A STUDY OF HEAD IMPACTS IN LIVING MAN USING RADIOTELEMETRY

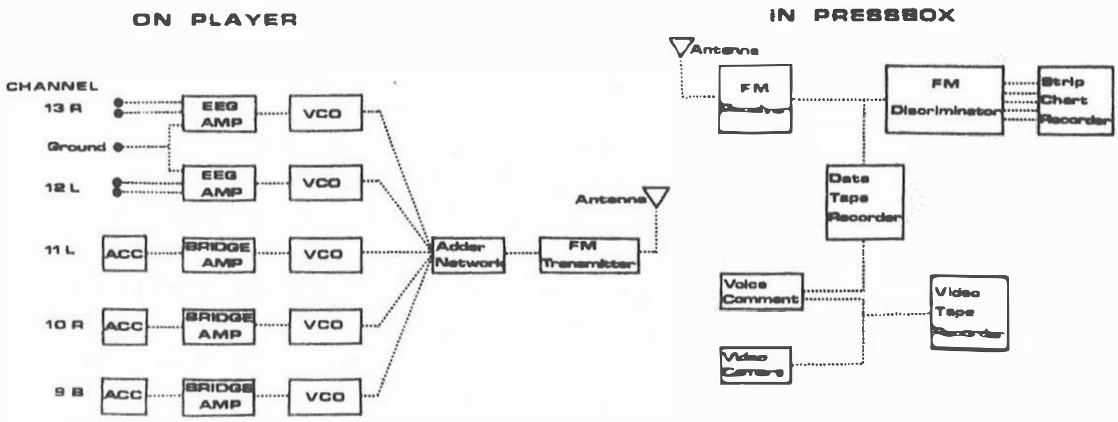
S.E. REID, H. M. EPSTEIN, T. J. O'DEA, M. W. LOUIS, S. E. REID, JR., Evanston Hospital and Northwestern University Medical School, CHICAGO, ILLINOIS (U.S.A.)

This study was undertaken in 1961 at the suggestion of the American Medical Association because of its concern with the incidence of head injury suffered by contestants in American football. The injury statistics quoted by Robey (5) imply that fifty-four thousand concussions occur annually in high school football while others report a 13% incidence in intercollegiate play. The football field therefore presents an excellent opportunity to gather information on head mechanics during impact because in few other situations do human beings consent to such frequent and intense contact. The problem of adapting a telemetry system to a hostile environment that is complicated by extremes of temperature and dampness and developing instrumentation that will not interfere with the efficiency of the player presents a unique challenge. The verification and interpretation of the recovered data so unlike that developed under the static conditions of the laboratory presents an equally challenging problem. This paper describes the perfected telemetry system and includes measurements of 1085 impacts during the last five seasons at Northwestern University in Evanston, Illinois. Having developed a telemetry system capable of recording reliable impact data from the football field, additional parameters will be measured to more accurately assess the behavior of the living human head to impact.

The method of telemetry and microelectronics was used in this head impact study to measure mechanical and physiologic data of a player during regulation football games. Telemetry involves the measurement of some quantity, converting that quantity to an equivalent electrical signal, transmitting the signal to its point of destination, then converting the signal back into usable form for observing the measurement. The system used in this study is capable of delivering six channels of data to the pressbox (Figure 1). The type and placement of the impact transducer is a critical part of the system. A description of the helmet used in this study is necessary to understand transducer placement. It consists of a smooth rigid plastic shell and a system of strap webbings which suspends the head within the shell. A space of about 1 inch between the head and the shell permits a certain amount of stretch of the suspension system to distribute the impact force in time and space. The suspension system, therefore, must fit the head so snugly that the head band and the head move in unison.

