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Annual Conference on Engineering in Medicine and Biology

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37th ACEMB General Chair

With approximately 400 papers in 53 traditional sessions, plus 30 poster presentations, this year's program is one of the most interesting and exciting ever. To ensure that we touched as many bases as possible in the vast field of biomedical engineering, many of the papers were invited. Introductory overviews, to provide background and create greater interest for those less familiar with subjects discussed, precede many sessions, and where possible, related sessions have been arranged in tracks to create several mini-symposia within the conference.

Abstracts of all submitted papers and poster presentations, as well as most of the invited papers in this year's Conference, are included in these Proceedings; they are arranged by session and paper number, with poster presentation abstracts following those of the traditional sessions. In many of the sessions there is no abstract for the introduction of the subject by the session chair, and in a few of the others, such as sessions 28 and 43, the only abstract is an overview of the entire session. Session 13, a panel presentation, did not require abstracts; however, one was submitted and it is included. Abstract numbers match presentation numbers in the program, and where abstracts were not submitted, the number was skipped in the proceedings.

Abstracts summarize the latest developments in biomedical engineering and related fields, and are the result of countless hours of research and development effort on the part of the many authors represented. We thank the authors and presenters of these papers for their intellectual effort.

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VA Medical Center, Sepulveda
Scientific Program Chair

September 1984

Table of Contents

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Page

Table of Contents--Continued

COMPUTER APPLICATIONS FOR ATHLETIC PERFORMANCE

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The computer has become indispensable in finance, industry, and government. Because it can follow instructions exactly, remember eveything, and calculate to the thousandth of a second, it can quickly and precisely analyze problems that would ordinarily require enormous amounts of time and energy to solve. In the past, athletic achievement depended mainly upon individual talent. Genetically superior athletes who successfully interacted with the available facilities, equipment, and personnel dominated the list of world-record holders.

Consider throwing, running, and jumping as examples. It is impossible to throw the shot 20 meters without attaining specific values in shot velocity and angle of release. These values cannot be altered for different athletes regardless of the amount of screaming or political beliefs. Maximum shot distance can result from a particular shot velocity at a specific optimal angle.

For a long jumper to leap 8 meters, he must produce certain forces on the ground to propel his body with a specific reaction force at a particular angle. This force is unique; it is impossible to cover the same distance with only a fraction of this force, as gravitational pull acts uniformly on all jumpers.

The concept emphasized is that all bodies, whether athletes, implements, or machines, are affected by and must adhere to the laws of motion. A number of scientists have long recognized these facts of force and motion and their relationship to humans. But they lacked the kind of equipment that could measure and analyze the motions and forces involved. The advent of the computer used in conjunction with high speed cameras, digitizers, graphic display devices, as well as force platforms and EMG equipment has introduced new and powerful tools.

A cinematographical analysis for the quantification of a motion begins with simultaneous filming, at speeds ranging from 100 to 10,000 frames per second, with at least two cameras. The individual frames of the filmed sequence are then "digitized" so that the location in X,Y coordinates for each body joint are stored in computer memory. The next step consists of numerical transformation which converts from two-dimensional relative coordinates to three-dimensional absolute coordinates using a method known as direct linear transformation. These data points are subsequently smoothed to remove "noise" introduced during the filming and/or digitizing stages utilizing cubic-spline or digital filtering algorithms. These smoothing procedures were found to be superior to polynomial approximations or some digital filter algorithms particuarly in sequences with high acceleration such as throwing events. The smoothed sequence of frames can then be viewed in stick-figure format in three-dimensional graphic displays. In addition, the three-dimensional coordinates for velocity, acceleration, and center of gravity for linear and angular coordinates can be calculated.

In addition to the "indirect technique" of cinematography, there are direct analytic techniques utilizing pizeoelectric force platforms and automatic digitizing through use of infrared diodes. Quantification of the electrical signal, or EMG, of an individual muscle permits quantification of an action, such as the tennis forehand. These equipment devices allow controlled laboratory testing of forces and real-time motion analysis.

Human judgment is still critically important, however. As in the world of commerce, where decisions are based upon an executive's experience and interpretive ability, the coach must be the ultimate decision-maker in performance and training. The computer and other analytic devices must be regarded as tools rather than as replacements in the progress towards optimum performance.

