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REVIEW OF CHEST DEFLECTION MEASUREMENT TECHNIQUES AND TRANSDUCERS

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16. Abstract

A summary is presented, based upon a search of the literature, the author's own work, and personal communications of the author, of measurement techniques and transducers that have been used, or are presently available and exhibit potential for use in the measurement of dynamic chest deflection. Various techniques and transducers are evaluated for their potential for use with dummies, cadavers, infra-human primates and living humans and those techniques and transducers found to have high potential for use with living humans are discussed in detail. Measurement requirements are summarized, inherent problems are pointed out, and recommendations for the solution of some of these problems and further investigation are given.

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PREFACE

The National Highway Traffic Safety Administration (NHTSA), in order to define reasonable injury criteria for use in establishing standards for motor vehicle occupant protection, has sponsored numerous efforts to develop appropriate instrumentation and gather information on human kinematic response to crash impact. The review presented in this report, the result of a literature search, the author's own work, and personal communications of the author, was conducted by the Transportation Systems Center in support of the NHTSA and summarizes the most significant work done to date in obtaining information on dynamic chest deflection (compression) during impact.

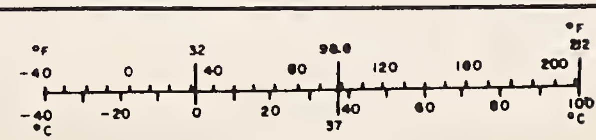
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

The increased use of three-point belt-type restraint systems in automobiles, while undoubtedly saving a great number of lives by preventing impact against hard interior surfaces of the vehicle, has resulted in a significant number of characteristic belt-related injuries.[1] Some of the more prevalent and serious injuries have been associated with severe chest compression by the restraint system during crash impact. Accident investigations have found that, in frontal collisions, when three-point belt restraint systems were being used, belt-related injuries accounted for a significant proportion of all injuries experienced (17.1 percent) and that chest injuries accounted for more than 25 percent of the belt-induced injuries.[1] Impact studies on unembalmed cadavers[2] (nine cadavers ranging in age from 32 to 61 years and weight from 122 to 226 pounds at time of death) have also shown rib fracture to be the most frequent belt-induced injury. Optimal design of the belt restraint systems is necessary to reduce the occurrence of chest injury, while preventing severe impact against interior surfaces of the vehicle by the occupant.

To develop design criteria and reasonable safety and compliance testing standards for belt restraint systems, a considerable amount of information is required on human tolerance to crash impact and the dynamic interaction of vehicle occupant and restraint system. However, this information is limited due in large part to the technical difficulties in the development of instrumentation to measure the appropriate variables. Since injury to the chest appears to be the most frequent belt-induced injury, there is a pressing need to develop a data base of information on thoracic response to restraint system impact -- that is, dynamic thoracic force-deflection characteristics -- and its relationship to injury. Investigators to date have concentrated on the measurement of blunt thoracic impact in cadavers and these measurements have been subject to a number of sources of error. Reliable data on thoracic response to restraint system impact will require the development of new and improved instrumentation.

The discussion that follows is based upon a search of the literature, and the author's own work and personal communications. It is a summary of measurement techniques and transducers that have been used, or are presently available, and exhibit some potential for use in the measurement of dynamic chest deflection. The various techniques and transducers are evaluated for their potential for use with dummies, cadavers, infra-human primates* and living humans and those techniques and transducers found to have high potential for use with living humans are discussed in detail. Measurement requirements are summarized, inherent problems are pointed out and recommendations for the solution of some of these problems and further investigation are given.

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*Infra-human primates as referred to in this report, is intended to designate those anthropoids (i.e., apes and large monkeys) closest to man in stature and development.

2. MEASUREMENT REQUIREMENTS

The requirements for the instrumentation and measurement of chest deflection may be grouped into four categories: requirements common to all subjects, requirements with use of anthropomorphic dummies, requirements with use of cadavers or infra-human primates, and requirements with use of living humans. The requirements when using dummies are usually dictated by purely technical considerations while the requirements when using cadavers and infra-human primates are dictated by technical and economic considerations. The instrumentation and measurement requirements are most restrictive when using living humans where the overriding consideration is safety.

2.1 REQUIREMENTS COMMON TO ALL SUBJECTS

The requirements common to all subjects are data processing and transducer physical requirements, and are independent of the type of subject. Unless precluded by unusual test restrictions, the data processing format (data channel characteristics) should comply with the suggested practice delineated in SAE Standard J211 for measurement of chest deflection. This standard recommends various classes of electronic data channel characteristics which are intended to encompass the information bandwidth likely to be encountered when measuring the variables commonly measured in impact testing. For the measurement of chest deflection, channel class 180 is recommended, which essentially allows the passage of a signal with frequency information up to 180 Hz with little attenuation. The standard also contains recommended practice for channel class selection, scaling, determination of accuracy, analog and digital processing, several miscellaneous measurements and data reporting format. In most cases the recommended practice is quite easy to adhere to and allows a valid comparison of data among independent investigators.

Transducer selection is a very important consideration. With all subjects, the transducers and any associated electronics attached to the subject must be kept as small and lightweight as is technically and economically feasible in order to perturb the dynamic characteristics of the subject as little as possible.

2.2 SPECIFIC REQUIREMENTS WITH USE OF ANTHROPOMORPHIC DUMMIES

The use of anthropomorphic dummies as human surrogates presents the fewest problems to the investigator in instrumenting for the measurement of chest deflection. Placing the measurement instrumentation inside the thorax of the dummy is the logical approach. A number of linear displacement transducers are commercially available that could be used in this manner, with little effect on the dynamic response of the dummy, to obtain accurate and repeatable measures of dynamic chest deflection. Metal components in the structure of the dummy's torso preclude the use of electromagnetic, RF* and other sensing devices on the outside surface of the torso that depend, for reliable use, upon an unperturbed field distribution. As subject safety is not a consideration, measurement methods requiring part of the transducer to be attached to a stationary object relative to the dummy, which is free to move, are acceptable means of measuring chest deflection.