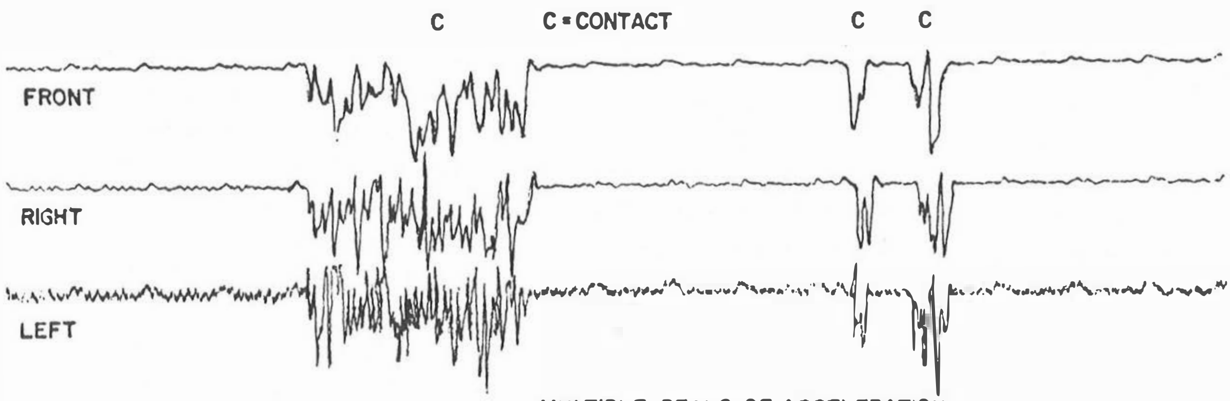
Accelerations are measured with a linear accelerometer mounted on the suspension system of the helmet at each of three points on the head--at the midoccipital region and at both temporal areas. These instruments are sealed

FIGURE 1



EEG AMP: EEG Amplifier
VCO: Voltage Controlled Oscillator
ACC: Accelerometer Endevco 2264-5000 at .267 volts excitation
R: Right
L: Left
B: Back

FIGURE 2



MULTIPLE PEAKS OF ACCELERATION
ON FOOTBALL FIELD

100G

100MS

transducers which are not sensitive to the physical properties of the suspension system and reject the accelerations of normal movements. Accelerations are converted into electrical signals and recorded in analog form. The maximum distance the recorded wave travels from its base line indicates the peak acceleration, and the time of the wave is the duration of the force acting on the head. In addition, the direction of the initial take-off of the wave from its base line indicates the direction of the blow. The orthogonal mounting of the accelerometers in the cross sectional plane of the head permits computation of the vector sum of the peak accelerations. To monitor the effects of impacts on the brain, a tracing of electroencephalography is recorded from each side of the brain by pairs of electrodes on selected areas of the scalp which are free of underlying muscle--at the parietal and occipital regions--and by a ground electrode at the inion. The electrodes are secured to the scalp with multiple applications of collodion, each dried with an air jet. Two channels of EEG are not sufficient to diagnose brain damage. They can, however, indicate gross changes when the basic background rhythm is disturbed (6). A small compartment at the back of the helmet houses a miniature transmitter and amplifiers for the two channels of electroencephalography. An umbilical cord extends from this compartment to the accelerometers in the helmet and to the impact electronics attached to the shoulder pads. Voice commentary recorded on both the video tape and on the electromagnetic taped data synchronizes the activity of the player on the field with the data obtained by telemetry.

Only one player was instrumented during each of five Northwestern University football seasons and during this time four young athletes encountered 1085 impacts that were acceptable for measurement. A complex response consisting of multiple peaks of acceleration of varying amplitudes results from each impact. The duration of the entire response to each impact rather than of any single acceleration is recorded because subsequent peaks of acceleration occur before some accelerations are completed (Figure 2). The vector quantity of the highest peak recorded on the frontally placed accelerometer and the highest peak recorded by the accelerometer placed on either side of the head is used as the measure of the amplitude of acceleration for each impact. Having arrived at these stipulations for recording data the complex responses of man to 1085 impacts were recorded (Table I). The peaks of acceleration ranged between 40 and 530 Gs and the durations of the entire response to each impact ranged between 20 and 420 Milliseconds. The greatest peak of acceleration encountered by the player of 530 Gs occurred on only one occasion but the duration of the entire response to this impact was only 60 milliseconds. During the response to the impact that measured 420 milliseconds there were many peaks of acceleration but the greatest peak measured only 120 Gs. Fifty-seven impacts produced acceleration peaks between 150 and 450 Gs and responses that measured between 200 and 400 milliseconds. Fifteen of these impacts were of special significance because they were the most intense, with acceleration peaks ranging between 180 and 400 Gs and durations of response between 300 and 400 milliseconds (Table II). A concussion followed one of these impacts. This

