been used to quantify caloric-induced nystagmus. These have included duration, latency, amplitude, frequency, and velocity (Figs 8-12 and 8-13).

Duration

Nystagmus duration (see Fig 8-12) was the measurement variable used in the bithermal technique of Fitzgerald and Hallpike. A stopwatch was started at the beginning of the irrigation, and timing was terminated at the point that nystagmus was no longer visible to the examiner. A time chart was made to depict graphically the asymmetries in the duration of the response. However, the duration of nystagmus is influenced by a number of factors unrelated to the responsiveness of the inner ear. The duration of the response is directly proportional to the amount of time required for the endolymph to reach its ambient temperature. That is, the endolymph in the horizontal semicircular canal is influenced by physiologic properties of the middle ear and temporal bone, which vary from person to person.

Latency

Following the development of electroneystagmographic instrumentation it was possible to quantify nystagmus in greater detail. Nystagmus latency (see
Fig 8–12 refers to the interval from the initiation of the caloric irrigation to when the nystagmus response begins. Many factors, however, determine the latency of caloric nystagmus, including the heat-transmitting properties of the temporal bone and middle ear space (as noted earlier), and the alertness of the patient.

**Amplitude**

The amplitude of the nystagmus refers to the magnitude (measured in degrees) of the nystagmus measured from the base of the nystagmus "beat" to its peak (see Fig 8–13). Thus, amplitude describes the distance the eye travels (measured in degrees) during a slow phase of a nystagmus beat. This measurement variable in isolation fails to provide useful information, as both low- and high-amplitude nystagmus may have the same velocity.

**Frequency**

Nystagmus frequency refers to the number of nystagmus beats that occur within a given time period. The time period may be (1) 5 or 10 seconds, or (2) the duration of the entire caloric response. The "culmination frequency" is a term that refers to the total number of nystagmus beats that occur within a 10-second period at the peak of the caloric response (see Fig 8–12). However, Torok stated that culmination frequency has a smaller standard deviation than the more popular measurement of slow-phase eye velocity.

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**FIG 8–13.**

Symmetrical diagram illustrating variables of slow and fast phase durations and slopes.
Velocity

Velocity is the most useful measurement variable for quantifying the caloric response (Figs. 8–14 and 8–15), nystagmus velocity (amplitude as measured over time) has been shown to have the lowest coefficient of variation, reported by Hendricksen as 39%, and the greatest sensitivity to the presence of asymmetries in peripheral vestibular system function.

Nystagmus SPV incorporates both amplitude and duration information and is quantified as the number of degrees of eye excursion over a 1-second period (°/sec). The SPV has been quantified by the highest velocity of a single nystagmus beat. More typically, SPV is quantified as an average of either of the following:

1. The three nystagmus beats with the greatest SPV at the peak of the caloric response;
2. All nystagmus beats in a 5-second period;
3. All nystagmus beats in a 10-second period at the peak of the caloric response; or
4. Ten beats at the peak of the caloric response regardless of the sampling interval.

It has been our preference to calculate nystagmus velocity based on the average SPV of ten consecutive nystagmus beats at the peak of the caloric response. The choice of the average SPV of ten consecutive beats is an attempt to control for the sampling error that occurs when a fixed time of measurement is used. For example, for one ear, three beats of nystagmus might occur in a 5-second period, whereas five beats of nystagmus might occur for the other ear within the same period of time.

There are two methods for hand-measuring nystagmus velocity. These methods are illustrated in Figures 8–14 and 8–15A–G. In the first method a line is drawn through the slow phase of a beat of nystagmus (see Fig. 8–14). The line is extended above and below the limits of this beat so that it reaches the margins of the paper. One then counts 10 mm horizontally, as the paper speed is normally 10 mm/sec and SPV is specified in the degrees (that is, amplitude) per second (time) as a unit of measure. The last step is to create a right triangle by connecting the 10-mm time mark to the diagonal line running through the nystagmus beat. The number of millimeters that constitute this vertical line up to the intersection are the number of degrees per second for that nystagmus beat (since eye movements are calibrated so that 1 mm of vertical pen excursion equals 1° of eye movement). The SPV of a number of nystagmus beats are calculated and averaged.

A second method that may be used to average the velocities of a number of nystagmus beats is illustrated in Figures 8–15 and has been referred to as the “gridding” method. To use this method one need only have an 8 × 11-inch sheet of blank paper, a pencil, and a calculator. The first step is to block-off three (or five, or ten) beats of nystagmus at what appears visually to represent the peak of the nystagmus response. The bottom corner of the vertical side of the paper is placed next to the base of the
first beat of nystagmus. A tick is placed on the paper at a position representing the height of the peak of the first nystagmus beat (see Fig. 8–15.A). This pencil tick becomes the reference base for the second beat of nystagmus. A second tick is placed over the first one, representing the height of the second nystagmus beat, and so on until the desired number of nystagmus beats have been sampled (see Fig. 8–15.B). The horizontal part of the paper is used to "grid" the duration of each of the sampled nystagmus beats. The corner edge of the paper is placed next to the base of the first nystagmus beat. A pencil tick is placed on the paper at a point representing the time from the base to the peak of the nystagmus beat (Fig. 8–15.D). This pencil tick becomes the point of reference for the measurement of the second beat of nystagmus. The second beat of nystagmus is measured the same way, and so on (Fig. 8–15.E). Finally, the height (in millimeters) is measured on the vertical axis (nystagmus amplitude; see Fig. 8–15.C) and this value is divided by the total ticks (in millimeters) on the horizontal axis (nystagmus time; see Fig. 8–15.F). This value is then multiplied by a factor of 10 and the result represents the average velocity in degrees per second (amplitude/time) for the total number of nystagmus beats (see Fig. 8–15.G).