2.3 SPECIFIC REQUIREMENTS WITH USE OF CADAVERS OR INFRA-HUMAN PRIMATES

The requirements for instrumentation to measure the dynamic chest deflection of cadavers and infra-human primates are more restrictive than those for dummies. Structural intervention of the subjects' thorax is not recommended if reliable and repeatable data are to be gathered. With either cadavers or infra-human primates, instrumentation that penetrates or in any way violates the structure of the thorax is certain to change its dynamic response to impact forces. Firm attachment to bony structures such as the sternum or spinous processes would be an acceptable limited intervention. As subject safety is not important, firm attachment of part of the transducer to an object that is stationary relative to the subject, is an acceptable procedure.

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* Radio frequency.

2.4 SPECIFIC REQUIREMENTS WITH USE OF LIVING HUMANS

Because there is still considerable uncertainty in the fidelity of dummies, cadavers, and infra-human primates as human surrogates, it is highly desirable that tests be performed on living humans. Low-level non-injurious testing of living humans will add to the data available for use in surrogate design and give absolute assurance of the surrogate's human fidelity at low levels.

Obviously, safety must be regarded as the prime concern in the system design. The instrumentation must be fail-safe. This places enormous restrictions on system design, compounding the difficulty in taking the measurement, as unobtrusive sensing is a necessity. Attachment of the transducers must in no way present a hazard to the subject and in this case, rigid attachment of part of the transducer to an object that is stationary relative to the subject, is unacceptable.

3. CURRENTLY USED MEASUREMENT TECHNIQUES

To date, most of the information on thoracic tolerance to impact has taken the form of careful examination of laboratory-induced impact injuries in cadavers. Information such as type, location and number of rib fractures, ruptures of spinal ligaments and discs, and spinal fractures, have been related to variables such as impact force and deflection, belt materials, configuration and width, and subject age and sex. Investigation of accident data has also concentrated on these types of variables. Very little data has been gathered on the direct measurement of dynamic chest deflection of living humans during impact.

A number of investigators have accomplished the measurement of chest deflection in cadavers by inserting a steel rod through a hole in the subject's thorax.[3,4,5,6,7] The rod was generally fastened to the sternum with a ball joint and passed through a bushing sutured near the spine. Targets were placed on the free end of the rod and the data was gathered by measuring the differential displacement of the rod target and the subject's back using high-speed motion pictures. In one case,[6] the probe also actuated a potentiometer, providing an additional measure. This method represents a means of measuring the deflection between two distinct points on the subject's thorax in a difficult field environment, but also represents an undesirable structural intervention which may have an effect on the dynamic response of the thorax to impact. This method also limits the ability of the investigator to examine the effect of the impact on the internal organs of the subject, as some of the organs are displaced by the intervention of the rod. Structural intervention can be avoided in more easily controlled laboratory experiments using a blunt thoracic impactor.[8,9,10] Targets are placed on the impactor and the subject's back. As the impactor strikes the subject's chest, the dynamic differential displacement of the targets is measured using high-speed motion pictures. This method is considered to measure an "average deflection as the impactor has a broad, flat surface and the measurement does not consider a single point on the subject's chest. As there is no structural intervention, this method also enables investigators to examine the integrity of the subject's internal organs after impact.

Another method which has been used on cadavers and avoids structural intervention of the thorax is the use of accelerometers firmly attached to the bony processes of the sternum and spine.[8,11] Using this technique, the signals from the two accelerometers are doubly integrated and then subracted to yield differential displacement. The major difficulties associated with this technique are transducer alignment, zero adjustment, and problems with intergration drift with resultant poor agreement with high-speed motion picture analysis. In one study,[11] the integrated data indicated consistently, larger deflections (68 percent larger in one case) than the motion picture data. On two occasions in this study the integrated signal increased without bound.

The other methods which do not require structural intervention of the thorax and have had limited use in the field [5,8,12,13] use the principle of near field electromagnetic induction and ultrasonics. Both methods rely on transmission of energy through the thorax and detection of the magnitude and variation of this energy to establish a measure of chest deflection. In spite of limited success in initial tests with these methods, they still exhibit considerable potential and are discussed in detail in section 4.

4. SUMMARY OF READILY AVAILABLE TRANSDUCERS AND THEIR RELATIVE POTENTIAL FOR USE IN MEASURING CHEST DEFLECTION

A great number of techniques and transducers are available for use in the measurement of linear displacement. The application of these techniques and transducers to the measurement of dynamic chest deflection introduces a great number of restrictions which limit and preclude their use in many cases. The principal difficulties encountered in almost every case are transducer attachment to the subject and maintenance of transducer positioning and alignment during testing. Transducers attached to the skin on the thorax of an infra-human primate, cadaver or living human are subject to lateral and angular displacement when exposed to the forces encountered in restraint system testing. A reliable measurement technique should be relatively insensitive to these displacements. Transducers requiring rigid mechanical coupling between the subject and a frame of reference stationary with respect to the subject are inappropriate for use with living humans as a rigid coupling presents the hazard of thoracic puncture in the event of system failure. In cases where remote sensing is used, the presence of hazardous transducer radiation may preclude the use of certain transducers with living humans.

In a number of cases, a differential measure from transducers placed on the subject's chest and back is taken to represent chest deflection. In these cases, the alignment of the two transducers is often critical[11] (see appendix). Difficulties with reliable transducer attachment to the subject compound the alignment problem. Following is a discussion of a number of specific techniques, the problems likely to be encountered in the implementation of these techniques, and an estimate of their potential for use with dummies, cadavers, infra-human primates, and living humans. The relative potential of each technique is summarized in Table 1 in section 5.

