VISUALISATION OF HEART MOVEMENT FOLLOWING NON-PENETRATING IMPACT USING CINE AND FLASH X-RAY

by

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INTRODUCTION

A non-penetrating impact to the thorax results in the rapid displacement of the chest wall. Maximum chest wall displacement (Pmax) occurs at a time dependent on the pre-impact kinetics of the impactor and its size. A light impactor of mass 0.14 kg will take 2-3 ms to reach Pmax following initial contact with skin (Ref 1). A mass of 21 kg may take up to 20 ms (Ref 2). These rapid chest wall movements make prediction of the distortion and displacement of the thoracic contents difficult. The organs are of different masses and relative fixations and therefore possess different degrees of inertia.

The heart is relatively unfixed and is loosely contained within a sac, the pericardium, which has loose attachments to the underlying sternum, the sternal part of the diaphragm and the lateral thoracic wall. The insertions of the great vessels and the associated ligaments provide a degree of fixation cranially. A mid-sternal impact will result in considerable deformation of the heart itself and displacement of the whole organ within the thoracic cage. Cardiac and pulmonary contusion may result from impacts of less severity. Previous experiments have demonstrated the relationship of the severity of heart injury following non-penetrating chest injury to the dynamic behaviour of the chest wall and the kinetics of the projectile (Ref 1). This paper describes a method designed to determine the 3-dimensional distortion and displacement of the heart within the thorax following mid-sternal impact. The method uses a combination of flash and high-speed cine X-radiography and implantation of silver spheres. An example of its use in assessing heart movement following non-penetrating chest impact is given.

METHOD

There have been several studies to determine the distortion of the thoracic contents following non-penetrating impact. Roberts (Ref 3) struck the mid-sternum of mongrel dogs with an impactor of mass M = 5.4 kg, diameter D = 7.6 cm and velocities V between 5.5 ms and 6.7 ms. Flash radiographs were taken in the lateral and left anterior oblique planes both before impact and after the sternum had been compressed by 7.6 cm (3"). The heart was visualised by the delivery of radiopaque contrast medium before and during impact. These impacts were severe and only limited quantitative information was available describing heart distortion and displacement. Shatsky (Ref 4) accelerated Macacca mulatta monkeys within the weight range 3 kg - 6 kg against a fixed impactor at terminal velocities in the range 3 ms^{-1} - 8 ms^{-1}. The animals were hit mid-sternally. The heart and aorta were visualised by the infusion of a radiopaque contrast medium during the impact. A high-speed cine radiography emitter and camera were positioned lateral to the animal and therefore heart and aortic movement was only assessed in two dimensions (x and y in the system described below). It was not possible to determine motion quantitatively.

The experiments described in this paper were performed on anaesthetised pigs. The experiments described earlier (Ref 1) to derive a simple mathematical model to predict gross heart injuries and the dynamic behaviour of the chest wall were used as a biomechanical basis for the present radiographic experiments. The experiments of Ref 1 were performed on pigs with weights in the range 20 kg-90 kg. For the radiographic experiments it was convenient to use pigs in the weight range 20 kg-30 kg. Preliminary experiments demonstrated that the visual resolution of the thoracic contents (especially of the heart and great vessels) was not of sufficient quality to accurately measure 3-D movement. This major problem was resolved by the use of small (3 mm-4 mm) radiopaque silver markers attached to the heart and the aorta. The markers were surgically implanted 4-6 weeks prior to the chest impact and provided good visual definition as well as being invaluable anatomical identifiers.

Thirteen balls were used in this study. Ball 0 was sewn to the fixed aorta, ball 1 to the junction of the aorta and the subclavian artery, and the remainder (balls 2-12) follow the course of the circumflex and the anterior and posterior coronary arteries (Fig 2). Distortion of the heart and gross heart movement can then be inferred from the relative and absolute displacement of the spheres respectively.