**Calculation of Parameters**

The caloric test is used to determine if the level of function of one peripheral
vestibular system differs in a statistically significant manner from the other. Thus, there are three primary and one secondary measurement techniques used to determine normality of the caloric response. These methods are:

1. Interaural (left ear versus right ear) differences in nystagmus SPV (referred to as unilateral weakness);
2. Differences in the SPV of right-beating as compared with left-beating caloric responses (referred to as directional preponderance);
3. The capability of the central nervous system to exert control over the vestibular nuclei and thereby attenuate caloric nystagmus when the eyes are opened and gaze is fixed on a point (referred to as FSI); and
4. The overall hyper- or hypoeexcitability of the peripheral vestibular systems (referred to as hyperactive responses and bilateral caloric weakness).

What constitutes clinical significance in these calculations and the diagnostic implications of these findings will be discussed in detail in Chapter 9.

Formula for Determining Symmetry of Function

The calculation in equation (8.2) is designed to compare the responses obtained from the left ear with those obtained from the right ear. Data are provided on symmetry of function, which also allow determination of unilateral weakness to be computed. The formula used to calculate these differences is as follows:

\[
\frac{(LC + LW) - (RC + RW)}{(LC + LW + RC + RW)} \times 100
\]

where the LC, LW, RC, and RW refer to the average SPV values for the left cool, left warm, right cool, and right warm caloric irrigations. LC + LW give total left-side responses; RC + RW give total right-side responses. The denominator contains the total of all responses. The result of this equation is multiplied by 100 to yield a percent difference between the left and right sides.

Formula for Calculating Directional Preponderance

Fitzgerald and Hallpike originally described the phenomenon of directional preponderance in their historic article that described the alternate binocular bithermal caloric test. The following formula enables calculation of the propensity for nystagmus beating in one direction to be greater than the nystagmus beating in the opposite direction (directional preponderance).

\[
\frac{(LC + RW) - (RC + LW)}{(LC + LW + RC + RW)} \times 100
\]

where LC (left cool) + RW (right warm) = total of right-beating caloric responses, and RC (right cool) + LW (left warm) = total of left-beating responses, and the denominator is expressed as in the preceding formula. The practical significance of the observation of directional preponderance will be described in Chapter 9.

Formula for Assessment of Fixation Index

The fixation index (FI) is used to assess the tightness of connections between the vestibular nuclei and the midline cerebellar structures. Fixation index is calculated by using a modification of the FI formula developed by Demanze and Ledoux:

\[
FI = \frac{SPV(EO)}{SPV(EC)}
\]

where SPV (EO) represents the average slow-phase nystagmus eye velocity that occurs for 5 seconds after the eyes are opened and fixated allowing up to 2
seconds for visual fixation to occur) and SPV (EC) represents the average slow-phase nystagmus eye velocity that occurs for 5 seconds before the eyes are opened at the point of greatest nystagmus velocity.

Other Issues: Display of Data

Once caloric data have been collected and analyzed the data must be presented to the referral source in the form of a report or summary. Several types of reports have been developed over the years. Some reports consist of little more than a sheet of paper having check-marked boxes and a table of numbers representing the slow-phase velocities for each of the caloric irrigations and the percent directional preponderance and unilaterial weakness. Other report forms consist of these summaries with the addition of illustrative raw data. This raw data may consist of extracted EKG strips that have been pasted on paper. Similarly, the newer commercially available ENG systems permit illustrative raw data to be printed on standard 8½ x 11-inch computer printer paper. The requirement of any report is that the data should be displayed in a clear and understandable manner.

Several types of pictorial formats have been offered for illustrating the results of the caloric test. If a pictorial format is used, there should be no ambiguity as to the meaning of the illustration. The following are examples of display types that permit a rapid visual appraisal of the intensity of the caloric response.

Fitzgerald and Hallpike Method.—The earliest technique for illustrating postcaloric intensity was developed by Fitzgerald and Hallpike. The measurement variable was the duration of the caloric response. The investigators created a scale that consisted of an abscessa below which were placed numbers representing time measured in seconds (Fig 8–6). An arrowhead was used to denote the time value representing the duration of a given caloric response. There were four of these scales for each caloric examination, representing the results of the two warm and two cold caloric tests. This display technique permitted the reader a clear representation of asymmetries in the caloric response.