SPORTS AND DYNAMIC STEREOPSIS

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Action sports require visual performance testing that is different from normal vision testing, since routine testing only samples static vision. There is ample psychophysical and neuropsychological evidence that the visual system operates differently for static and dynamic vision.

For testing dynamic stereopsis, a new instrument has been developed and used on 182 athletes. These results were compared with both the Titmus and TNO stereopsis tests. The results were significant suggesting:

1. Dynamic stereo-acuity appears to have no relation to the usual static stereo-acuity
2. The dynamic visual system can easily differentiate at least 2 sec. of arc.
3. Approximately 30% of the population tested have poor or no dynamic stereopsis
4. A strong correlation exists beween baseball batting ability and dynamic stereopsis.

To measure dynamic stereo-acuity, Walter Zinn, O.D., and I, designed an instrument that incorporates elements of disparity, movement and time. Four variable polarized targets were mounted in a square arrangement on a frosted Fresnel plastic screen (30 cm x 14 cm). The target area was 10 x 10 cm. and evenly illuminated from behind. The light box was fastened to a wheeled dolly running on tracks and the speed was controlled by a variable speed motor which propelled the dolly at 1 meter per 3.5 seconds. The effective travel range was 200 cm. or 7 seconds of time. The stereo-acuity was calculated using Griffin's Formula.

Griffin's Formula (disparity)

$$\text{Eta} = \frac{\text{IPD}}{d2} (X) (206{,}000)$$

$$X \text{ is computed from } \frac{x}{\text{displacement}}$$

$$= \frac{x + d}{\text{IPD}}$$

d = target distance

IPD = interpupillary distance

Each subject was screened with Keystone Vision Skill cards for distance visual acuity, 2nd. degree fusion, vertical phoria and lateral phoria. Static stereo-acuity was measured at 40 cm. with either the Titmus or TNO test. All subjects wore their normal habitual spectacles or contact lenses.

A comparison of dynamic and static stereo-acuity indicated a resultant correlation of only 0.129. Approximately one third of those tested failed dynamic stereopsis test. Statically the correlation with the Titmus is 0.129; with the TNO it is 0.128.

A similar visual screening was done on 36 members of two Big Ten baseball teams. The correlation between batting average and dynamic stereo-acuity was .71 suggesting that dynamic stereopsis may be a major factor in predicting batting performance

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THE KINEMATICS OF BASEBALL PITCHES

R. Watts * and J. Walton **

Sporting events are, in general, a hotbed of folklore. Theories abound as to the "best" way to perform a particular skill. The coaches, the media, the spectators, and of course the athletes themselves, all play a significant role in perpetuating the myths so often found in athletic competition. Not that these myths detract from the game, on the contrary, in many cases they have in fact become an integral part of the activity. However, in top-flight competition, where millimeters and milliseconds can be the difference between success or failure, a scientific analysis is perhaps more appropriate.

The flight of an object is an integral part of most sporting activities. More often than not this "object" is a ball, or the athlete himself. The free-fall motions of baseballs are typical, and are the focus of this presentation.

Experiments have been performed to determine the precise trajectories of baseballs pitched by Scott McGregor and Ray Miller (Pitching Coach) of the Baltimore Orioles. Using strobe photography and close-range photogrammetry, the three-dimensional path of the ball has been determined to within one-tenth of an inch over its 60-foot trajectory. Detailed analyses of McGregor's curveball and fastball have been performed, and the trajectories of Miller's spitball, knuckleball and slider have been recovered.

Each of the trajectories has been plotted using computer graphics. With a three-dimensional path available for each pitch it was possible to illustrate the path of the ball as it would be seen from any particular vantage point--the mound, the plate, or the Goodyear blimp! In addition to the measured curve, a theoretical (no-air interaction) curve was generated and plotted. The latter provides a standard which can be used to appreciate the deviations in the flight of the ball due to viscous drag and the rotation of the ball. A wealth of additional information has also been recovered by simply manipulating the raw three-dimensional coordinates of the ball.

A theoretical discussion of baseball mechanics is provided. Air-flow around the ball is described and a discussion of the viscous effects is provided. A simple analysis of the forces generated by spinning the ball has shown that these forces can be quite large when compared to the weight of the ball; and further, such forces can produce significant deflections in the path traversed by the ball. The mechanisms used to produce a knuckleball, spitball and scuffball are also examined.