4.1 HIGH-SPEED MOTION PICTURES

High-speed motion pictures have been traditionally used to measure displacement vs. time in impact studies. For accurate measurements, however, the motion of the points of interest must be in a plane perpendicular to the optical axis of the camera. In many cases, because the object of interest either leaves the field of view (as happens when a subject penetrates an air bag restraint system) or becomes disoriented with respect to the optical axis of the camera, the perpendicularity requirement is sacrificed and approximation methods using multiple cameras and viewing angles must be utilized.[14] This is highly undesirable for measuring chest deflection where the deflection is small (about 2 inches before rib fracture).[5] Film analysis techniques are also subject to operator error, further degrading the reliability of the measurement. The technique has been used satisfactorily under well controlled laboratory experiments on thoracic tolerance to blunt impact, but as a technique for measuring chest deflection in the field while using various types of restraint systems, under less controlled conditions, it may be questionable. However, because with it the investigator can gain insight, at least in a qualitative sense, into the dynamic interaction of a subject and restraint system, it is good practice to utilize high-speed motion pictures at least as a secondary system for the measurement of chest deflection. This technique would be equally effective for use with dummies, infra-human primates, cadavers or living humans.

4.2 ACCELEROMETERS

Accelerometers have been used to determine dynamic chest deflection by measuring the acceleration at points on the chest and back of the subject, doubly integrating both signals to obtain absolute displacement, and subtracting to obtain differential displacement or chest deflection.[8,11] The problems encountered using this technique are numerous. The sensitive axes of the two accelerometers must be accurately aligned during mounting; maintaining this alignment in a dynamic impact test is very difficult. Gravitational forces are measured by dc accelerometers if their axes deviate from a horizontal plane. Even if the transducer used cannot sense a dc acceleration it will sense gravitational effects if its sensitive axis is moved in and out of a horizontal plane at an appreciable frequency during the dynamic test. The uncertainty and drift that is often associated with the double integration of a signal make a reliable measure of residual chest crush more difficult to obtain.[11] Difficulties in effecting a rigid attachment and maintaining the required alignment make accelerometers a poor choice for use with living humans. They still exhibit potential, however, for use with dummies, cadavers, and infra-human primates, as it is possible to rigidly attach the accelerometers to the superstructure of the dummy or the sternum and spinous processes of the cadaver or infra-human primates. Two types of accelerometers are found to be most prevalent today. They are the piezoelectric and piezoresistive types.

4.2.1 Piezoelectric Accelerometers

Piezoelectric materials generate an electric charge when subjected to a mechanical deformation. A number of ceramics exhibit this characteristic and are used in piezoelectric accelerometers. In a typical accelerometer, an acceleration produces a force on the piezoelectric material which deforms and, with proper design of the accelerometer, generates an electrical charge that is proportional to the acceleration. These devices need no external power source and are useable to very high frequencies. However, piezoelectric accelerometers exhibit very high output impedance, requiring the use of relatively sophisticated and expensive signal conditioning electronics such as charge amplifiers or extremely high impedance voltage amplifiers. These accelerometers are often difficult to use in a harsh field environment because of their impedance characteristics and relatively high sensitivity to temperature changes. These characteristics and the fact that they have limited low frequency response (precluding the measurement of residual chest crush) have made piezoelectric accelerometers of questionable value in measuring chest deflection, although recent developments[24] in integrated electronics built into the accelerometer case have reduced the importance of a number of these problems. A simpler device, with more appropriate characteristics for this application would be the piezoresistive accelerometer.

4.2.2. Piezoresistive Accelerometers

Piezoresistive accelerometers, unlike piezoelectric accelerometers, need an external power source for their operation and employ semiconductor materials in strain gage configurations for the measurement of acceleration. The piezoresistive accelerometer generally takes the form of a cantilevered beam with paired piesoresistive strain gages bonded to it. An acceleration deflects the beam and places the paired gages in compression and tension respectively. These paired gages are connected as the arms of a Wheatstone bridge circuit and the resultant bridge output is proportional to the applied acceleration. This technique can be effected with a half-bridge configuration using two piezoresistive elements and two "dummy" resistive elements or with a full bridge configurations using four piezoresistive elements. These bridge configurations are capable of measuring dc acceleration, are relatively insensitive to temperature changes and have low output impedance, requiring only very simple signal conditioning electronics. These characteristics make piezoresistive accelerometers the more logical choice for use in the measurement of chest deflection.

4.3 POTENTIOMETRIC TECHNIQUES

Potentiometric techniques are perhaps the most extensively used means for measuring linear displacement. With this technique, linear displacement is converted to a change in position of a moveable contact on a resistive element.[15] The moveable contact may be actuated linearly or may have a rotational configuration in which case the contact is actuated through a rack-and-gear arrangement or the contact is circular in nature. Commercially available products are abundant. In the case of anthropomorphic dummies, where these transducers can be mounted to the inner walls of the chest and back of the subject, these transducers represent an excellent choice for the measurement of chest deflection.

A potentiometric device has been used in the measurement of chest deflection in cadavers.[6] A steel rod, inserted through a hole in the cadaver's thorax and attached to the sternum, actuated a potentiometer at its other end which had been firmly attached to a vertibral body. While the measurements in such a case would be accurate, the creation of a hole in the subject's thorax is undesirable.

While the potentiometric technique should be very effective for use with dummies and moderately effective for use with cadavers, there seems to be no reasonable way to use it with infra-human primates or living humans to obtain the differential displacement of the chest and back necessary to measure chest deflection.

4.4 INDUCTIVE TECHNIQUES

4.4.1 Near Field Induction

Instrumentation using the principle of near field induction appears to be one of the more promising methods available for use in measuring chest deflection in living humans. A chest deflection monitor using this technique, an improved version of a laboratory device developed at General Motors,[16] was developed at the Transportation Systems Center. The instrumentation consisted of a transmitting coil which was placed on the subject's chest, and a receiving coil placed on the subject's back. The transmitting and receiving coils act in the same manner as the primary and secondary coils of a transformer. The transmitting coil is driven with a sinousoidal excitation, creating an electromagnetic field that is detected by the receiving coil (a small, standard RF choke). The signal from the receiving coil is then rectified and filtered to yield a dc signal proportional to the distance between the transmitting coil and the receiving coil. An electrical schematic for this device is shown in Figure 1 and calibration results are shown in Figure 2. The principal factor limiting the reliable use of this device as a chest deflection monitor is the presence of misalignment error. If the transmitting and receiving coils are not spatially aligned on a common axis, erroneous data results. The magnitude of these errors is illustrated in the appendix as well as a discussion of a potential solution to the alignment dependency of the receiver coil.