Butterfly Chart.—Clausen and von Schlachta developed another visual display method for plotting the intensity of caloric-induced nystagmus. The measurement variable for this technique is nystagmus frequency. Warm and cool responses for the right and left ears are plotted in a rectangular coordinate system that produces a butterfly-shaped graph (Fig 8–17). Responses on the "butterfly" chart are plotted by marking the maximum frequency on the four vertical scales (right warm, right cool, left warm, and left cool) and then connecting the four marks with the 0 point located in the center of the graph.

Pods.—The MacSTR (ICS Medical) computerized ENG system permits the display of a nystagmus velocity "envelope" following each caloric irrigation. This envelope is actually a graph with "itié (in sec/°a 0.1°/sec) on the abscissa (as in the Fitzgerald and Hallpike report technique) and nystagmus velocity (measured in degrees/second) represented on the ordinate. A computer algorithm is used to measure the velocity of each caloric nystagmus beat. The result of each measurement is a "dot" that is placed on the graph. The normal caloric response begins with low-velocity nystagmus. The nystagmus builds to a crescendo and then gradually declines. The
Stimulus-Related Variables

Water Temperature

A number of investigators have examined the relationship between warm and cool temperature effects and caloric responses.\(^{3, 5, 6, 6, 6}\) Higher intensities with shorter response times have been associated with warm water in comparison to cool water stimuli.\(^{6, 6}\) In this connection, Boersch et al.\(^{6}\) indicated that warm water irrigations result in increased blood flow through the skin and bone, resulting in increased thermal conduction of heat to the horizontal canals, and producing a strong caloric response; however, the caloric response declines rapidly because the warm irrigation acts to equalize temperature dif-

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**Figure 8-17.**
Data representation technique used by Clausen\(^{36}\) to illustrate nystagmus frequency.

Scatter plot of these data from a healthy individual looks like a normal bell-shaped curve. The left ear caloric responses are represented on separate sides of the graph, and the velocity scatter plots are placed one above the other. The velocity profiles following warm and cool caloric stimulation are opposite in direction. Therefore, if the velocity profiles for left ear cool and warm caloric responses for a healthy individual are placed directly over each other the result is a picture that resembles a pea pod (hence the term "pods"). Figure 8-18 illustrates responses obtained from a normal subject. Cool and warm caloric data for the right and left sides of the figure, respectively. In this example, responses begin approximately 25 seconds after the onset of the irrigation, reaching a maximum slow-phase velocity between 60 and 80 seconds, followed by a decline in response intensity. In healthy subjects, responses to cool and warm irrigations are almost mirror images of each other (that is, warm caloric irrigation tend to elicit slightly stronger mean nystagmus velocities). Further, response strength is essentially equivalent between the right and left ear.

It is the recommendation of the present authors that a signed cover letter summarizing the findings of the entire ENG examination, together with a summary sheet giving numeric data and raw traces illustrating abnormalities, should be forwarded to the referring source. This will permit the referring physician who is less sophisticated in ENG examination the option of reading a summary letter, whereas the physician who is more sophisticated will have the opportunity to evaluate the numeric data.
ferences faster than cool irrigations. Therefore, warm irrigations have shorter response times. In contrast, cool water irrigation gives rise to less intense responses with longer durations. The arteries in the external meatus and temporal bone constrict, causing a reduction in heat transmission to the horizontal canals. Further, the decay time of the resultant temperature difference is increased, causing a longer response time. Sills et al. indicated that from a clinical standpoint, temperature effects must be taken into account particularly when evaluating a directional preponderance in a patient having only one ear tested or in the case of a unilateral weakness.

Finally, it is critical that the calibration of the water stimulus be as accurate as possible. The warm and cool caloric temperatures are only 7°C above and below normal body temperature. This means that a 1°C variation away from the ideal 30°C or 44°C will result in a 14% difference in the magnitude of the stimulus. It is unclear what effect this degree of deviation from the ideal temperature will have on the caloric response.

**Habituation**

Repeated irrigation of the same ear with the same caloric stimulus will result in a gradual decrement in the caloric response. This phenomenon has been termed vestibular habituation. Fluur and Mendel examined 24 subjects, half of whom received repeated warm water irrigations and half of whom received repeated cool water irrigations. The caloric response was allowed to end before the next irrigation began. Each subject received between 8 and 12 caloric irrigations for each temperature. The examiners found for warm water irrigations that there was a regular decrement in the duration of the caloric response but that the response never did disappear. The authors were able to completely extinguish the caloric response following cool water irrigations.

**Subject-Related Variables**

**Subject Attention, Arousal, and Vigilance**

It is a common occurrence that during caloric irrigation little nystagmus may be observed until the patient is asked to perform some type of alerting
exercise. This practice of conducting alerting exercises during caloric testing grew out of a number of investigations demonstrating that caloric nystagmus may be inhibited by drowsiness and boredom in a patient. These same investigations demonstrated that brisk caloric nystagmus may be elicited by having a patient perform mental alerting exercises.