The analysis of McGregor's curveball has shown that it does not contain any sharp deviations in its path from the mound to the plate. As was expected, the ball followed a smooth, curved trajectory until it reached the ground; however, the trajectory of the ball was significantly depressed below the path it would have followed had it been thrown without rotation.

An analysis of several knuckleballs thrown by Miller has shown that the ball did not hop from left to right, or up and down in mid-flight; rather these pitches tended to drift in a particular direction. The nature of the drift appears to be unrelated to the initial speed and direction of the ball.

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1.4

BASEBALL PLAYERS CANNOT KEEP THEIR EYES ON THE BALL

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Ted Williams, perhaps the best hitter in the history of baseball, has described hitting a baseball as the most difficult single act in all of sports. The velocity of the ball approaches 100 mph, producing angular velocities greater than 500 deg/sec as the ball passes the batter. Humans cannot track targets moving faster than 70 deg/sec; yet, professional batters manage to hit the ball with force consistently and are able to "get a piece of the ball" in over half their swings. In this paper we investigate how they do this by examining a professional athlete tracking a pitched ball, and we demonstrate the superiority of his eye movements and head-eye coordination to those of our other subjects.

Why did we want to study a batter tracking a baseball? We wanted to learn more about how the brain controls movement, and we therefore were searching for a situation in which a human was performing optimally. This condition is fulfilled by a professional baseball player hitting a baseball.

There are four basic types of eye movements: saccadic eye movements, which are used in reading text or scanning a roomful of people; vestibulo-ocular eye movements, used to maintain fixation during head movements; vergence eye movements, used when looking between near and far objects; and smooth-pursuit eye movements, used when tracking a moving object. These four types of eye movements have four independent control systems, involving different areas of the brain. Their dynamic properties, such as latency, speed, and high-frequency cutoff values, are different, and they are affected differently by fatigue, drugs, and disease.

The batter has the potential to use the head-movement system in addition to each of these eye-movement systems. Does he? Earlier studies have suggested several strategies for tracking a baseball: track the ball with head movements and smooth-pursuit eye movements and fall behind in the last 5 ft of flight; track with eyes only, or with head only, and fall behind in the last 5 ft; track the ball over the first part of its trajectory with smooth-pursuit eye movements, make an anticipatory saccadic eye movement to a point ahead of the ball, continue to follow it with peripheral vision, and finally, at the end of the ball's flight, resume smooth-pursuit tracking with the ball's image on the fovea, the small area in the center of the retina that has fine acuity. We will examine each of these strategies.

To discover how well a batter tracked the ball, we had to be able to determine the position of the ball at all times, and thus we could not use a real pitcher or a throwing machine. Instead, we simulated the trajectory of a pitched baseball. We threaded a fishing line through a white plastic ball and stretched this line between two supports, which were set 80 ft apart in order to accommodate the 60.5 ft between pitcher and batter; a string was attached to the ball and wrapped around a pulley attached to a motor, so that when the motor was turned on, the string pulled the ball down the line at speeds between 60 and 100 mph. The ball crossed the plate 2.5 ft away from the subject's shoulders, simulating a high-and-outside fastball thrown by a left-handed pitcher to a right-handed batter.

We ran several subjects through our simulation, including graduate students, students on the University baseball team, and Brian Harper, a member of the Pittsburgh Pirates; all had 20/20 uncorrected vision. Typically our students tracked the ball well (less than 2 deg error) until the ball was 9 ft in front of the plate. The professional ballplayer keept his eye on the ball longer than our other subjects did. He was able to keep his position error below 2 deg until the ball was 5.5 ft from the plate.

Although the professional athlete was better than the students at tracking the simulated fastball, it is clear from our simulations that batters, even professional batters, cannot keep their eyes on the ball. Our professional athlete was able to track the ball until it was 5.5 ft in front of the plate. This could hardly be improved on; we hypothesize that the best imaginable athlete could not track the ball closer than 5 ft from the plate, at which point it is moving three times faster than the fastest human could track.

Our findings should generalize to other sports. In tennis, for example, the distances are similar, 60 ft for baseball and 78 ft for tennis, as are the linear velocities, 100 mph for a fast pitch and 110 mph for a fast serve. There is often an abrupt change in the ball's trajectory just before the player hits it: the baseball breaks and the tennis ball bounces. Tennis coaches, even more than batting instructors, teach beginners to use the strategy with the anticipatory saccade in order to see the ball hit the racket; this strategy is probably only useful as a learning tool. Therefore, we suggest that neither baseball players nor tennis players keep their eyes on the ball. The success of the good players is due to faster smooth-pursuit eye movements, a good ability to suppress the vestibulo-ocular reflex, and the occasional use of an anticipatory saccade.