The positions of the markers during the experiment are recorded in two ways using X-rays:

1. A cine X-ray exposure is made every millisecond during the impact, in the lateral plane.

2. Flash X-rays are taken 10 minutes before impact and at impact +10 ms (variable), anteroposterior.

<u>Co-ordinate System</u> The co-ordinate system used (Fig 1) is defined as follows:

+ve x from animal head to tail

+ve y orthogonal to x, from sternum to spine (animal front to animal back)

+ve z orthogonal to x and y, from animal left to right

The co-ordinate system is standard right-hand Cartesian.

<u>Cine X-ray System</u> The system is a Hewlett Packard Model 760/273 cine X-ray unit, with Varian Image Intensifier, and Fastax rotating prism camera for recording the output from the intensifier. The camera speed is feedback controlled via a magnetic pick-up to within 10 frames per second, and initiates an X-ray pulse when the camera shutter is fully opened. The system can give up to 50 X-ray pulses, each of duration 30 ns, with a minimum separation of 1 ms. The intensifier output is recorded on Kodak Video News Film 7250 (Colour).

Flash X-ray System The system is a Field Emission (Hewlett Packard) Model 730/2710 350 kV max stereo flash X-ray system. In this series of experiments only one stereo channel was used and the output was limited to 250 kV. The X-ray pulse length is 50 ns. The X-ray image is recorded on Kodak Xomat L film between 3M Trimax Intensifier Screens.

Layout of Equipment A schematic diagram of the equipment layout is shown in Fig 3. The animal is supported with its spine horizontal, ie +ve y is vertically up; x and z are horizontal. The cine X-ray records images in the x-y plane. The flash X-ray head is in the vertical plane through the cine X-ray head and at an angle of about 20 degrees to the vertical. Because of the layout, fogging of each X-ray recording system is possible from the other X-ray source. To reduce the fogging, the following procedure is adopted:

1. To reduce fogging of the flash X-ray plate, the cine system is limited to 20 pulses.

2. To reduce fogging of the cine X-ray film, the second flash is timed to occur between two cine X-ray pulses. The position of the spheres in the cine system at this time is obtained by interpolation between the frames on either side of the flash X-ray exposure.

Synchronisation The heart is an organ which changes its shape and volume as part of its normal function. These changes could affect the results and it is therefore important to ensure that the two flash X-rays are taken at the same point on the cardiac cycle, even though they may be spaced by 10 minutes. The volume and shape of the heart will not change due to normal heart function in the 20 ms of the experiment and any measured movements will therefore be due to the impact alone.

The initial x, y, z co-ordinate of each ball can be calculated from the pre-impact flash X-ray and the cine X-ray frame immediately prior to impact. (The mathematics is lengthy but straightforward and must be omitted due to shortage of space). Two dimensional x, y ball movement can be determined at 1 m s intervals from the cine X-ray data, and a second 3-D ball position calculated from the second flash X-ray and the interpolated cine X-ray data. There will be 13 ball movements/cine frame and a vast amount of data will be accumulated during the course of a single impact. Analysis of the results - in the form of co-ordinates for each ball in each frame - is then a function of what information is required.

A typical sequence for a trial might be as follows:

1. Implant silver balls onto the heart and aorta of the anaesthetised animal and allow it to recover from the effects of anaesthesia.

2. 4-5 weeks later, anaesthetise the animal again and subject it to non-penetrating chest impact. Animal weight 22-24 kg.

3. Impactor kinetic energy and the maximum transient displacement (Pmax) of the chest which it produces are measured from conventional high speed cine at 5000 fps.

4. Movement of the radiopaque silver spheres is monitored by lateral cine X-radiography at 1000 fps for a few frames prior to impact and for 20 frames after. Flash radiographs are taken anteroposterially 10 minutes before impact and at nominally 10 ms after impact.

5. The cine and flash X-ray records are then analysed as outlined above to give marker positions in 2-D on all frames except those where flash X-rays occur, for which 3-D data is available.

The results of a typical analysis are shown in Fig 4. The motion of the silver balls 1-12 in the x-y plane is shown relative to ball 0 (represented by +) for the first 4 ms of the impact on the mid-sternum by an impactor of diameter 3.7 cm and mass 0.14 kg. The position of the impactor is shown for reference only. The legends "tail", "head", "sternum" and "spine" are direction indicators and not precise locations of these structures.

