Gait Analysis: Yesterday and Today: Part 1

Here's a modern approach for today's specialist.

BY JOSEPH C. D'AMICO DPM, DSC

Goals and Objectives

- To present an overview of the history and evolution of gait analysis
- To discuss its importance in the assessment of ambulatory ability
- To compare various methods that may be employed
- To present a framework for its clinical indications
- To offer a rationale and protocol for its application

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*Following this article, an answer sheet and full set of instructions are provided (pg. 106).—**Editor***

When one looks through a microscope at one-celled organisms moving rapidly across a slide, there are always a few that don't move at all. This is because these are the ones that are no longer alive. Life in all its manifestations and forms is movement, and you can't move without your feet.

The responsibilities of the human foot are both static and dynamic: statically to support body weight while dynamically to transport the individual from one point to another. We don't need our feet for sitting or lying down, so any examination that takes place solely off weight-bearing will not provide critical information regarding the level of proficiency with which the locomotor system is functioning. Even standing radiographic assessment of skeletal alignment does not uniformly predict symmetrical function.[1,2]

Verne Inman, MD, founding director of the legendary University of California Biomechanics Laboratory at Berkeley and mentor of some of the most widely recognized and respected names in biomechanics, once said, "It is obvious that any improvement in either surgical and physiotherapeutic procedures and in braces and prostheses must rest upon an accurate knowledge of the functional characteristics of the normal locomotor system."[3] It then stands to reason that any specialist involved with foot and limb dysfunction, deformity and/or disability should possess a knowledge of normal functional ability and have a methodology available to be

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able to objectively assess, document and address abnormal function.

In the past, and if at all, clinical gait analysis was primarily assessed by observational gait analysis (OGA), whereas today video gait analysis (VGA) along with 3-D imaging techniques that were once reserved for advanced laboratory assessments can now be performed on a smartphone in the office. Likewise, computer-assisted gait analysis (CAGA), which previously was relegated to scientific studies, is now easily utilized in a clinical setting. Adding VGA to OGA with or without the addition of CAGA provides today's practitioner with an enhanced appreciation, understanding and documented evidentiary assessment of locomotor performance.

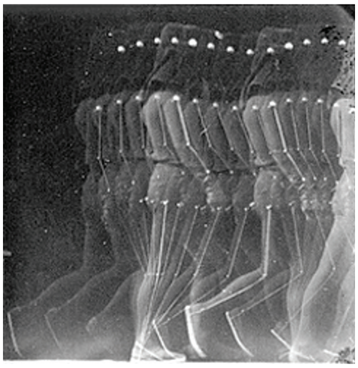

Figure 1: Early time-lapse photography of a subject walking in a "skeleton suit" with iridescent buttons placed in key locations depicting sagittal plane oscillations and segmental relationships during gait.

Walking is the most widely practiced form of aerobic exercise, beneficial not only for cardiovascular health but for its positive effects on the entire musculoskeletal system. Proper form during walking enhances efficiency, whereas improper form may cause additional strain on the body and result in such issues as spinal degeneration and diffuse pain syndromes. Good posture promotes proper form during walking, and since the foot is the foundation, this starts with the feet. It's difficult to achieve and maintain good posture in the superstructure if you don't have good posture in the infrastructure. Improving foot function not only improves foundational stability but enhances performance and ambulatory ability as well. Walking is a participation component and the key activity in mobility assessment, which may be negatively impacted by musculoskeletal and neuromotor pathology.

Aristotle first described the ground reaction force.

Walking appears to be a simple act but in reality is a complex biomechanical process involving not only muscles and tendons but the entire central nervous system.[4] The inner labyrinth of the ear, retina of the eye and proprioceptors in the neck, trunk and lower extremity all contribute to an efficient walking pattern while disorders in these systems negatively impact movement. Gait is visually driven; therefore, any disorder that affects vision significantly and negatively impacts gait. How and why a patient walks the way they do is the result of a complex constellation of factors including age, gender, walking velocity, biomechanical imperfections and accompanying compensations. Furthermore, since locomotion is the sum total of integrated system function, the presence and influence of systemic disease adds to these factors; consequentially, the evaluation of gait is not an easy task.