Collins et al.\textsuperscript{29} observed a caloric nystagmus of longer duration when their subjects were performing mental arithmetical tasks. The investigators also noted that the electroneystagmograms of relaxed or drowsy subjects often revealed the presence of slow aminostakal (pendular) eye movements. These eye movements were described by Barber and Wright\textsuperscript{13} under similar conditions. Sokolovsky\textsuperscript{22} evaluated the effects of three conditions of mental alertness and visual fixation on caloric nystagmus: (1) visual fixation without mental activity; (2) visual fixation with mental activity; and (3) no visual fixation with mental activity. These authors found that the velocity, duration, frequency, and amplitude of the caloric nystagmus were superior in the third alerted condition. Torok\textsuperscript{24} found that subjects were as likely to have consistent caloric responses if they were asked to remain relaxed and keep their eyes open in darkness as if they were forced to complete arithmetical calculations under the same fixation conditions. Torok argued for a flexible approach to tasks for maintaining the ENG record, which could be tailored to each subject. Barber and Wright\textsuperscript{14} developed a standardized taped list of questions (difficulty of questions ranging from 30 months’ mental age to sophisticated mathematical calculations) for patients undergoing caloric testing. The authors commented on the presence of nystagmus suppression and dysrhythmia (beat-to-beat fluctuation in the amplitude and frequency of nystagmus that has been attributed to the presence of central vestibular system disease) occurring in patients who were not adequately alerted during caloric testing. Because of the known effects of attention on the nystagmus record it has become a standardized part of the caloric test protocol for mental alerting tasks to be performed by the patient during and following the caloric irrigation (as noted earlier in this chapter).

Bell’s Phenomenon

Bell’s phenomenon refers to the saccades, afferent (rolling up) and adducting (moving laterally toward one another) of the eyes that occurs upon eye closure. The magnitude of the upward movement can be as great as 151°. Indeed, as stated earlier, Hood and Koresz\textsuperscript{16} demonstrated that the caloric response could be completely suppressed by Bell’s phenomenon. Attempts have been made to quantify Bell’s phenomenon. Goebl et al.\textsuperscript{30} reported a mean upward deviation of 151° upon eye closure in 20 normal subjects. The authors reported that 89% of their sample demonstrated a decreased nystagmus regularity during voluntary eye elevation. This nystagmus dysrhythmia decreased once the eyes returned to baseline. The investigators demonstrated further that the effects of the Bell’s phenomenon could be offset by approximately 47° by initiation of mental exercises by the subject. The authors also reported that 53% of their sample demonstrated bursts of nystagmus inhibition that correlated with the involuntary vertical eye movements (see Figure 4, page 1130, in reference 30).

The experience of the present authors is somewhat different from that of Goebl and associates. In our investigation of seven healthy young neurologically intact subjects, in which electro-oculographic instrumentation and monocular recording techniques were used, we found a mean upward deviation of 40° (±12°) and a mean lateral deviation of 9° (± 8°) following bilateral eye closure. The magnitude of the vertical eye devia-
Subject Age

A number of investigations have been conducted since the late 1960s that have served to describe the effect of age on corneal nyctagmus. These investigations have been published in international journals without the benefit of English language translation or abstracts. The interested reader is directed to reviews of these early studies found in Mulich and Petersmann49 and Oosterwold.50 In general, these studies have demonstrated that decrements in vestibular responsiveness occur with age regardless of the measurement parameter that is chosen to quantify the magnitude of the corneal response. For instance, we have observed a weak but statistically significant negative correlation between total corneal NPV and subject age, total corneal SPV and subject age (see Table 9-6). In an early study, Ayslan et al evaluated 50 healthy subjects between the ages of 49 and 64 years. The investigators reported that, in general, middle-aged subjects showed hyperactive responses and subjects aged 70 years and older showed hyporeactive responses. Almost 20 years later, van der Laan and Oosterwold51 reported their observations from a group of 334 normal subjects. The authors reported a lower nyctagmus frequency and greater nyctagmus amplitude in younger subjects (up through the third decade of life) compared with older subjects. The nyctagmus frequency increased and amplitude decreased in the older age groups. The investigators suggested that these findings in the older age groups (subjects over 50 years of age) could be explained by decreased blood supply (due to atherosclerosis) reaching the vestibular end organ. Brunner and Norris52 reported their observations culled from examinations of 293 corneal examinations from individual with negative findings on vestibular system testing. The authors quantified nyctagmus latency, amplitude, frequency, average maximum SPV, and duration. The only statistically significant parameters to show age-dependent changes were nyctagmus frequency for cool corneal stimuli, maximum SPV, frequency for warm corneal stimulation, and total (combined warm and cool) corneal stimulation. In general, the authors found these nyctagmus parameters to peak in the 66- to 70-year-old age group and to decline thereafter. In a much-quoted study, Mulich and Petersmann49 evaluated corneal responses in 102 subjects aged 11 to 70 years. The authors quantified the total number of beats of nyctagmus, maximum SPV, frequency, and amplitude over a 10-second period. Like Brunn and Norris,52 Mulich and Petersmann reported significant age-dependent increases in the total number of beats, maximum frequency, amplitude, and SPV up to about 60 years of age, after which decrements in function occurred. Karsen et al53 reported their results following conventional bithermal corneal testing in 75 subjects aged 18 to 81 years. The authors quantified nyctagmus amplitude, latency, duration, frequency, and SPV following irrigations. All parameters showed an age-related decrement. The suggestion from this investigation was that there is a decline in vestibular system responsiveness beginning around age 65 to 70, which is in general agreement with previous studies. Gough54 reported the results of serial vestibulometry on 78 subjects who were divided into seven age groups spanning 10 to 71 years. In serial vestibulometry, the car was irrigated with water at 45° C, 33° C, 29° C, 25° C, 21° C, and 17° C. The maximum SPV following each irrigation was the measurement parameter. The author reported that there were greater age-related differences in the corneal nyctagmus SPV at the extremes of irrigation temperatures. Age had a gen-
oral effect of decreasing SPV. The mean performance of subjects above the age of 51 years fell outside normal limits. No parametric analysis was reported, although the significance of reduced caloric SPV as a function of age is consistent with the findings of previous research.