There are obviously errors in the analysis procedures because of magnification and shadowing effects, so the quantitative information may not be accurate in all cases. However, qualitative information can be readily interpreted. In the example in Fig 4, the heart was severely distorted at 3 ms. Those balls on the anterior surface of the heart (3, 4, 5) were accelerated rapidly by the advancing chest wall. However, those on the posterior surface (8, 9) moved slowly. The separation in the y plane between balls 4 and 8 decreased from 62 mm to 31 mm in 3 ms. The compression of the heart in the y plane was responsible for the extremely high transient overpressures (up to 160 kNm) observed within the ventricles at 3 ms.

CONCLUSIONS AND DISCUSSION

A general technique has been described which can be used to visualise heart movement as a result of blunt impact to the mid-sternum. The technique can be adapted to suit the requirements of individual experiments. The answers to the following questions are easily established using the technique:

a. What are the relative motions of the anterior and posterior walls of the heart?

b. What is the magnitude of the displacements of the anterior and posterior walls of the heart relative to the referenced ball 0 on the aorta?

c. Does the heart move significantly in the cranial/caudal (x) plane?

d. Does the heart move significantly into the left or right chest?

e. How does ball 1 (at the angle of the left subclavian artery and the aorta) move relative to the fixed ball 0 on the aorta? The answer may shed light on the mechanism of rupture.

f. What is the magnitude of the distortion in the particularly thin portion of the myocardium in the right ventricle close to the pulmonary infundibulum? (This is a common area for cardiac rupture to occur.)

g. Is there a relationship between the distortions of the body of the heart and its movement within the thoracic cage and the diameter of the impactor?

Three dimensional information can only be obtained when two X-ray sources are used. However it is possible to obtain extremely useful information from the cine X-ray data alone.