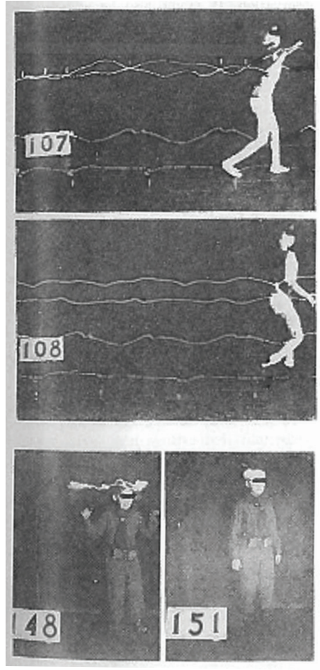

Figure 2: Child with cerebral palsy without custom foot orthoses (CFO) 107,148 and with CFO 108, 151. Note the marked reduction of vertical oscillations, smoothing of all segmental waveforms; and since a stable base and enhanced proprioceptive signaling have been provided, a dramatic reduction of now unnecessary arm movements is observed.

Historical Perspective

Hippocrates, in 400 BC, expressed an interest in the relationship between muscles and function.[6]

Aristotle was one of the earliest biomechanists who, in 350 BC, presented the first scientific and geometric analysis of gait. He was also the first to accurately describe the Ground Reaction Force (GRF)—"for as the pusher pushes so the pusher is pushed".[5]

In 1836, the Weber brothers were the first to clearly describe the gait cycle and defined temporal parameters such as swing and stance phases of gait, trunk movement, step length and duration.[7] They furthermore dispelled the notion that gait requires active intent with each step but rather depends on the rhythmic pendulum-like oscillations of the limbs resulting from the force of gravity perpetuated by inertia, and it does not require an act of will in order to produce regularity of successive steps. In essence, once the process is begun, it continues to go with very little energy required. Therefore, any limitation or impediment in the normal range of motion,

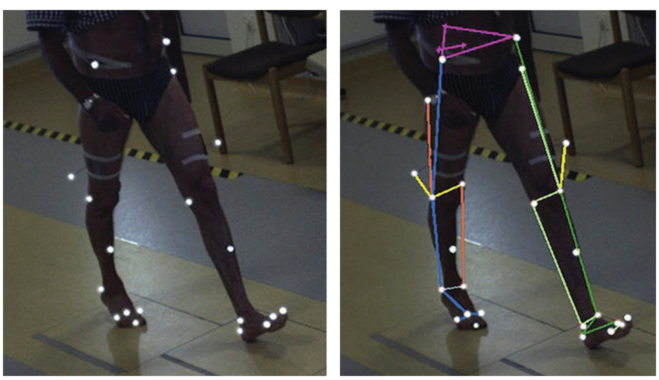

Figure 3 a, b: Modern, clinically applicable kinematic assessment of lower extremity movement patterns.

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whether it be in the upper or lower extremity regardless of etiology, will pathologically affect gait.

Kinematics

Kinematics is that branch of biomechanics that studies joint motion without regard or reference to the forces creating that motion. Variables include stride length, speed, acceleration and distance. Heralded as the founder of human motion studies is Etienne Jules Marey, a French scientist, physiologist and chronophotographer, who in 1873-1874 published *La Machine Animale (Animal Mechanism)*, studying terrestrial and aerial locomotion.[8]

Marey developed a "skeleton suit" with iridescent buttons sewn on in strategic locations and then photographed human movement with a self-invented "gun camera" that took 12 exposures per photographic plate (Figure 1). Richard O. Schuster, DPM, in a 1959 article "The Photo-Kinegram in Foot Therapy", depicted the use of kinematics with light markers and time-lapse photography to record gait variations and their response to treatment with custom foot orthoses (Figure 2).[9] Today, 3-D motion-capture gait systems using landmark-based markers are available for use in clinical practice (Figures 3 a, b).

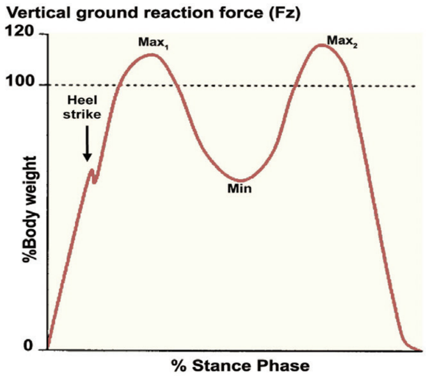

Figure 4: Characteristic soft "M"-shaped normal force vs time gait cycle curve.