TABLE I

VECTOR PEAKS IN G's

DURATION IN MILLISECONDS	0-50	51-100	101-150	151-200	201-250	251-300	301-350	351-400	401-450	451-500	501-550
0-50	53	32	43	35	31	9	5	6	5	0	0
51-100	53	79	106	151	82	38	21	21	14	9	3
101-150	3	6	10	19	17	10	7	11	3	0	0
151-200	6	13	37	37	18	9	6	4	1	1	0
201-250	0	1	3	4	4	1	4	1	0	0	0
251-300	1	0	5	13	7	3	1	1	1	2	0
301-350	1	0	0	1	2	3	0	1	0	0	0
351-400	1	1	1	4	2	1	1	0	0	0	0

DISTRIBUTION OF 1085 MEASURED IMPACTS

TABLE II

VECTOR PEAKS IN G's

MILLISECONDS	180-200	201-250	251-300	301-350	351-400
301-350	1	2	3	0	1
351-400	4	2	1	1	0

DISTRIBUTION OF THE FIFTEEN HIGHEST INTENSITY IMPACTS occurred when the instrumented player spun away from two opponents and rotated into a position to cause the left side of his head to be struck by the knee of a charging ball carrier (3). Frame by frame analysis of the video tape showed the impact and the resultant whiplash action of the head and verified the duration of the recorded response of 310 milliseconds. The telemetered data additionally showed that complex accelerations resulted with the highest peak measuring 188 Gs and the EEG recorded asymmetrical flattening of the tracing from the right side of the brain (Figures 3 & 4). On one other occasion although there was no clinical evidence of concussion, there was a distrubance in the basic background rhythm of the telemetered EEG. This occurred after a series of impacts of intermediate intensities and the instrumented player noted some mental confusion (Figure 5).

The telemetered data of head impacts encountered on the football field show that the peaks of accelerations are quite similar in magnitude to those produced in the laboratory. However, the durations of acceleration complexes collected from human beings in this vigorous uncontrolled environment were found to be forty times greater than the durations of accelerations in controlled laboratory studies using anesthetized animals, cadavers and head models. This highly significant difference can be explained by the complex nature of the forces exerted by random human contact and by the complex dynamic response of the human body undergoing stress of high risk head trauma. This physiologic response to impact is highly developed in the well conditioned athlete who is alert on the field in a subconscious attitude of self preservation. This type of reaction is absent in laboratory testing and even in man when he receives an unexpected blow at some unguarded moment. For example, a motorist incurs a whiplash injury to his neck when his car is struck from behind by another vehicle because his head reacts as a freely movable body. Impacts delivered under these conditions are of short duration, in the order of 2-10 milliseconds. During this short period the muscles in the neck are unable to afford protection because the involuntary spinal reflexes cannot react in such a short period of time. For example, the time consumed for the passage of an impulse along the peripheral pathway of a reflex arc and the contraction time for a large muscle is about one hundred milliseconds. In addition, the elasticity and deformation characteristics of living tissue also have a latent period with regard to reaction to impacts. When man anticipates an assault his physiologic response adds a new dimension to the measurement of brain tolerance. The head of the athlete in his state of readiness no longer reacts as a freely movable body because the tensed muscles in his neck resist motion of his head resulting in a sustained rather than a simple response. This prolongs the time of the impact. This protective mechanism was demonstrated in the laboratory by Denny-Brown (1) when he found that he had to inflict a crushing blow to a supported head to produce the same concussion that resulted from a milder blow to a movable head. Ommaya (2) reported that little is known about the relation of impact to response and still less about the response itself.