The device developed at TSC was used on cadavers in the field with erroneous results due to the physical distortion of the transmitting coil that occurred during impact.[12] This result could possibly have been avoided by placing the receiving coil, which was much more rigid, on the subject's chest and the transmitting coil on the subject's back. If the solution to the alignment dependency of the receiver coil proposed in the appendix is effective, and the receiver coil is placed on the subject's chest, the system may represent a very effective means of measuring chest deflection with infra-human primates, cadavers and living humans. The technique of near field induction is inappropriate for use with most dummies because the metallic superstructure of the dummy would distort the magnetic field produced by the transmitting coil, causing erroneous measurements.

4.4.2 Eddy Current Losses

Another technique that shows considerable promise for use in measuring chest deflection with living humans is the use of eddy current losses in a conductive material to alter the inductance of a sensing coil in order to obtain a measure of the distance between the sensing coil and the conductive material. The conductive material reduces the impedance of the sensing coil by setting up eddy currents in the material that tend to oppose the magnetic field that created them. The sensing coil may be one arm of an ac bridge and the electrical imbalance of the bridge is proportional to the distance between the sensing coil and the conductive target material. Changes in phase angle as well as amplitude may be detected and utilized as a measure of target displacement. Very thin targets may be used and temperature sensitivity is minimal. The angular dependency of the paramagnetic target material is not very pronounced as long as the material being used has dimensions greater than the diameter of the sensing coil.[17]