Muscle Power as an Indicant of Performance in Weightlifting.

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An exemplary short duration-high power weightlifting event was examined to determine whether the ability to lift heavier loads and whether variations in the level of skill were accompanied by quantitative changes in selected aspects of lower extremity muscle power-time histories. Six experienced weightlifters, three skilled and three less-skilled, performed the double-knee-bend execution of the pull in Olympic weightlifting, a movement which lasted approximately one second. Each lift was filmed and the ground reaction force simultaneously measured. Both the trunk-knee and thigh-ankle angle-angle displacement profiles revealed a triphasic pattern of lower extremity activity during the movement which indicated a change in the direction of rotation about the ankle and knee joints as the barbell was raised to hip height. Muscular power across each of the three lower-extremity joints (ankle, knee, and hip) was determined with respect to the mass of each segment (foot, leg, and thigh, respectively) as the product of the resultant muscle torque across the joint and the relative angular velocity of the adjacent segments. With a temporal alignment of the angular-velocity and resultant-muscle-torque histories, it was possible to delineate the patterns of net muscular activity during the movement. The net shortening contraction of the back and hip extensor muscles throughout the movement is indicated as continuous power production, the plantarflexor pattern of activity is represented as power production-absorption-production, and the net activity about the knee joint is illustrated as a complex production (shortening-extensor), absorption (lengthening-flexor, lengthening-extensor), production (shortening-extensor), and absorption (lengthening-flexor) sequence.

Analysis-of-variance statistics were performed on selected peak and average values of power generated by the three skilled subjects as they lifted three loads (80, 90, and 100% of a presumed experimental-paradigm maximum) and on the 100% lifts of the skilled subjects in comparison to 100% lifts of their less-skilled colleagues. The results indicated that the skilled subjects lifted heavier loads (80-90-100%) by increasing the average ($p < 0.05$), but not the peak (all p values > 0.2), power during the two periods of knee power production and the first period of ankle power production. There were no significant changes in the parts of the movement which involved power absorption. The ability of the skilled subjects (100% = 1226 $\pm$ 102 N) to lift a greater load than the less-skilled subjects (100% = 1056 $\pm$ 130 N) was associated with a greater net power production by the muscles about the hip joint (peak = [$F(14,15) = 18.1$, $p < 0.05$]; average = [$F(99,99) = 2.2$, $p < 0.05$]) and a greater peak production [$F(14,15) = 26.7$, $p < 0.05$] and average power production [$F(37,45) = 2.3$, $p < 0.05$] and absorption [$F(36,45) = 14.8$, $p < 0.05$] for the knee-joint musculature of the skilled subjects.

It is apparent that the ability to lift heavier loads is accomplished, at least partially, by quantitative changes in the lower-extremity power-time profiles. Over the range of loads tested, the qualitative characteristics of the power records remained remarkably constant and the increase in average power production for periods of knee and ankle activity underscored the significance of this musculature to the double-knee-bend execution of the pull. While these data do not unequivocally demonstrate that power production is a performance-limiting parameter, they do suggest that since power production increases with load, it has the potential to assume this role. In a similar vein, all the differences due to skill (the 100% loads for the skilled versus the less-skilled subjects) can be interpreted as representing statistically significant differences which existed between the two groups of subjects due to expertise rather than variations in absolute load.

In summary, increases in average power that accompanied increases in load and the greater peak and average power values due to skill suggest that power generation may represent a performance-limiting and success-dependent capability in the double-knee-bend execution of the pull in Olympic weightlifting.

Supported by Biomedical Support Grant 61-2300 and RR-07096 NIH awarded to the Department of Kinesiology at the University of Washington and by the University of Arizona Computer Center.