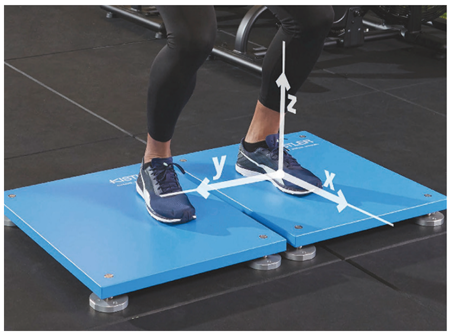

Figure 5: Subject standing on a force plate performing deep knee bends depicting the three force component pathways that are being measured. Note the elevation of the plates, causing "targeting" when conducting gait studies.

Kinematics is the branch of biomechanics that deals with motion without regard or reference to the forces creating that motion.

Gaston Carlet was a student of Marey and in 1872 published the first essentially correct gait cycle description to record pressure and duration.[10] Carlet and his student Ampar utilized air-reservoirs to measure GRF, which produced a soft "M" shaped curve that is the characteristic model of a normal gait pattern (Figure 4)[10] Braun and Fischer at the turn of the nineteenth century performed the first 3-D gait research useful in developing mechanical gait parameters.[7,11]

Ground Reaction Force

GRF is the force between the foot and the ground necessary to support body weight (ground force) and accelerate the center of mass of the subject (inertial force).[12,13]

There are three components to GRF: vertical (Fz), medial-lateral (Fly) and anterior-posterior (Fx) (Figure 5). The vertical GRF is depicted by the familiar double-humped, soft "M" shaped curve. Most systems that are capable of detecting plantar pressure in a clinical setting record vertical GRF's but not medial-lateral or anterior-posterior forces. If this information is critical it can be obtained by force plate analysis, which in the past has primarily been employed in a research setting but now has found increasing application in the clinical evaluation of forces occurring in the foot and ankle during sports activities such as those that occur during jumps, starts or squats.

Force plates are usually cost-prohibitive for the average practitioner and require specific and extensive installation criteria. On the other hand, in-shoe pressure testing insoles such as the F Scan (Tekscan) or Pedar (Novel) systems capture vertical GRFs in the environment in which these forces occur, i.e., inside the shoe (Figure 6).

GRFs reveal an abnormality but not its etiology. Assumptions can be made, but such factors as structural imperfections, muscle strength, imbalance or weakness are neglected. Conclusions that are derived from this data are more tenuous the further away from the site from which it was obtained.[14] For example, an individual demonstrating a higher GRF on the lateral aspect of the right calcaneus could be confidently linked to the individual's complaint of lateral genicular pain on that side; however, if one were to attach this finding with the patient's adjunctive complaints of right cervical and shoulder pain, it would be a more tenuous assumption.

Figure 6: In-shoe pressure sensor systems collect vertical GRF and temporal data in an unobtrusive realistic environment.

It's About Time

GRFs are of little value by themselves unless taken in context with time. Since the foot functions in move-

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able segments—and since each segment must be in a specific ideal position on the ground and in the air at the appropriate time and for the appropriate length of time in the gait cycle—it is the direction, duration and amplitude of pressure in a time context that must be assessed. The forces influencing these events occur under the foot and inside the shoe. They are unable to be seen with the naked eye, timed with a stopwatch or measured with a conventional scale, yet their identification, acquisition and quantification is vital in assessing foot and limb function, identifying pathology, prescribing treatment, evaluating management and many other facets of foot and ankle pathology.

Kinetics is the study of the forces and torques that affect motion and explains how a body responds when a force is applied to it with respect to the interactions of sequence of motion in relation to time and forces present. In the 1930s, Herbert Elftman PhD at Columbia University in New York designed the first mechanical, 3-component force plate and was able to perform the first dynamic kinetic pedobaraographic studies recording plantar pressure distribution.[15,16] Since that time, the onset of computers allowed the creation of complex models to simulate various type of movements and the forces that accompany them.

In 1953, Saunders, Inman and Eberhart published a landmark article entitled "The Major Determinants in Normal and Pathological Gait" that still guides clinicians and researchers.[17] They began by assuming that a gait pattern is most efficient when it minimizes vertical and lateral excursions in the center of gravity COG and then identified those determinants that would minimize those excursions and suggested this would indicate normal or pathological function.