Drugs

The ingestion of certain drugs may affect the physiological control of eye movements and the patient's level of arousal. Both of these factors may invalidate and/or complicate the interpretation of ENG findings.

It is well known that ocular motility studies may be affected by therapeutic and toxic doses of various drugs. Smooth pursuit is known to be impaired by phenytoin,18 phenobarbitals and other barbiturates,12,19 and alcohol.12 Gaze-evoked nystagmus is produced by ingestion of phenytoin,15,46,49,74 carbamazepine,59 and barbiturates.12 Downbeat nystagmus has been reported in two epileptic patients taking phenytoin, which disappeared when the dosage was reduced.2 Similarly, Wheeler and his coworkers30 documented a reversible downbeat nystagmus produced by ingestion of carbamazepine in an epileptic patient with no evidence of structural abnormality on computed tomographic scanning. Saccadic system abnormalities including reduced peak velocity,10 increased latency,40 and hypometria40 have been attributed to alcohol intoxication. Thus, abnormal eye movements caused by a number of drugs should not be misinterpreted as pathologic nystagmus associated with central nervous system disease.

Although the ocular motility subtests of the ENG battery are particularly susceptible to various drugs, as indicated, the caloric examination also may be influenced by certain agents. Haciski14 evaluated caloric responses obtained from eight young adults.1 hour after ingestion of a barbiturate (300 mg of sodium amytriobarbtiore-amytal sodium). It was observed that when the subject's eyes were closed, the nystagmus was either absent or weak. However, when the eyes were opened and fixation was attempted, regular strong beats of nystagmus appeared. Haciski concluded that barbiturates depress function in the reticular formation, the site of origin for the fast phase of nystagmus. In contrast, physiology within the medial longitudinal fasciculus is unaffected. This makes it possible for the conjugate slow phase of nystagmus to occur. Thus, during barbiturate intoxication the eyes deviate in the direction of the slow phase and remain in a lateral position during eye closure. However, following eye opening the gaze system brings the eyes to midline. The force of the slow component generated by the medial longitudinal fasciculus deviates the eyes laterally, and this is followed by a relaxation saccade. This may be misinterpreted as failure of fixation suppression. In addition to barbiturates, Barber and Stockwell71 have indicated that failure of fixation suppression for caloric nystagmus may result from antiepileptic drug (AED) intoxication as well. The latter authors also attributed this phenomenon to drug interference with reticular formation activity.

The mild sedative effects of barbiturates, antihistamines, and tranquilizers may result in a lowering of the patient's level of alertness.12,15,52 which in turn, may suppress caloric-induced nystagmus. Although alerting exercises may be used assiduously, it might be difficult or even impossible for the examiner to maintain an adequate level of arousal necessary for conducting the caloric examination. In this situation, it is important for the clinician to be aware of this potential source of error and act inadvertently interpret the obtained responses (or lack thereof) as reduced or absent vestibular function.

In the foregoing discussion it is apparent that the ingestion of certain drugs may (1) cause impaired smooth pursuit, gaze-evoked nystagmus, or sac-
cadic system deficits to occur that are normally associated with the presence of cerebral nervous system disease; (2) abolish or impair fixation suppression ability, and/or (3) suppress caloric nystagmus. It is recommended that patients should be instructed to discontinue medications and to eliminate the intake of alcohol for 48 hours prior to the ENG examination. Prior to testing, the examiner should confirm compliance with instruction. Exceptions to these instructions include those patients who are taking antiepilepsy medications, and psychiatric patients who are taking behavior-modifying medications (for example, antipsychotic medications). If there are no contraindications whether a patient referred for ENG testing can be told to discontinue their medications for a 48-hour period, the responsible clinician should consult the referring physician. We have found that (for the most part) referring physicians are unaware of the effects that medications have on the vestibulo-ocular reflexes or an oculomotor instability. Likewise, most referring physicians are agreeable, when possible, to having their patients not take these medications for the period of time necessary to obtain an interpretable test. It is incumbent on the clinician to note any medications or drugs ingested by the patient and to interpret the ENG findings accordingly, or, more preferably, to reschedule the examination.