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1.6 Kinesiology of a Karate Strike

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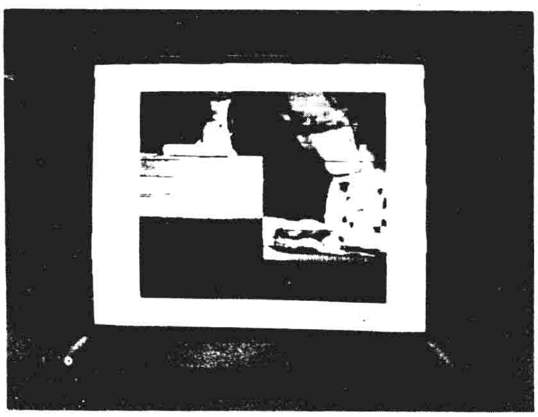
The dynamics of a karate strike were investigated when the bare human hand was driven through pine wood and through concrete blocks. The types of karate strikes observed were; hammer, fist, finger, palm, inside chop, and outside chop. Velocity and acceleration measurements were calculated for all impacts. Deformation of the hand and wrist were observed and recorded.

Time - displacement measurements were obtained using miniature accelerometers, high speed rotating drum cameras, and high speed (real-time) video. Velocities and accelerations were calcu- for the hand prior to its impact with the target. These velocities ranged from 15 ft/sec for the fist strike, to 55 ft/sec for the hammer strike. Impact and post-impact displacement of the soft tissue and bony structure of the hand and wrist were also observed and recorded.



The above photograph shows the face of the high speed video system. This system made it possible to observe two orthogonally positioned cameras simultaneously. The ability to record the braking of the target while displaying the reaction of the hand and wrist was provided. The subject in the picture had a measured body fat of 3.8%. This was a fist impact, imparted on three concrete blocks, each block one inch thick, recorded at 2000 frames/sec. Velocity prior to impact was 17 ft/sec.

It appears that in the fist type of impact, that the blow of the impact is absorbed in the wrist, which tends to widen on striking the object and then recovers to almost its original width shortly after the blow. Several experiments were conducted, such as the one shown, in which the targets were broken. Other experiments in which the energy of the human hand was not sufficient to rupture the stack of concrete blocks were also recorded. The gross deformation of the hand and wrist were more pronounced in the latter experiments.

The techniques of karate differ significantly from those of Western methods of empty-hand combat; i.e., fisticuffs. The karateka concentrates his blow on a small area of the target and seeks to terminate them about a centimeter inside it, and without the long deliveries and follow-through of the punches in Western boxing. The fist of the trained boxer, in the last few inches of travel, can accelerate to a velocity of 40 mph, which explains why boxers receive/deliver knockout punches which travel less than one foot.

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Studies of locomotion have been mainly restricted to walking or running over homogeneous level ground. Here gait is normally regular, which has led to the idea that it is controlled by a pre-wired generator. However, in the normal cluttered environment gait needs to be flexible: to secure footing, strides have to be regulated to match the terrain. The regulatory role of vision was examined by having subjects run at a steady speed on irregularly spaced marks on the ground, simulating stepping stones. The results suggest that adjustment is made by modulating the vertical impulse or lift of the steps on the basis of information about the time to reach the next stone, which is specified by a simple parameter of the optical input to the eye. The information can be rapidly picked up and acted on, enabling gait to be regulated step by step.

The experiments were run on a treadmill equipped with an extension belt on which the stepping stones were marked. The stones were in groups of five with about 10 m between groups. Inter-stone gaps were 1.0 m to 1.6 m. The treadmill speed was 4 m/s. Subjects had a 15 minute warm up on the treadmill and then carried out a series of 40 s tests running on the "stepping stones". During each test the subject's limb movements were monitored by a Selspot opto-electronic system linked to a computer. Infra-red diodes, positioned on the subject's feet and major joints, were viewed by a Selspot camera at the side of the subject. Temporal resolution was 3 ms, spatial resolution 2 mm.

From the Selspot records were measured the three components of a stride: (1) the trail distance - the horizontal distance moved by the hip (relative to the treadmill belt) from when it was vertically above the supporting foot to when the foot left the ground; (2) the flight distance - the horizontal distance moved by the hip during flight; (3) the reach distance - the horizontal distance moved by the hip from when the (next) foot hit the ground to when the hip was vertically over the foot. The stride distance is the sum of these components. Analysis indicated that stride distance was regulated primarily by changing flight distance. This makes sense in terms of efficiency: reach distance needs to be kept short to avoid retarding thebody when the foot strikes the ground, but it must not be too short or else the foot will not be on the ground long enough to power the body; trail distance needs to be kept reasonably constant to avoid excessive vertical movement of the hips.