The "Founding Father of Clinical Gait Analysis" is

FIGURE 8

Selected Elementary Gait Analysis Observations

Pronation and supination
Knee position and pathology
Pelvic rotations and tilt
Postural alignment and derangement
Heel position at contact and midstance
Increased shock (visible/audible)
Arch collapse
Angle of gait
Active or passive propulsion
Digital clawing

FIGURE 7

Limitations of Observational Gait Analysis

No permanent record
Eye cannot observe high-speed events
Movements not forces observed
Dependent on examiner skill and experience
Hawthorne affect skews observations
Office or lab different from reality
Subjective shaded by assessor bias

Michael Polchaninoff invented the in-shoe pressure testing system capable of measuring plantar pressure and path of pressure, temporal parameters, and waveform analysis.

Donald H. Sutherland, an orthopedic surgeon and student of Verne T. Inman, who in 1957 interposed dynamic EMG recordings on 16mm film. In 1972, with special cameras and a superimposed advanced coordinate system coupled with synchronized EMG, he studied gait in children.[7,12] This procedure spawned the development of 3-D movie and video game animation. In 1959, J.R. Close performed film recording of phasic muscular activity during gait.[18]

In the 1960s-1980s M.P. Murray, PT, PhD, utilized interrupted light photography (1964), a 3-D imaging system that studied normal walking in men, women and children.[19-22] John V Basmajian, MD, a student of Inman, developed a technique for EMG that did not require local anesthesia and that allowed the study of multiple muscles simultaneously.[12,23,24]

Another key figure in gait analysis, student of Inman and former physical therapist, is Jacqueline Perry, MD, noted for her work on post-polio syndrome, gait analysis and dynamic use of EMG.[25] Dr. Perry also developed instrumentation to monitor foot-floor contact, joint motion and the energy cost of walking. Bringing us up to date is Sheldon Simon, MD, who developed the gait laboratory at Boston Children's Hospital utilizing force plates, 3D-camera, 16mm high-speed system, Vanguard motion analyzer and computer to analyze data simultaneously.[26]

These technologically advanced, laboratory-based research systems were capable of measuring force/time in two- or three-dimensional graphic representation, depict-

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ing and measuring movement patterns, calculating temporal parameters and more. The information was derived while the patient walked over a "plate" or along a walkway either barefoot or in a shoe. These captured forces generated from the foot to the ground or shoe to the ground; however, none of these systems measured the forces occurring under the foot inside the shoe.

It was in the early 1980s that Michael Palchaninoff, DPM, a New York College of Podiatric Medicine graduate and Orthopedic Fellow, invented a compact, portable computer-assisted pressure testing system that Langer Biomechanics marketed as the Electrodynogram (EDG).[27-29] It was under his tutelage and guidance that we began to understand and appreciate the applications and possibilities of the then-groundbreaking technology. It became immediately apparent that this system enabled the unencumbered acquisition of gait data, which not only included vertical GRF inside the shoe but temporal parameters as well.

Figure 9: Obvious asymmetrical gait pattern with a head, pelvis and torso shift to the right. This patient had a significant right limb discrepancy with subsequent alterations in gait secondary to recurrent bone tumor induced iliac crest excision.

The data proved to be repeatable, relevant and reliable. The information it provided either affirmed or raised concerns regarding the biomechanical examination and observational gait analysis findings. In essence, this new technology offered a broadened functional perspective by revealing what was actually taking place under the foot/inside the shoe while the subject was walking—which is often quite different from what can be deduced from static and even dynamic clinical observations. Several research projects were undertaken and completed for publication.[30,31]

It is interesting to note that Tekscan acquired the EDG program in the 1990s and incorporated it into its F-Scan system.[32]

Observational Gait Analysis

Human gait should be smooth, symmetrical, effortless and efficient with minimal energy expenditure and minimal shift in the COG from its protected, balanced position anterior to the second sacral vertebrae as it moves forward to its intended destination.[33] The greater the number of contact points in the locomotor apparatus, the simpler the effort. In the case of a wheel, the number of contact points is infinite; however, in humans there are only two.[33]

The most commonly performed, simplest and least costly way of assessing gait is by watching someone walk. However, observing someone walk and noting abnormalities is by itself of limited value since what is being observed is the result of a problem and not its cause (Figure 7). In reality, what is viewed is the subject's attempts to compensate for an underlying pathology after all available avenues of compensation have been exhausted.[33]

In OGA, observations vary from examiner to examiner, and it is difficult to record and compare findings from visit to visit.[1,2,15,16,36,37] Movements—not forces—are being surveilled, and pronouncements that are made are dependent upon the synthesis of these observations, taking into account history and examination findings coupled with the intelligence and experience of the examiner (Figure 8). Gait is virtually impossible to measure through OGA, and although this method is an unreliable indicator of the body in motion, significant deviations from the norm should be relatively easy to discern even to the inexperienced clinician (Figure 9).