Recording Variables

Illumination and Visual Fixation

A number of studies have analyzed the effects of different types of visual fixation on the caloric response. The initial study conducted by Fitzgerald and Hallpike was conducted before the advent of electro-oculographic (electro-oculography) techniques, and thus nystagmus could not be observed behind closed eyelids. Therefore, patients were evaluated with their eyes open and fixating their gaze on a distant point, much the same way that fixation suppression testing is conducted today. After electronystagmography became available, studies were conducted with the purpose of examining the effects of different types of ocular fixation and room illumination on caloric nystagmus. The ultimate purpose of these studies was to determine optimal data recording conditions for conducting the caloric examination. The caloric test is usually conducted under one of three conditions: (1) with the patient's eyes open in a completely dark room; (2) with the patient's eyes closed in a semi-darkened room, and (3) with the patient's eyes open and wearing Prenzel's lenses in a semi-darkened room. It is extremely difficult to create a light-proofed environment that is required to eliminate visual fixation during the caloric test. However, conducting the examination with eyes open in darkness eliminates the effect of Bell's phenomenon on the caloric response. Most clinicians conduct the examination with the patient's eyes closed in a semi-darkened room. Baloh et al. examined these testing conditions and determined that the coefficients of variation of the caloric response were lowest with the patient's eyes open in a dark room. The next best recording technique was with the patient's eyes open and wearing Prenzel's lenses. The authors noted that nystagmus was periodically suppressed and there was slowing of the fast component when the examination was conducted with the patient's eyes closed.

Like Baloh et al. and Klareskog et al. examined visual fixation during caloric testing. These authors observed that nystagmus SFV was equivalent in both the "eyes open in darkness" and "eyes closed in darkness" conditions. Further, in contrast to the findings of Baloh and co-workers, the coefficient of variation was found to be largest for the conditions where Prenzel's lenses were used (such as eyes opened and lighted lenses, eyes opened with unlighted lenses, eyes opened with lighted lenses and strobe
lighting). In fact, the authors reported that caloric nystagmus was suppressed in the lighted lenses conditions (presumably because of the subject's ability to fixate their gaze on objects within the glasses).

The clinician should be aware that the visual conditions under which the caloric test is performed are not trivial considerations. The present authors recognize the practical limitations that must be dealt with in a hospital or outpatient clinic. We recommend that caloric testing be conducted with eyes opened in darkness, or with eyes closed in a semi-darkened room. The importance of effective alerting exercises is critical if the latter technique is used.

**Head/Body Position**

Coats and Smith conducted a meticulous study of the caloric response as subject body position (12 subjects) was varied over 360°. Data from this study (see Figures 5 and 6 from reference) illustrated that the maximum caloric response occurred when the head (and body) was positioned between 0° and 60° upward from the supine position for both warm and cool caloric irrigations. From their data it appears that small deviations in the position of the head from the ideal 30° vertical (with the subject in the supine position) probably have little effect on the magnitude of the caloric response.

**Variables Affecting Fixation Suppression Ability**

**Caloric Temperature**

It is surprising that little is known about the effect that specific stimulus variables have on FS. For instance, it is generally accepted that warm water (44°C) caloric stimuli elicit stronger slow-phase nystagmus velocities (SPV) than cool caloric (30°C) stimuli. It is also known that the pursuit system can follow smoothly moving targets with a gain of 1.0 for targets that move from 30° to 60° per second. As this upper limit is exceeded the target slips off of the retina and the smooth eye movements are replaced by catch-up saccades. It would follow that if the pursuit system plays a role in cancellation of vestibulo-ocular reflex that caloric stimuli associated with greater SPV would be associated with lesser amounts of vestibulo-ocular reflex cancellation. An investigation conducted by Jacobson and Henry demonstrated temperature-dependent changes in FS ability. It was shown that warm caloric stimulations were associated with poorer FS ability. It is interesting to note that these differences were small (mean difference in FS ability = 0.12) and they were associated with relatively small differences in the mean maximum SPV for the cool and warm caloric irrigations (20.31°sec and 29.59°sec, respectively).