Flight distance, which is the product of the horizontal speed of the hips during flight and the flight time, was found to vary systematically with flight time but not with flight speed, which varied a little. Thus stride length was apparently regulated solely by changing flight time - a result which accords with how long jumpers regulate their strides in the run-up to the take-off board (Lee, D.N., Lishman, J.R. and Thomson, J.A., Regulation of Gait in Long Jumping, in Journal of Experimental Psychology: Human Perception and Performance 1982, 8, 448-459.) This too makes sense. Firstly, with horizontal speed, trail distance and reach distance constant, flight time can be controlled simply by changing the vertical component of the thrust on the ground. Secondly, the information for specifying the flight time required - namely, the time to the next stepping stone - is given in a simple way in the optic array at the runner's eye (Lee, D.N., The optic flow field: The foundation of vision, in Philosophical Transactions of the Royal Society of London B, 1980, 290, 169-179).

A further experiment investigated how quickly the visual information could be picked up and acted on. Baffles placed over the belt carrying the stepping stone marks limited how much of the ground ahead the subject could see. Accuracy was not reduced when a stepping stone came into view as late as the beginning of the footfall one stride away. Thus information pick-up is apparently fast enough to allow regulation of gait on a step by step basis.

The work was supported by the Medical Research Council (U.K.) and the National Institutes of Health (U.S.).

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NUCLEAR MAGNETIC RESONANCE -- AN INTRODUCTION TO THE PHYSICAL PRINCIPLES

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Introduction and Overview

Nuclear magnetic resonance (NMR) is a technique which is rapidly moving from the in vitro analytical laboratory to the medical imaging clinic. This new application of old principles has been made possible by several recent advances in technology which can be used to map the NMR characteristics of living tissue into high quality cross-sectional body images.

This presentation will develop the basic concepts of nuclear magnetic resonance and illustrate how the various NMR parameters contribute to image formation.

Tissue Resonance

Concept

Resonance (Latin: resonantia, an echo) is a property of certain objects or systems to "tune in" to specific frequencies. In many situations the resonant object will readily absorb energy if the energy has a frequency which matches the resonant (natural frequency) of the object. Resonating objects can generally store absorbed energy for a short period of time after which the energy is usually re-radiated or transferred to the environment.

The strings of musical instruments are among the most common examples of objects with resonant characteristics.

In its normal state tissue does not have resonant characteristics, at least to energy frequencies which can penetrate into the human body. However, by placing tissue in a strong magnetic field it develops very specific resonance characteristics.

Radiofrequency (RF) Signals and Pulses

When placed in an appropriate magnetic field some of the chemical elements within human tissue resonate at frequencies which correspond to radio signals. If pulses of radio frequency (RF) energy are applied to tissue which is resonating in a magnetic field some of the energy will be temporarily absorbed by the tissue and later re-radiated in the form of weak radio signals. Certain characteristics of the emitted signals are related to the physical, chemical, and biological characteristics of the tissue. The analysis of these signals provides the parameters which form magnetic resonance images.

The Magnetic Field

The primary function of the magnetic field is to resonate the tissue at radio frequencies. One of the important characteristics of a magnetic field is its intensity or field strength. Most magnetic resonance imaging systems use field strengths in the range of 1.5 to 15 kilogauss (0.15 to 1.5 tesla). The strength of the magnetic field determines the frequency at which specific nuclei resonate and also the strength of the RF signals produced by the tissue.

The magnetic field used to create the resonant condition must have a high degree of spatial uniformity and temporal stability. However, a much weaker time varying gradient magnetic field is superimposed to scan through the different body sections.

Resonant Nuclei Characteristics

All nuclides do not have NMR properties. In order to participate in the NMR process the individual nuclei must have a magnetic moment and behave as small magnets. This property is found in certain nuclei which have an odd number of neutrons or protons. For many of the chemical elements some of the isotopes will have the ability to participate in the NMR process and the other isotopes will not.

In magnetic resonance imaging the major factor which limits image quality and rapid imaging is the strength of the RF signal from the tissue. The strength of the NMR signal from a specific volume of tissue is determined by the following four factors.

1. Receptivity of specific nuclides.
2. Concentration of specific element in tissue.
3. Abundance of specific isotopic form.
4. Strength of magnetic field.