Additionally, the more time you spend watching someone walk, the more clues you will discover leading to a better appreciation of the character and location of the imperfections that have caused the patient's pathology. Simplistically put: THE MORE YOU LOOK, THE MORE YOU'LL SEE!

The correlation of the biomechanical examination findings, as well as knowledge of musculoskeletal constraints, is critical in the evaluation of gait observations. The goal of OGA is to gain an appreciation of how the body moves as a whole. When observing gait, begin by obtaining a gross review of the organism in motion that will provide a sense of flow to the action taking place. Richard Blake, DPM, MS, in *Practical Biomechanics for the Podiatrist Book 1* has an almost 50-page section on OGA that is highly recommended reading for anyone involved in care of the foot and ankle.[38] Dr. Blake likes to begin from the head downward while this author typically begins from the foot upward. In either approach, compare each segment with normal and with the contralateral side, paying particular attention to the lower extremity articulations.[14]

Alteration in a patient's gait in response to them being observed is referred to as the Hawthorne effect.

Figure 10: Fundamental VGA can be a simplistic, inexpensive, in-office method of documenting foot and limb function that adds to information provided by OGA but is not without its shortcomings.

Note head tilt; shoulder, spinal, or pelvic deviations; arm swing; or limp. The eyes should be level to the

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horizon and the mouth parallel to the eyes. Shoulders should be level. The knee should be straight ahead at heel contact without excessive adduction or abduction of the femur. Dr. Blake finds it helpful to place a marker or dot at the center of the knee to facilitate these observations.

There should be neutral to inverted calcaneus at heel contact without undue impact and normal sequencing of the gait cycle. The heel should not be seen to "bounce" up prematurely during propulsion, and all observations should be symmetrical and expected. The gait angle and base of gait should be within normal ranges and symmetrical. During swing phase, the foot should clear the ground efficiently without excessive activity of the extensor group.

With the subject walking at their self-selected pace, OGA can be performed in a hallway preferably 10-30 feet in length, but even observing a few steps is better than no steps. Alterations in gait in response to being observed is known as the Hawthorne Effect, which gives rise to the golden rule of gait analysis: *observe the patient's gait when they are unaware of you observing them.*[8] OGA is performed, and findings are recorded with the patient walking barefoot, in shoes, and in shoes plus custom foot orthoses. Although replete with shortcomings, OGA is an essential examination component not only in determining ambulatory ability but also in identifying the cause of any disability.

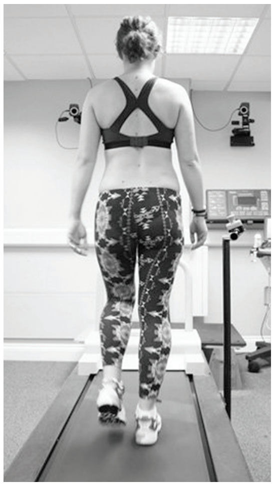

Figure 11: Sophisticated laboratory-based, multi-camera, computer-assisted VGA provides additional information but is still incapable of determining plantar pressure, path of pressure and accurate assessment of temporal parameters.

Video Gait Analysis

In today's technologically advanced society, it seems as if everyone from the clerk in the running shoe store, the chiropractor, the pediatrician, therapist, personal trainer, yoga or Pilates instructor and others have all proclaimed themselves to be experts on foot and limb biomechanics. In reality, very few really are. The ability to gather information through modern technology does not automatically convey an understanding of this information nor how it can be applied clinically. This ability or inability is determined by the level of training, intelligence, experience and skill of the examiner. In any event, additional information does provide additional insights; however, its significance is limited by the perspective from which it is being viewed.