FIGURE 3

MEASURED ACCELERATION OF CONCUSSION PRODUCING PLAY 18 NU-IND 1970

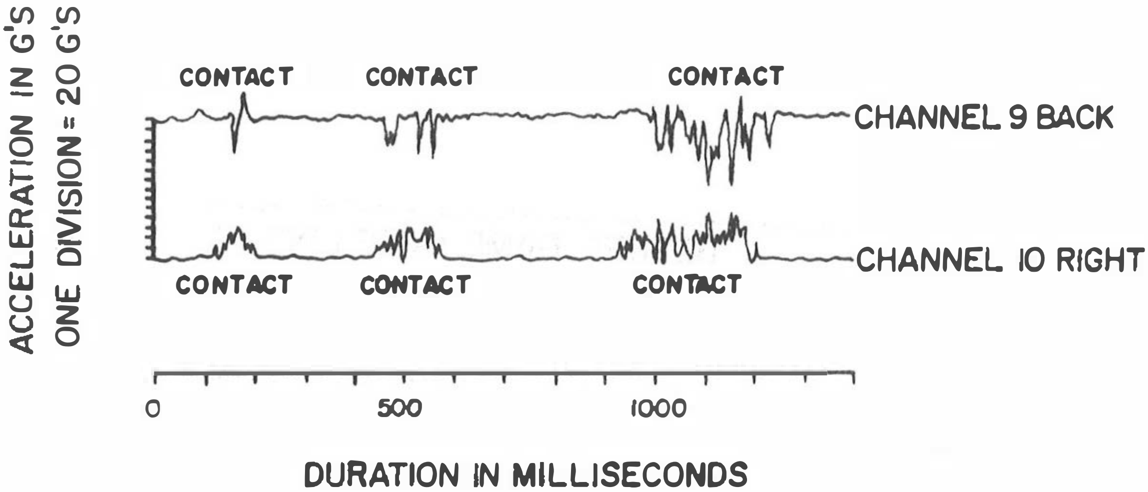


FIGURE 4

RESTING EEG 15 CYCLE FILTERED NU-IND 1970

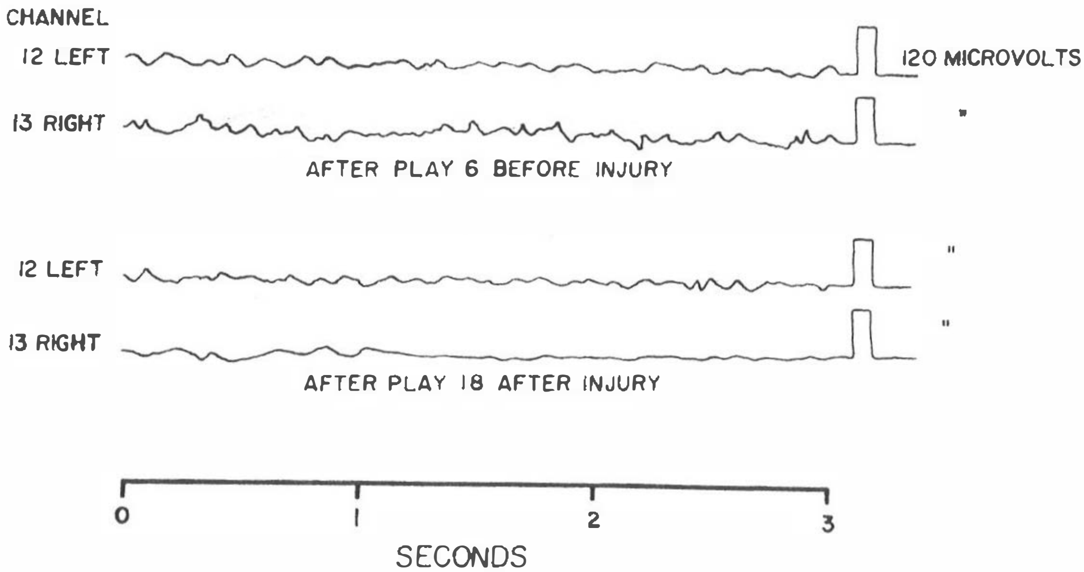
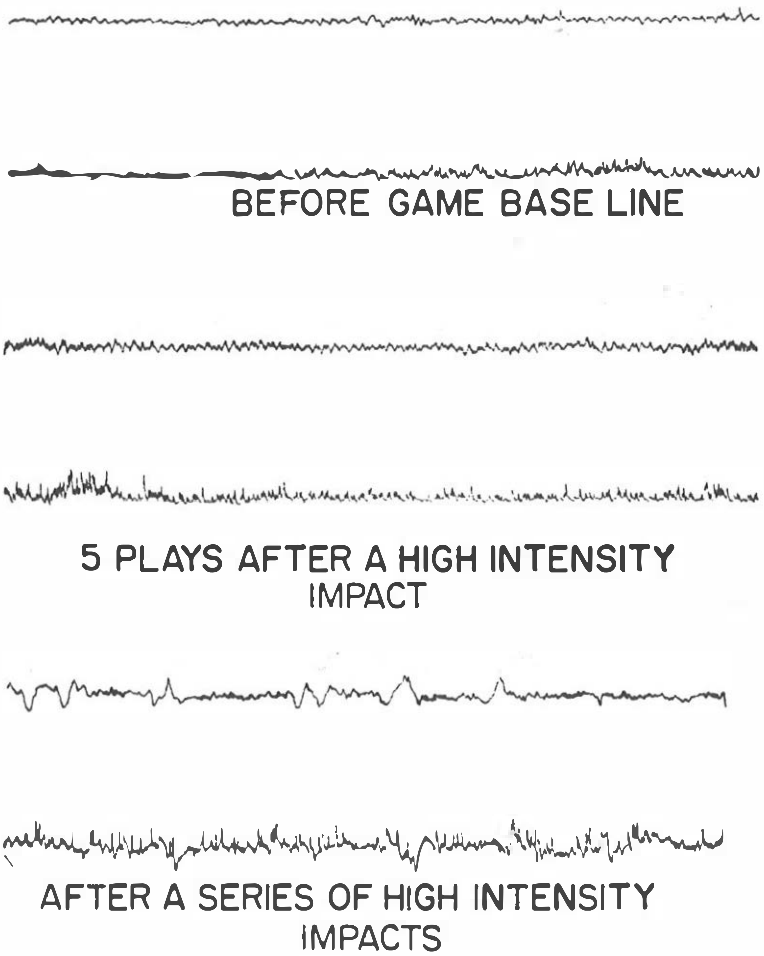


FIGURE 5


BEFORE GAME BASE LINE
5 PLAYS AFTER A HIGH INTENSITY IMPACT
AFTER A SERIES OF HIGH INTENSITY IMPACTS

The reactions of the instrumented player undergoing test impacts were studied to analyze the physiologic response and to document the methods employed to dissipate the force (4). The first reaction of the player was instinctively to dodge the blow. His whole body reacted in such a way that the efficiency of the impact directed at his head was reduced by causing the blow to be of a glancing type and allowing the smooth hard exterior of the shell of the helmet to deflect the blow. This allowed the helmet to receive only a percentage of the intensity of the impact. The player was then instructed to allow the blow to strike the side of his helmet. In anticipation of the blow the player was observed to lean in the direction of the source of the blow, to tense all muscles in his body, and to brace himself for the assault. This set of reactions restricted the movement of the head by creating other forces, produced by muscle tension, to oppose the force of impact. These opposing forces can be considered as an increase in the mass involved in the impact. The weight of the head plus the torso must now figure in the calculation of the mass. By applying Newton's Law of Motion ($F = MxA$), the same force (F) applied to a greater mass (M) results in less acceleration (A). Since the magnitude of acceleration is responsible for head injury, its reduction is an important protective response. The athlete in anticipation of the blow did not indiscriminately offer maximum resistance but looked out of the "corner of his eye" in order to know when to react. He appeared to feel for the blow and, if the magnitude of the force were so great that structural failure were likely, he seemed ready to cause his head to catch the blow. This line of defense is demonstrated with another application of Newton's Law of Motion ($F = \frac{M \Delta V}{t}$). The force (F) of impact is less when the speed of the blow is reduced (ΔV) over a longer period of time (t). For example, a boxer avoids a head injury when he "rolls with the punch" because it takes a longer time for the glove of his opponent to come to rest on his chin. This physiologic response becomes operative after about 70 milliseconds. The state of readiness is a conscious reaction before this time but after this period the response is mainly due to muscular reflexes. An impact to the head stimulates the stretch reflex of the taut muscles in the neck. This results in an initial large phasic response followed by a continuous tonic response. This entire response of muscle fibers occurs in about 10 milliseconds but large groups of muscle fibers react to match the load placed on them. This muscular response to impact probably varies the resistance to the force and brakes the speed of the blow in such a way that structural failure is avoided at one end of the spectrum and fluid shifts and whiplash are avoided at the other end.