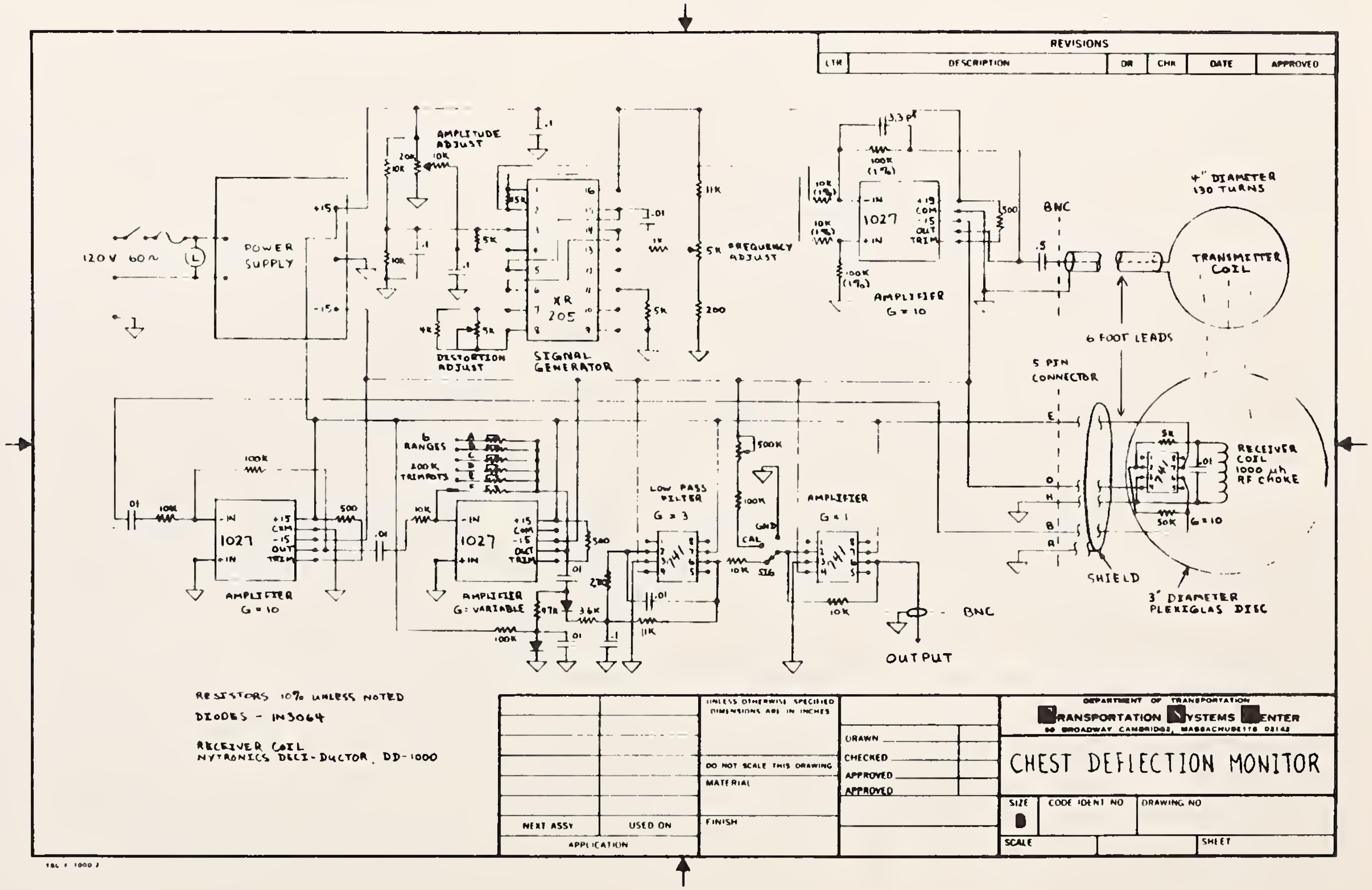

FIGURE 1 SCHEMATIC OF CHEST DEFLECTION MONITOR

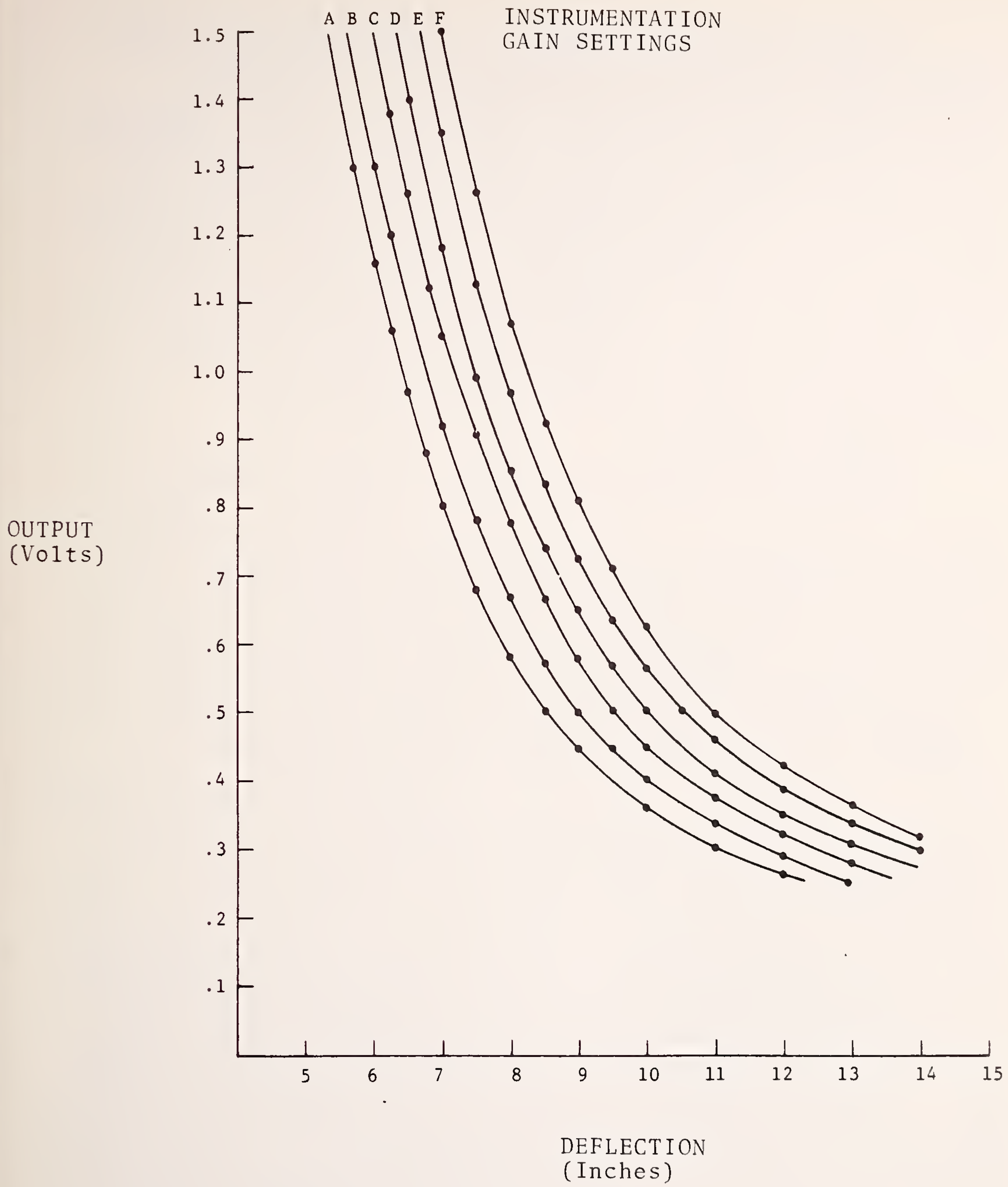

FIGURE 2 CALIBRATION OF CHEST DEFLECTION MONITOR

A system using the technique of eddy current losses has recently been developed for the NHTSA by KAMAN Sciences Corporation.[18] It consists of a sensor coil, 7.5 inches in diameter, mounted on the subject's back and a flexible conductive material on the subject's chest. The sensor coil and the conductive target material are made in the form of a jacket that the subject wears and can adjust tightly. To the author's knowledge, this system has not been extensively tested or used in a field environment. In theory it exhibits high potential for use with cadavers, infra-human primates and living humans but further work will be necessary to establish this conclusively.

4.4.3 Variable Reluctance

The variable reluctance techique can take a form quite similar to that of eddy current losses with the only difference being that the conductive material used in the technique using eddy current losses is replaced with a ferromagnetic material.[17] In this case, the magnetic material tends to increase the sensor coil impedance by introducing a low reluctance path into the field. As in the technique using eddy current losses, the sensing coil is one arm of an ac bridge and the electrical imbalance of the bridge is proportional to the distance between the sensor coil and the magnetic target material. This technique is a valid means for measuring chest deflection of cadavers, infra-human primates and living humans.

The variable reluctance technique may also use a change in the reluctance path between two or more coils by the displacement of a magnetic core used to electrically couple the coils. The linear variable differential transformer (LVDT) uses this concept and is a highly reliable and accurate field-proven device.[15] The LVDT should be very useful in the measurement of chest deflection in dummies as it may be mounted within the thoracic cavity. It appears to have little potential for use with cadavers, infra-human primates or living humans, however.

4.5 CAPACITIVE TECHNIQUES

The measurement of linear displacement using capacitive techniques is usually accomplished using concentric cyclindrical electrodes as the plates of a capacitor with a dielectric sleeve inserted between the inner and outer electrode.[15] The inner electrode or the sleeve may be moved in and out of the device constituting a moving rotor or moving dielectric design, respectively. The moving of the electrode or the sleeve causes a change of capacitance between the two electrodes that is proportional to linear displacement. The capacitor is usually placed on one arm of an ac bridge circuit that is driven by an oscillator. The electrical output of the bridge is then rectified and filtered to yield a dc level proportional to linear displacement.