**Effects of Age on Fixation Suppression Ability**

The same investigation by Jacobson and Henry showed a relationship between FS ability and subject age but only for the warm caloric stimulus. The authors explained this finding based on the assumption that (1) warm caloric stimuli yield larger SPV's than cool caloric stimuli, and (2) that FS is mediated by the pursuit pathway. It is known that the upper limit for normal pursuit gain (a gain of 1.0) for healthy subjects is 30°/sec for target excursions of 5° 10° from primary gaze. A pursuit gain of 1.0 for elderly subjects is not seen for target velocities greater than 5°/sec. The mean age of the subjects in the study conducted by Sharpe and Sylvester was 72 years. The mean age of the subjects who participated in the study conducted by Jacobson and Henry was 57 years. In fact, 65% of the subject population was 60 years of age or older. Thus, it is likely that FS ability differed in the older subjects because the warm caloric irrigations resulted in a nystagmus SPV that exceeded the age-related limits of the pursuit subsystem.
Practice Effects

Takei et al. has reported that fixation suppression ability in normals improved with repeated testing.

PROBLEMS, PITFALLS, AND ARTIFACTS ASSOCIATED WITH CALORIC TESTING

**Perverted Nystagmus**

In a patient with normal anatomy, there is no circumstance where stimulating the horizontal semicircular canal can result in a vertical nystagmus or a vertical component to a primarily horizontal nystagmus. The observation of vertical nystagmus during caloric testing is referred to as “perverted” nystagmus. This type of nystagmus occurs rarely and denotes disease affecting the vestibular nuclei. The vestibular nuclei process afferent activity from the peripheral system. The efferent outflow from the vestibular nuclei is then routed through the oculomotor system.

It is important to be aware that other sources may account for the presence of a vertical component during caloric testing. During calibration it is important to determine whether the vertical channel shows pen movement during horizontal eye movements. It is possible for the vertical electrodes to record a small potential difference during horizontal eye movements. If this phenomenon can be detected during calibration and during oculomotor subsystem testing, contamination of the vertical channel by horizontal nystagmus may be expected during caloric testing.

**Eye Blink Artifact in the Horizontal Channel**

Eye blink activity can be observed in the horizontal channel of the two-channel nystagmus record (Fig. 8–19). However, the biphasic eye movement generated by eye blinking is usually sharply peaked without a definite slow or fast phase. It is helpful in these instances to attempt to correlate in time the eye blinking in the vertical channel with the

**Figure 8–19.**

Example of eye blink artifact. Note the synchronization of peaks in the horizontal channel (top) with the eye blinks in the vertical channel (bottom).
questionable nystagmus in the horizontal channel. If the two are correlated in time it is probable that the horizontal nystagmus is eye blinking artifact.

Week or Absent Responses

As discussed earlier, one of the four caloric irrigations may yield a minimal response. This may occur in the presence of both a unilateral weakness on the ipsilateral side and a directional preponderance for nystagmus beating toward the opposite ear. Alternatively, this may occur because the irrigation was less than optimal or because the patient was not properly alerted. It has been suggested that the sign of an adequate water irrigation is the presence of a drop of water on the ear drum. It is always wise to visualize the ear drum prior to the caloric irrigation. This accompanies two purposes. First, otoscopy will identify the presence of large amounts of cerumen that could obstruct the flow of water or air. Second, visualizing the ear drum provides information about which direction to orient the delivery tube during the irrigation.

Occasionally, all four caloric irrigations will not yield nystagmus. This may be caused by a number of reasons. It has already been stated that inattentive or drowsy subjects may not show a caloric nystagmus. Additionally, it has been noted that many medications that act on the central nervous system will affect the vestibulocerebellar reflex arc. These medications may have a profound effect on the intensity of caloric nystagmus. Also, those patients who fail to generate caloric-induced nystagmus with eyes closed may have a saccadic system deficit. These patients are often unable to generate saccades during sac- cadic system testing. During caloric testing only the slow phase (the vestibular phase) of the nystagmus occurs. The eyes behind closed lids become tonically deviated in the direction of the slow phase. This phenomenon may only be observed when the patient's eyes are open. Thus, when an absent caloric response occurs it is important to observe the position of the patient's eyes during fixation suppression testing as soon as the eyes are opened. The finding of sac- cadic system abnormality of this type implicates the pontine brain stem reticul- ular activating system. Finally, it has been noted by ourselves and others that some subjects who do not demonstrate caloric responses will demonstrate nor- mal responses to rotational testing. It is known that water or air caloric stimulation is analogous to a rotational stimulus at around 0.003 Hz. Rotational testing usually begins at or about 0.01 Hz. Thus, it is possible that these patients have reduced peripheral vestibular system function at the lower end of its operating range.

Spontaneous or Congenital Nystagmus Superimposed on Caloric Response

Spontaneous nystagmus can complicate the interpretation of the gaze, optokinetic, positional, and positioning tests. Spontaneous nystagmus can also complicate the caloric test. Spontaneous nystagmus algebraically adds to or subtracts from the evoked caloric nystagmus. Thus, a 30/sec right-beating caloric response will be attenuated by a preexisting 15/sec, left-beating spontaneous nystagmus. The same caloric re- sponse will be eliminated by a preexisting 30/sec, left-beating spontaneous nystagmus. It often occurs that the responsiveness of an end organ can be as- sessed only by calculating the difference in the velocity of the spontaneous nys- tagmus before and following caloric irri- gation.