Nuclides which have magnetic resonance properties and a potential clinical significance include:

1. Hydrogen - 1
2. Carbon - 13
3. Nitrogen - 15
4. Phosphorus - 31
5. Oxygen - 17
6. Sodium - 23

P. Sprawls

Tissue Magnetization

Tissue, in its normal state, contains many very small magnets in the form of the individual nuclei which have magnetic moments. These are randomly oriented in all possible directions so that there is no overall or net magnetization of the tissue. However, when the tissue is placed in a magnetic field some of the nuclei align their magnetic moments with the direction of the field. When more nuclei are aligned in one direction than in the other direction the tissue becomes temporarily magnetized in that direction. This condition is typically represented in illustrations by means of an arrow, the magnetization vector. The strength of the magnetization depends on the number of nuclei available and the strength of the magnetic field.

Excitation and Relaxation

Concept

When tissue is placed in the magnetic field it becomes receptive to radio signals which match its resonant frequency. In the MRI process pulses of RF energy are transmitted into the body. This energy is absorbed by the resonant nuclei. The individual nuclei absorb the RF energy by reversing their direction in the magnetic field. This is an unstable or excited condition for the nuclei. In this position the nuclei are temporarily storing the absorbed RF energy.

Over a period of time the nuclei will relax by returning to a position which is in alignment with the magnetic field. During this relaxation process the nuclei re-radiate the absorbed RF energy. These RF signals emitted by the tissue during the relaxation process contain the information which is used to create the magnetic resonance image.

During both excitation and relaxation the tissue magnetization undergoes a change.

Prior to excitation the tissue is magnetized in the longitudinal direction relative to the magnetic field.

During the excitation phase the magnetization of the tissue is rotated to some other direction. The direction of the magnetization after the excitation depends on the strength and duration of the RF pulses used to produce the excitation. The pulses are usually adjusted to produce either 90° or 180° changes in the direction of the magnetization.

After the excitation pulse is terminated the excited nuclei will gradually relax and return to their direction of alignment with the magnetic field. There are two phases to the relaxation process. One is the period during which the magnetization produced by the excitation pulse decays away. The second phase of relaxation is the regrowth of the magnetization in the direction (longitudinal) of the magnetic field.

Relaxation Times

The duration of the relaxation phase depends on the physical and chemical characteristics of the tissue. The difference in relaxation times is a major discriminator among various tissue types in the magnetic resonance image.

There are two distinctly different relaxation times. These are generally designated as relaxation times, T1 and T2.

T1 -- Spin-Lattice -- Longitudinal

Concept

Relaxation time, T1, is the time required for a majority of the excited nuclei to regain their alignment with the magnetic field. This represents the regrowth of the tissue magnetization in the longitudinal direction. T1 is often referred to as the longitudinal relaxation time.

Mechanism

Relaxation occurs as the nuclei (spins) transfer their excitation energy to the surrounding tissue structures (lattice). It is sometimes referred to as the spin-lattice relaxation time.

Values

T1 values for tissue generally fall in the range of 150 to 1,000 mSec. Specific values depend on the characteristics of the tissue and the strength of the magnetic field. Representative values can be found in the references given below.

T2 -- Spin-Spin -- Transverse

Concept

Relaxation time, T2, is related to the decay of the transverse magnetization

P. Sprawls

produced during the excitation phase.

Mechanism

After certain excitation pulses some of the nuclei will be oriented in the transverse direction and also spinning around a longitudinal axis in phase (or, in step) with each other. These nuclei spinning together produce the transverse magnetization of the tissue.

The transverse magnetization dissipates or decays as the spinning nuclei get out of phase because of local inhomogeneities in the magnetic field. During this process some energy is transferred from one nucleus (spin) to another nucleus (spin). This is therefore sometimes referred to as the spin-spin relaxation time.

Values

The decay of the transverse magnetization generally occurs faster than the regrowth of the longitudinal magnetization. Therefore in most materials T2 is shorter than T1. In most tissues the value of T2 is in the range of 50 to 150 mSec.

The Magnetic Resonance Image Contrast Characteristics

The magnetic resonance image is a map of specific NMR parameter values. The Gray scale value at each point in the image and the contrast between different points within an image is determined by the specific value of the following parameters.

1. Nuclear Concentration
2. Relaxation Time, T1
3. Relaxation Time, T2
4. Flow

Imaging Protocols

Pulse Sequence Characteristics

The degree to which each NMR parameter is represented in a specific image is determined by the sequence of RF pulses used to produce the excitation and sample the RF signals from the tissue. Some pulse sequences will emphasize the T1 and other sequences will produce images which are strongly related to the T2 values of the tissue.