While these transducers could be used with dummies for the measurement of chest deflection and in a more limited fashion with cadavers, a number of other techniques would be more appropriate to this application. There appears to be no reasonable configuration for using capacitive techniques in the measurement of chest deflection with infra-human primates or living humans.

4.6 ULTRASONIC TECHNIQUES

As discussed in section 4.2, a piezoelectric material is a material that generates an electric charge when subjected to a mechanical deformation. The inverse is also true. If an electrical potential is placed across a piezoelectric material, the material is mechanically deformed. If the piezoelectric material is properly coupled to another medium, the mechanical deformation imparts an ultrasonic pressure pulse into the medium. This ultrasonic energy may also be detected using piezoelectric materials and, in some cases, the same transducer is used to both generate and detect an ultrasonic pulse. The nature of the transmission and reflection of this pulse in the medium is dependent upon the acoustic characteristics of the medium. With appropriate hardware and scanning techniques, the internal structure of the medium may often be reconstructed and visualized in a number of formats using video display systems.

Ultrasonic techniques have been used extensively in diagnostic medicine to visualize internal structures of the human body.[19,20] Tissue discontinuities and abnormalities may be characterized and diagnosed in many cases. These techniques have also been widely used in non destructive testing of materials, including a recent application in automobile tire inspection.[21] Its potential as a technique for measuring chest deflection remains to be effectively demonstrated.

4.6.1 Reflection Ultrasound

If the acoustic impedance of a medium is designated as Z, and an unbounded logitudinal sound wave is incident normally at a boundary between two media (1 and 2), then the pressure amplitude reflection coefficient R, or the proportion of energy reflected from the boundary is given by:

$$R = \frac{Z_1 - Z_2}{Z_1 + Z_2} \quad \text{Eq. (1)}$$

The proportion transmitted is simply:

$$T = 1 - R \quad \text{Eq. (2)}$$

It can be seen from equation (1) that a large impedance discontinuity between the two media will result in a large reflection coefficient and much of the energy will be reflected. This principle is utilized in pulse-echo ultrasonic techniques to determine the character and spatial position of discontinuities within materials by measuring the transit time of a high frequency ultrasonic pulse to and from the discontinuity. As the depth of a subject's chest is from 6 to 11 inches, the ultrasonic pulse would travel twice that distance, and an excessive amount of input energy would be required to yield a reliable return signal. For this reason, reflection ultrasound may be considered inappropriate in measuring chest deflection.

Transmission ultrasound, on the other hand, represents a more promising technique.

4.6.2 Transmission Ultrasound

Transmission ultrasound utilizes two transducers, one to generate a pulse and another to detect it. This technique was used at the Southwest Research Institute in an attempt to measure chest deflection in cadavers.[22,23,13] A gated oscillator was used to excite a crystal placed on the subject's chest while two crystals were placed on either side of the spine to receive the pulse. A crystal assembly with a natural frequency of approximately 1.5 MHz was used with an oscillator gate period of .12 μsec. The gate repetition rate was 4000 Hz. Information was gathered on chest depth by measuring the transit time of each pulse through the thorax and integrating over each time period to obtain an output proportional to chest depth. In tests performed with embalmed cadavers, no signals were detected at the receiving transducers with one cadaver, and limited success was experienced with another presumably due to the enormous amount of scattering caused by the acoustic properties of embalmed human organs and the fact that, after embalming, the organs tend to separate with the remaining spaces being filled with embalming fluid, presenting a large number of acoustic discontinuities. Other problems encountered were difficulty in maintaining transducer aligment and complete reflection of the signal by air in the stomach or lungs which was aggravated by the fact that the diaphragm of the cadaver was positioned lower than that of a living human. Limited success was experienced in transmitting an ultrasonic pulse through the thorax of an unembalmed cadaver. Very high power levels were necessary to accomplish this and maintenance of transducer alignment was still a problem. It has been suggested that the alignment was still a problem. It has been suggested that the alignment problem may be solved by using a large array of detection transducers on the subject's back.[23]

While the power levels that were necessary to transmit the ultrasonic pulse through the thorax of an unembalmed cadaver were unsafe for use with living humans, it has been suggested that much lower levels would be needed to use this technique successfully with living tissue.[23] More work will be necessary to establish this.

It appears then, that the technique of measuring chest deflection with transmission ultrasound has not yet been ruled out for use with infra-human primates or living humans, although investigation of the potential hazards will be necessary before further experiments.

4.7 DIGITAL OUTPUT TRANSDUCERS

Digital output transducers, which do not require analog to digital conversion have been used primarily as angular position detectors or "shaft angle encoders," and to a lesser extent as linear displacement transducers.[15] In the linear configuration the displacement sensing element consists of a strip of material with coded discontinuities along its length. These discontinuties, which for example, may be holes through which light passes or ridges of ferromagnetic material such as gear teeth, may be sensed by the appropriate transduction principle and converted to an electrical output. Depending on the degree of sophistication, the coding may result in a simple pulse train to indicate incremental displacement or a more complex digital format to indicate absolute position.

As with other commercially available devices for the measurement or linear displacement, these transducers could be used with dummies for the measurement of chest deflection and to a limited extent with cadavers. Unless there is a need to produce data directly in digital form, other techniques may be more appropriate. The mechanical nature of these devices (requiring rigid coupling) makes them inappropriate for use with infra-human primates or living humans.

5. SUMMARY AND RECOMMEDATIONS FOR FURTHER INVESTIGATION

The measurement of chest deflection during restraint system impact is one of the most difficult biokinematic measurements to make. The requirement that it be safe and non invasive presents seemingly insurmountable problems to the investigator. The various techniques that have been reviewed here have been used previously for the measurement of chest deflection or are techniques of proven value in other areas of interest. Their application to the measurement of chest deflection was discussed and a number of techniques appear to exhibit reasonable potential for use in this measurement. The relative potential of the techniques and transducers considered is presented in Table 1 below. The potential of each technique is dependent upon the subject used as well as the experimental environment.