An explanation is required for the fact that only one of fifteen high intensity impacts resulted in a concussion. Several additional unknown factors must be considered to explain the apparent inconsistency of the magnitude of accelerations that cause concussion.

1. Stretching the cervical spinal cord results in some effect on the activity of the reticular core of the brain stem. This was evident in the whiplash that was seen in video action of the concussion-producing play.

2. The direction of the blow and its point of contact on the left frontotemporal area of the head resulted in an unmeasured amount of rotational acceleration of the brain. Flattening of cortical activity on the side opposite the blow, as demonstrated by electroencephalography, strongly suggests that this area absorbed more energy as a result of the rotational force or the contrecoup effect.
3. A similar high intensity impact was encountered at an area on the head directly opposite the site of impingement of the concussion-producing blow. Even though no clinical or electroencephalographic changes were observed after this blow, it may have contributed to the concussion because it occurred just two plays previously. The cummulative effect of multiple impacts on the brain was again demonstrated by a series of blows of intermediate intensities.

Future developments of this study include measurements of both the force applied to the head and the accelerations of the head in two orthogonal directions. The ratio of these parameters during the first 70 milliseconds should give a measure of the initial "inertial mass" of the head as an indication of the state of readiness of the head-neck system. The range of these "inertial masses" of the head will be available to those laboratories developing head models in the interest of correlating the laboratory studies with actual experience. Other parameters such as damping factors and coefficients of elasticity should also be measured.

Initial measurements of tangential accelerations of the head were made during the past year to study the role of rotation as the cause of brain trauma. A system of two linear accelerometers, mounted differentially on an axis through the head, will be used this year in an attempt to provide more accurate data on the tangential accelerations experienced in traumatic situations.

Finally, the close collaboration between those researchers who obtain their data from human beings in real life situations and those who obtain data in controlled laboratory investigations is essential. The field investigator can rarely approach the precision of laboratory studies but empirical data can aid the laboratory workers in their efforts to simulate reality.

SUMMARY

The football field is an ideal setting to study head mechanics during impact and the method of radiotelemetry afforded the means to obtain the measurements of 1085 impacts to the head of an athlete. His "state of readiness" prolongs the time of the impact and enables his physiologic response to become operative. A concussion was documented with impact data, EEG and video action. The cumulative effect of blows to the head was demonstrated in this study.

REFERENCES

1. Denny-Brown, D.E., and Russel, W.R. Experimental cerebral concussion. Brain. 1941. 64: 93.
2. Ommaya, A.K., Faas. F., and Yarnell, P. Whiplash injury and brain damage; an experimental study. J.A.M.A.. 1968, 204: 285.
3. Reid, S.E.. Tarkington, J.A., Epstein, H.M. and O'Dea, T.J. Brain tolerance to impact in football. Surg. Gynecol. Obstet. 1971, 133: 929.
4. Reid, S.E., Epstein, H.M., Louis, M.W.. and Reid, S.E. Jr. Physiologic response to impact. J. Trauma, 1975, 15: 150.
5. Robey. J.M., Blyth, C.S.. and Mueller, F.O. Athletic injuries; application of epidemiologic methods. J.A.M.A., 1971, 217: 184.
6. Shaw, J.C. A method for continuously recording characteristics of EEG topography. Electroencephalogr. Clin. Neurophysiol., 1970, 29: 592.