The following pulse sequencies are used in MRI.

Inversion Recovery
Spin Echo

References

The following references provide a more in depth discussion of many of the topics contained in this presentation.

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CLINICAL APPLICATIONS OF MAGNETIC RESONANCE IMAGING

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Magnetic Resonance (MR) imaging is a powerful new imaging modality which produces thin tomographic sections through the body without utilizing ionizing radiation. The technique is based on an interaction between strong magnetic fields, radio frequency radiation, and magnetized hydrogen nuclei in the body (1). Sections can be acquired directly in the sagittal, coronal, and transverse axial planes. Spatial resolution is currently on the order of .8 mm which is comparable to that of CT. Contrast resolution is significantly better than CT. The following is a survey of the current clinical applications for MR.

The greatest use for MR is currently in the brain and spinal cord. At the Huntington Medical Research Institutes, for example, 80% of the current case load is for suspected disease in the CNS.

In the brain, MR has been found to be particularly useful in evaluation of multiple sclerosis, detection of small brain tumors (primary or metastatic), detection of extraaxial fluid collections, and detection of subtle abnormalities of the brainstem and cerebellum which have never previously been seen by CT (2). MR is able to identify subacute hemorrhage by virtue of a shortened T1 relaxation time. It is able to identify vascular malformations by virtue of loss of signal intensity from rapidly flowing blood. Abnormalities of the pituitary region are well seen on direct sagittal sections. Small acoustic neuromas which are entirely within the internal auditory canal (and thus can only be seen by CT after air is injected in the lumbar subarachnoid space) are well visualized using MR. At this time, the principle limitations of MR relative to CT are in the occasional distinction of a brain tumor from surrounding edema and in the specific diagnosis of meningiomas which may have a nonspecific appearance on MR.

Abnormalities at the junction of the brainstem and cervical cord are well seen by direct sagittal imaging without need for intrathecal metrizamide. Arnold Chiari malformations and syringohydromyelia are well seen by MR using short repetition times to enhance the difference between cord and CSF. Cord tumors are well seen by virtue of contour abnormalities and the increased intensity generally associated with increased water content on T2-weighted MR images. Elsewhere in the spinal canal, MR is useful in the evaluation of extraaxial masses including tumors, metastases, abscesses, and hematomas. Disc space infections are well evaluated by MR. Although CT remains better able to evaluate disc disease with its concomitant hypertrophic bone formation, MR is useful in demonstrating degeneration of the nucleus pulposus and can demonstrate cord displacement and edema secondary to disc herniation. Following surgery, MR is useful in differentiating post operative scarring from recurrent disc herniation.

In the extracranial head and neck, MR is useful in evaluating the spread of carcinoma by virtue of its ability to image in three orthogonal planes. On T1-weighted images, lymph nodes can be distinguished from surrounding fat and are easily distinguished from adjacent vascular structures.

In the chest, MR is most useful in distinguishing small hilar masses from vascular structures. MR acquisition gated to the EKG is well suited for the evaluation of the heart and paracardiac masses. Myocardial wall thickening and pericardial disease is well seen where CT is limited by cardic motion and echocardiography is limited by intervening bone and lung.

MR is currently limited in the evaluation of the upper abdomen due to respiratory motion of the diaphragm, however, respiratory gating may improve imaging in this location. Evaluation of the kidneys is comparable by MR and CT. MR has the advantage of showing direct invasion of hypernephromas into the renal vein and inferior vena cava; CT has the advantage of demonstrating nephrocalcinosis and renal calculi. Like ultrasound, MR is able to demonstrate aneurysms of the abdominal aorta although MR may be able to demonstrate atherosclerotic plaquing to better advantage. In addition, MR is never limited by intervening bowel gas which can degrade ultrasound examination.

In the pelvis, MR has been shown to be useful in the evaluation of prostatic carcinoma while it is still confined to the capsule. MR is also useful in the evaluation of bladder carcinoma particularly at the bladder base which is poorly seen by axial CT. Invasion of the seminal vesicles and involvement of the perivesicle fat is easily accomplished by MR. MR is useful in the evaluation of asceptic necrosis of the femoral heads.

In summary, MR technology is currently competitive with CT in many areas of the body, particularly in the brain and spinal cord. With expected use of paramagnetic contrast agents and surface coils and with futher refinements in equipment, the applications of MR should be extended even further.

References:

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