When measuring chest deflection in anthropomorphic dummies, commercial devices such as linear variable differential transformers and linear potentiometers (placed within the thoracic cavity) appear to be the most logical choices. These devices have been extensively field proven in other applications and are known to be accurate and reliable. The use of anthropomorphic dummies as human surrogates is still open to questions of fidelity however, and is clearly inferior to the use of cadavers and human volunteers.

In well controlled laboratory experiments with infra-human primates and cadavers, photogrammetric techniques using targets on a thoracic impactor and the subject, appear to be the easiest and most reliable methods for measuring chest deflection. In less controllable field testing of restraint systems, non invasive techniques using the principles of near field induction, eddy current losses or transmission ultrasound may be the techniques of choice for infra-human primates and cadavers. All of these techniques however, require more study to improve their accuracy and reliability and to establish their limitations. The use of accelerometers with double integration of the data would be the

TABLE 1. RELATIVE POTENTIAL FOR MEASUREMENT OF CHEST DEFLECTION OF REVIEWED TECHNIQUES

TECHNIQUES	POTENTIAL FOR USE WITH			
	DUMMIES	CADAVERS	INFRA-HUMAN PRIMATES	LIVING HUMANS
<u>OPTICAL TECHNIQUES</u>				
High-Speed Motion Pictures	5	1*	1*	5
<u>ACCELEROMETERS</u>				
Piezoelectric Accelerometers	6	6	6	4
Piezoresistive Accelerometers	6	3	3	4
<u>POTENTIOMETRIC TECHNIQUES</u>	1	6	7	7
<u>INDUCTIVE TECHNIQUES</u>				
Near Field Induction	7	2	2	2
Eddy Current Losses	7	2	2	2
Variable Reluctance	1**	6	6	6
<u>CAPACITIVE TECHNIQUES</u>	6	6	7	7
<u>ULTRASONIC TECHNIQUES</u>				
Reflection Ultrasound	7	7	7	7
Transmission Ultrasound	7	4	3	3
<u>DIGITAL OUTPUT TRANSDUCERS</u>	6	6	7	7

<u>Key</u>

1 - Reliable with no further development.
2 - High potential with further development.
3 - Moderate potential with further development.
4 - Low potential.
5 - Useable as a secondary measure.
6 - Useable but other methods exhibit much more potential.
7 - Inappropriate.

* Reliable in a well controlled laboratory environment using an impactor - otherwise useable as a secondary measure.
** Linear variable differential transformer.

next choice for infra-human primates and cadavers in this environment. A third and less desirable choice for cadavers would be the use of a steel rod through the subject's thorax, firmly attached to the sternum, using the other end of the rod to actuate a potentiometer attached to the subject's back or the placement of targets on the rod and subject for photogrammetric analysis.

For measurement of chest deflection on living humans the choices are limited. Three non invasive techniques are available, all of which need further refinement and study for a true assessment of their value: near field induction, eddy current losses, and transmission ultrasonics. The near field induction technique may be used with allowance for angular and lateral alignment limitations. Further work with this technique is required to clearly establish its limitations and develop it further (see appendix). The technique using the principle of eddy current losses is embodied in a device recently developed for the NHTSA by KAMAN Sciences Corporation. To date, the author is unaware of any field tests performed using this device. It can be assumed that the accuracy of this device is affected by angular and lateral misalignments as is the near field induction technique. The extent of these misalignment errors is yet to be determined. The technique of transmission ultrasound may still have potential for use with living humans. A thorough study is needed however, to determine the power levels necessary to transmit ultrasonic energy through the subject's thorax reliably and the potential safety hazards, both short- and long-term. This technique may be more readily applied to infra-human primates due to the questions of safety.

In summary, it can be said that the measurement of chest deflection with anthropomorphic dummies should be a relatively easy task using commercially available displacement transducers. When using cadavers and infra-human primates, the task may be accomplished reliably in well controlled laboratory experiments using photogrammetric techniques but is considerably more difficult in field tests with restraint systems. The measurement of chest deflection with living humans remains a formidable task. Several non invasive techniques exhibit potential but will require a great deal more study to establish their value.

APPENDIX

POTENTIAL SOLUTION TO THE ALIGNMENT DEPENDENCY OF THE RECEIVER COIL WHEN USING THE NEAR FIELD INDUCTION TECHNIQUE

The measurement errors encountered due to spatial misalignment of the transmitter and receiver coils of the chest deflection monitor developed at TSC are summarized in Figure 3.

A potential method for eliminating the alignment dependency of the receiver system when using the near field induction technique may be the utilization of three receiver coils oriented orthogonally instead of a single coil. If these coils are oriented as shown in Figure 4, the output voltage of each is proportional to the sine of the angle it subtends with respect to the magnetic field present. A measure of the absolute magnetic field strength may be obtained by squaring the values of the three output signals, summing them, and taking the square root of the total. The arithmetic manipulations may be performed using digital techniques or analog modules which are readily available. The resultant signal will be a measure of the distance between the transmitter coil and the center of the three-coil receiving system regardless of the angular orientation of the receiving system. There are a number of characteristics of this system which must be examined however. The most obvious potential for error would be significant crosstalk or interference among the three coils due to distortion of the magnetic field by the coils. A lesser potential for error would be the fact that the axes of the three coils do not pass through a common point but are slightly offset. These potential error sources may be best evaluated empirically.