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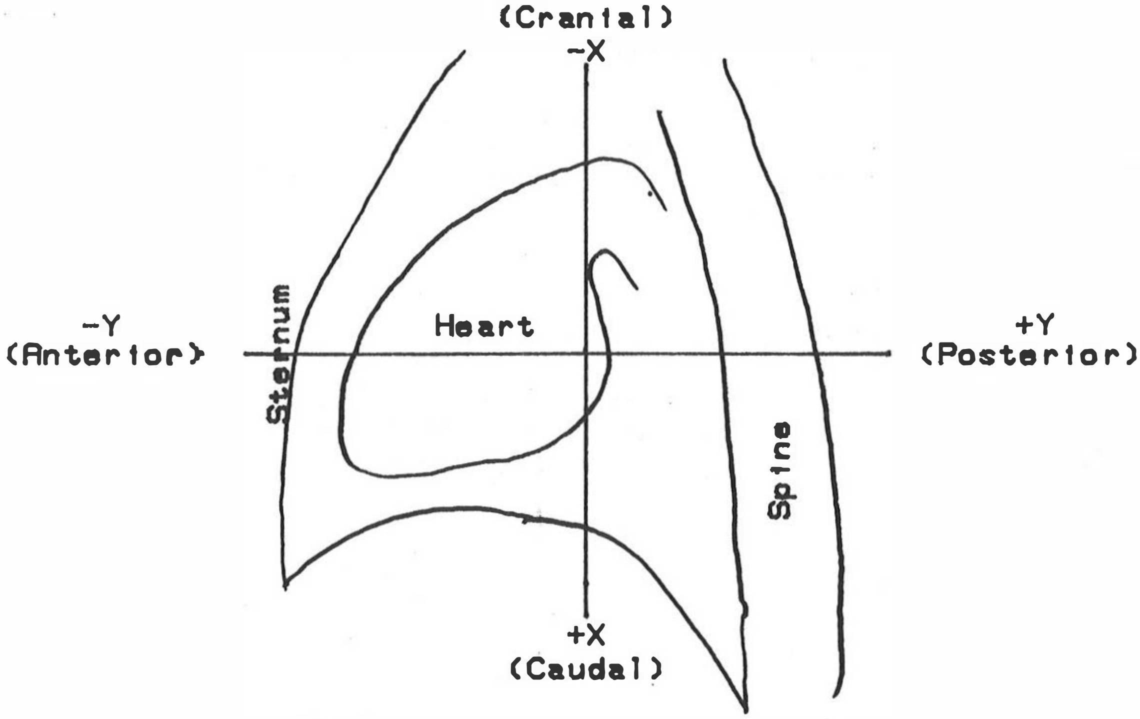
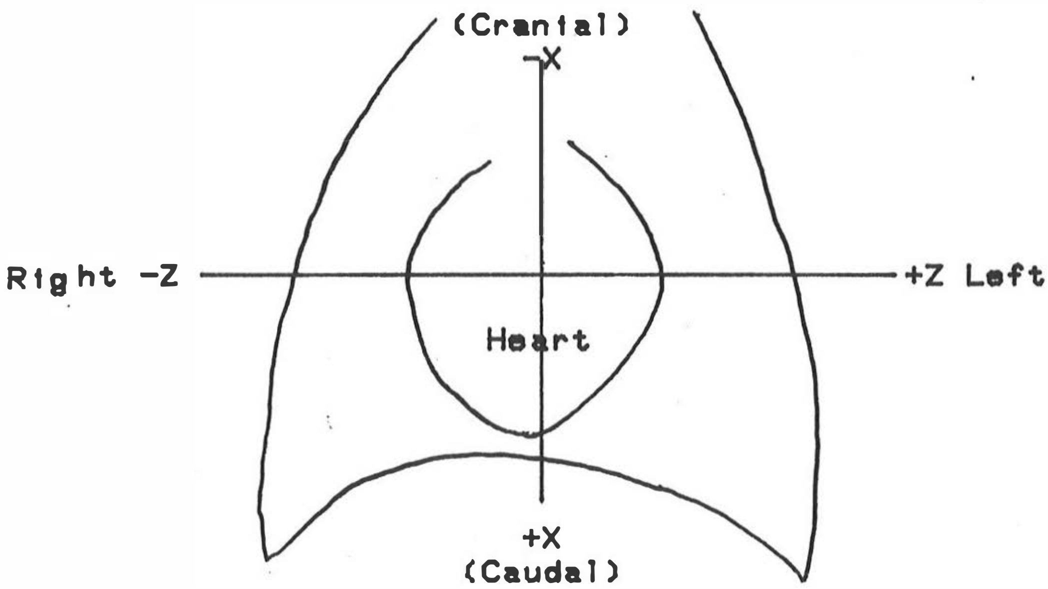