VGA allows documentation of high-speed events and provides movement patterns but does not assess plantar pressure, path of pressure or temporal parameters. It is a simple, inexpensive methodology useful for comparison with prior testing. A basic VGA can be performed with a smartphone or iPad, whereas more elaborate multi-camera systems with multiple cameras are more difficult to perform in clinical practice (Figures 10, 11). Kinematic assessment with key body point markers provide a detailed computer-generated depiction of movement patterns, which can then be correlated with examination findings and complaints (Figures 3 a, b).

Summary

Abnormalities in gait may be due to pathomechanical imperfections in the musculoskeletal system, manifestations of systemic disease or part of idiopathic gait changes associated with the aging process. Observation and recording of gait abnormalities by the astute clinician may enable early diagnosis of their associated underlying disorders, in turn allowing more appropriate, effective and immediate management to be instituted. This may be further enhanced through the use of CAGA, which will be discussed in Part 2.

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CME **EXAMINATION**

SEE ANSWER SHEET ON PAGE 107.

1) How and why a patient walks the way they do is the result of a complex constellation of factors including which of the following?

- **A) Age**
- **B) Vision**
- **C) Biomechanical imperfections**
- **D) All of the above**

2) Who first described the ground reaction force (GRF)?

- **A) Hippocrates**
- **B) Aristotle**
- **C) Root**
- **D) Galileo**

3) The branch of biomechanics that deals with motion without regard or reference to the forces creating that motion is known as

- **A) Kinetics**
- **B) Kinematics**
- **C) Kinesiometrics**
- **D) Kinesthetics**

4) A normal gait pattern force/time curve best resembles which one of the following letters?

- **A) W**
- **B) V**
- **C) M**
- **D) Y**

5) The force between the foot and the ground necessary to support body weight and accelerate the center of mass of the subject is referred to as

- **A) Momentum**
- **B) Inertia**
- **C) Ground reaction force**
- **D) Gravitational pull**

6) The most efficient gait pattern is represented by which of the following?

- **A) Least expenditure of energy**
- **B) Minimum vertical and lateral excursions**
- **C) Symmetrical function**
- **D) All of the above**

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Continuing Medical Education

CME **EXAMINATION**

(Continued from page 105)

7) Which individual invented the in-shoe pressure testing system capable of measuring plantar pressure and path of pressure, temporal parameters and waveform analysis?

A) Michael Polchaninoff
B) Merton Root
C) Richard Schuster
D) Donald Sutherland

8) What is the LEAST reliable method of gait analysis?

A) Computer-assisted gait analysis
B) Observational gait analysis
C) Video gait analysis
D) None of the above

9) Alteration in a patient's gait in response to them being observed is referred to as

A) Antalgic gait
B) The Hawthorne effect
C) Overcompensation
D) Individualization

10) Disadvantages of video gait analysis (VGA) include which of the following?

A) Does not assess plantar pressure
B) Does not assess path of pressure
C) Does not assess temporal parameters
D) All of the above

SEE ANSWER SHEET ON PAGE 107.

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Over, please

ENROLLMENT FORM & ANSWER SHEET *(continued)*

EXAM #8/25
Gait Analysis: Yesterday and Today: Part 1
(D'Amico)

Circle:

1.	**A**	**B**	**C**	**D**	**6.**	**A**	**B**	**C**	**D**
2.	**A**	**B**	**C**	**D**	**7.**	**A**	**B**	**C**	**D**
3.	**A**	**B**	**C**	**D**	**8.**	**A**	**B**	**C**	**D**
4.	**A**	**B**	**C**	**D**	**9.**	**A**	**B**	**C**	**D**
5.	**A**	**B**	**C**	**D**	**10.**	**A**	**B**	**C**	**D**

Medical Education Lesson Evaluation

Strongly agree [5]	Agree [4]	Neutral [3]	Disagree [2]	Strongly disagree [1]

1) This CME lesson was helpful to my practice ____

2) The educational objectives were accomplished ____

3) I will apply the knowledge I learned from this lesson ____

4) I will makes changes in my practice behavior based on this lesson ____

5) This lesson presented quality information with adequate current references ____

6) What overall grade would you assign this lesson?
A B C D

7) This activity was balanced and free of commercial bias.
Yes _____ No _____

8) What overall grade would you assign to the overall management of this activity?
A B C D

This CME has been certified by a psychometrician as taking a minimum of 1.5 hours to complete.

What topics would you like to see in future CME lessons? Please list :

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