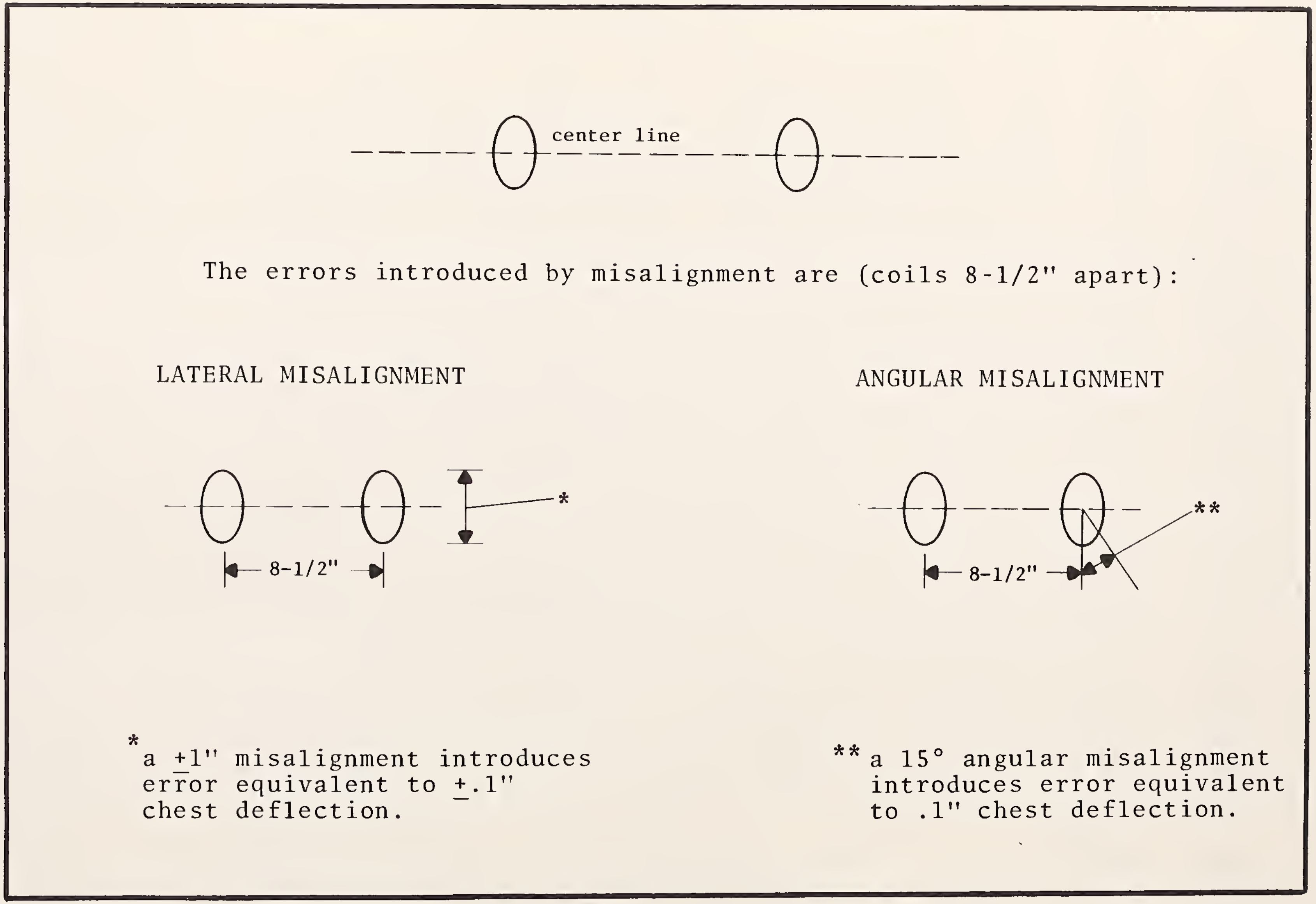

FIGURE 3. ERRORS DUE TO MISALIGNMENT OF CHEST DEFLECTION MONITOR

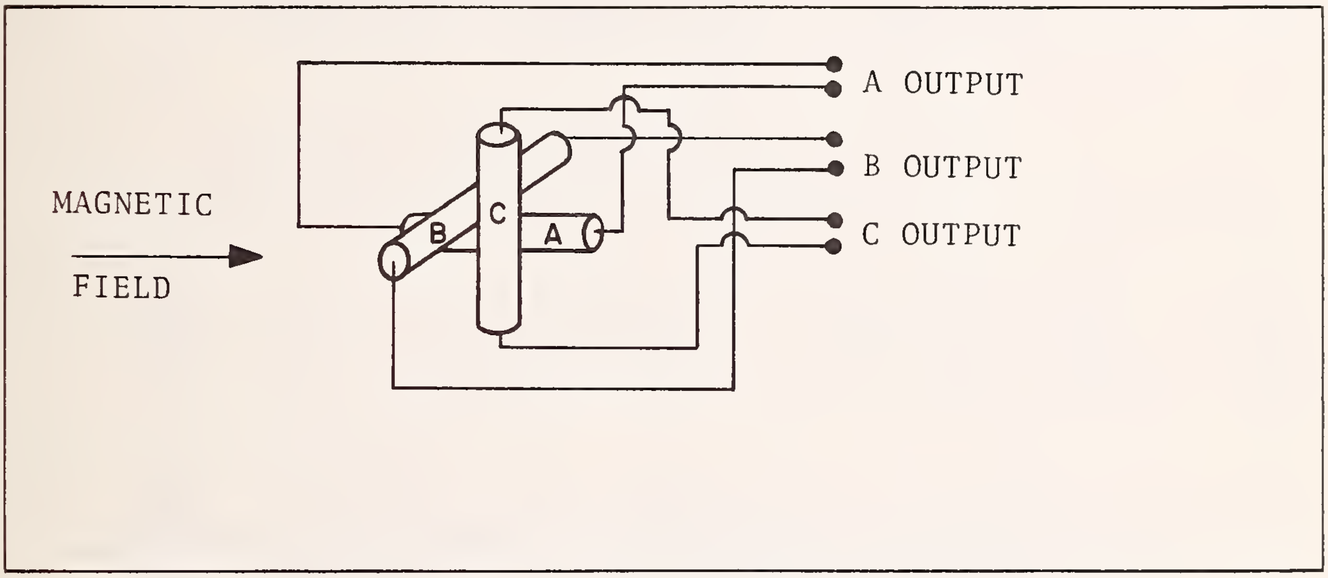

FIGURE 4. ORTHOGONAL RECEIVER COILS FOR NEAR FIELD INDUCTION TECHNIQUE

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