CONTROVERSIES IN CALORIC TESTING

In recent years a number of published reports have been critical of Bar- ney's theory of caloric transduc-
These papers were published for the most part following the voyage of Spacelab I in November 1983. During this mission, caloric stimulations were conducted on two subjects. The caloric medium was air, and both ears were irrigated simultaneously with air at 15°C for one ear and 44°C for the other ear. The test was to create as intense a stimulus as possible. If the thermal convection theory was the only method for transduction, no nystagmus would have resulted from the caloric stimulation. According to the theory, differences in the density of endolymphatic fluids would not exist. However, nystagmus (albeit weak) was elicited by the air stimulus. For a second subject, the horizontal semicircular canal of squirrel monkeys and subjected to ice water caloric irrigation. The results are similar to the results obtained in the absence of caloric nystagmus. Finally, Coats and Smith (1982) elicited the effects of body position on the presence of caloric nystagmus. The investigators conducted caloric stimulations with their subjects fixed on a table that could be rotated about the binaural axis. The nystagmus was measured every 30° of movement of the table through the full 360° range. The authors demonstrated that the evoked nystagmus intensity was clearly greater in subjects in the face-up than in the face-down condition. The thermal convection theory would have predicted an equal and opposite direction and intensity of nystagmus when the table was inverted. Taken together, these findings have caused investigators to search for alternative or adjunctive explanations for the presence of caloric nystagmus.

It is now believed that there are at least two additional routes of thermal stimulation in the vestibular system. These (1) through direct thermal stimulation of the vestibular end organ and/or neural elements, and (2) through volume expansion of endolymph and the resulting mechanical transduction of the end organ.
that the direct thermal effect contributed 42% and 34%, respectively, to the total myotrigonus responses of warm and cool stimulation with the subject in the position of maximum response.

Direct Volume Expansion From Thermal Stimulation

A second explanation for the results reported by Coats and Smith[2] has been offered by Witt et al.[8] According to this theory, the heat transfer following caloric stimulation results in an overall expansion of the fluid in a closed system like the membranous labyrinth of the horizontal semicircular canal, warm caloric stimulation results in uniformly distributed pressure being exerted on the cupula. Thus, a warm stimulation would be expected to increase and cool stimulation would be expected to decrease the volume of endolymph and the resulting endolymphatic pressure on the cupula. This increase or decrease of pressure would result in an increase (depolarization) or decrease (hyperpolarization) of spontaneous activity on the affected side.

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The stimulus for water caloric testing is either 30° C or 44° C water presented to the ear over a 30-second period for a total volume of 250 ml (8.3 ml/sec). The temperature, flow rate, and duration of caloric irrigations must be precisely controlled. The instruments needed to calibrate the water caloric stimuli consist of a stopwatch, a graduated cylinder that will hold at a minimum 250 ml of water, and a laboratory-grade thermometer that measures temperature in degrees centigrade. The objective is to deliver 250 ml of water over a 40-second interval. This water should be 30° C for the cool caloric irrigations and 44° C for the warm caloric irrigations.

Duration of the irrigation can be measured with the stopwatch. This is done by simultaneously starting the stopwatch when the irrigating water is delivered and stopping the stopwatch when the irrigating water is no longer delivered. The difference in time is noted. There is an adjustment on the water caloric irrigators that permits the duration of the irrigation to be varied. If duration of the irrigation is less than 40 seconds an adjustment is made on the timer and the irrigation is measured again with the stopwatch.

The total flow (for example, 250 ml) is evaluated by running the water into a graduated cylinder during the irrigation. At the end of 40 seconds the total volume of water is measured. If the total volume is less than 250 ml, one of two methods may be used to increase the total volume depending on the brand of irrigator that is purchased: (1) the pump can be adjusted to force more water through the delivery system during the 40 seconds, or (2) the delivery tip can be systematically shortened, thereby decreasing the internal diameter of the tip and allowing more water to flow in the 40-second period. If the total water volume is more than 250 ml during the 40-second period, the pump can be adjusted to produce less water flow, or a new tip can be put on the delivery hose and the process of shortening the tip to produce the desired total volume can be started again.

The method of determining water temperature is a bit more complicated. The incorrect method of measuring wa
ter temperature is by placing the laboratory thermometer directly into the water bath. It is important to remember that although water is a good temperature-conducting medium there is still some heat loss as the water passes from the bath to the irrigating tip. Therefore, measurements of water temperature are made at the irrigation tip as the water exits. It is important to purge the system (if the irrigation system is not a "closed-loop" system) before temperature measurements are made. If the temperature is greater or less than the desired temperature, an adjustment can be made to the thermostat on each bath to increase or decrease the temperature. If an adjustment is made to increase the temperature of the bath, the warming light will illuminate and will terminate when the feedback circuit within the bath verifies that the water has reached the chosen temperature. The measurement should be made again with the thermometer, and adjustments should be made until the water is 30° or 44° C. Be aware that 5 to 10 minutes may elapse, once an adjustment has been made, before the water reaches the desired temperature.