a) Lateral view of thorax



b) Anteroposterior view of thorax

Fig.1 Silver ball coordinate system

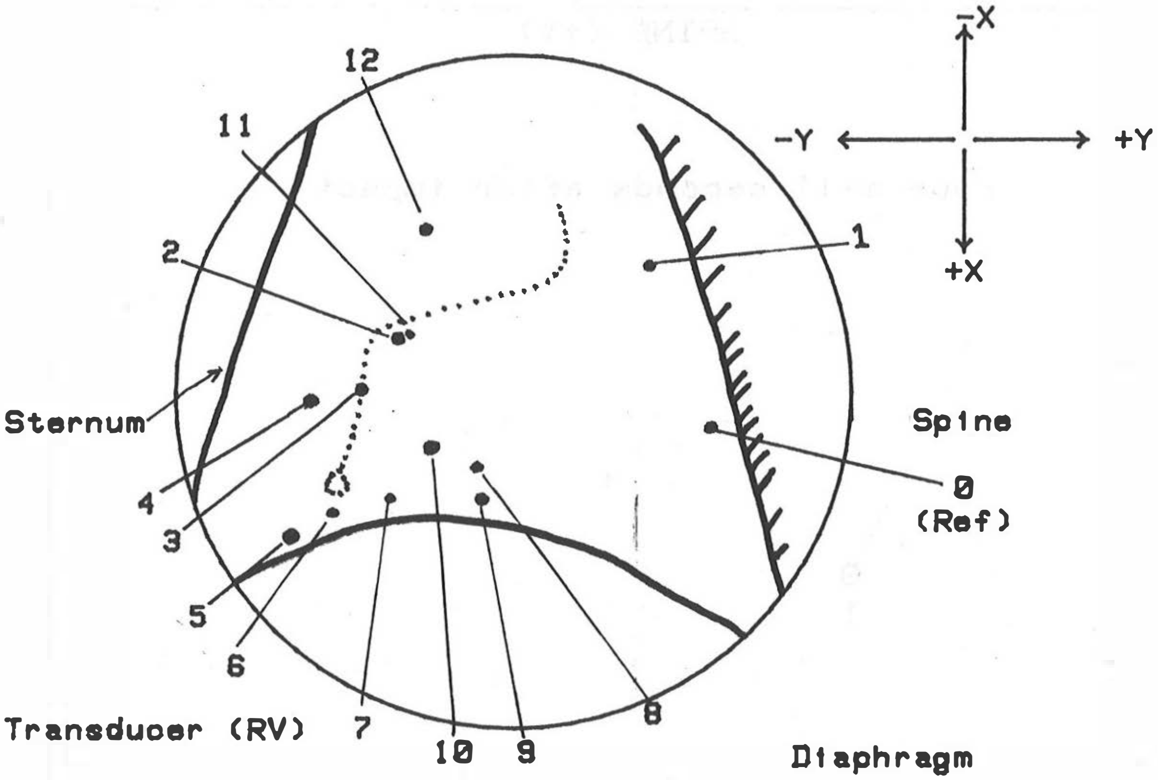


Fig.2 View of silver balls in cine X-ray system

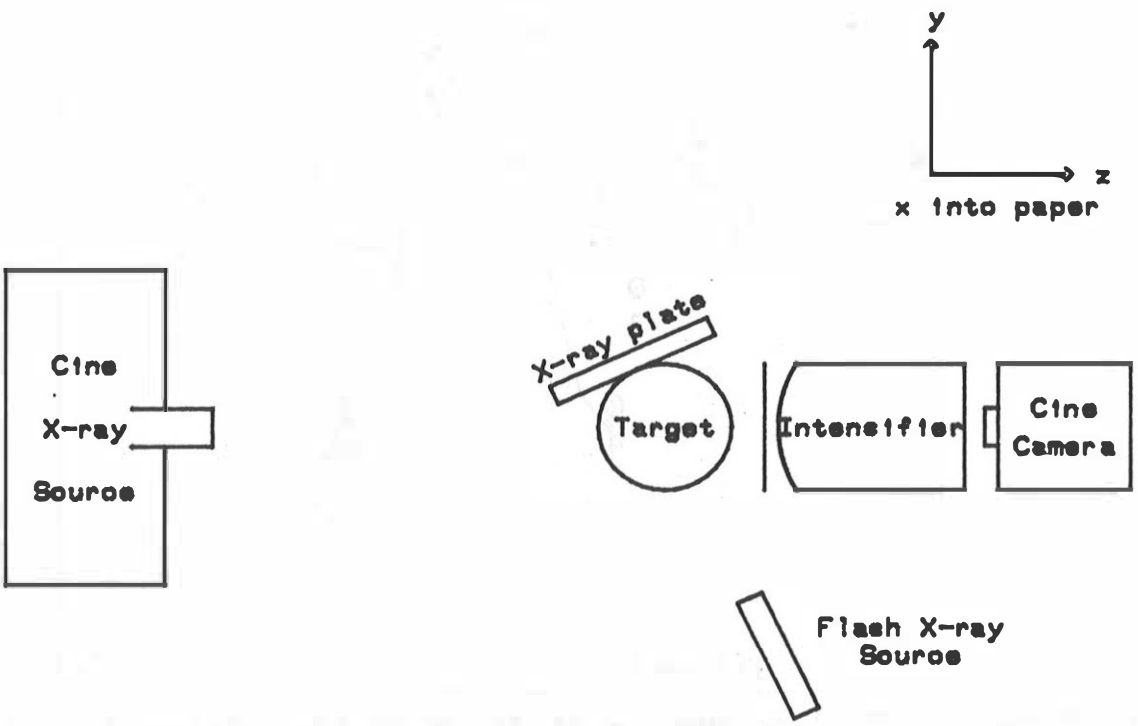
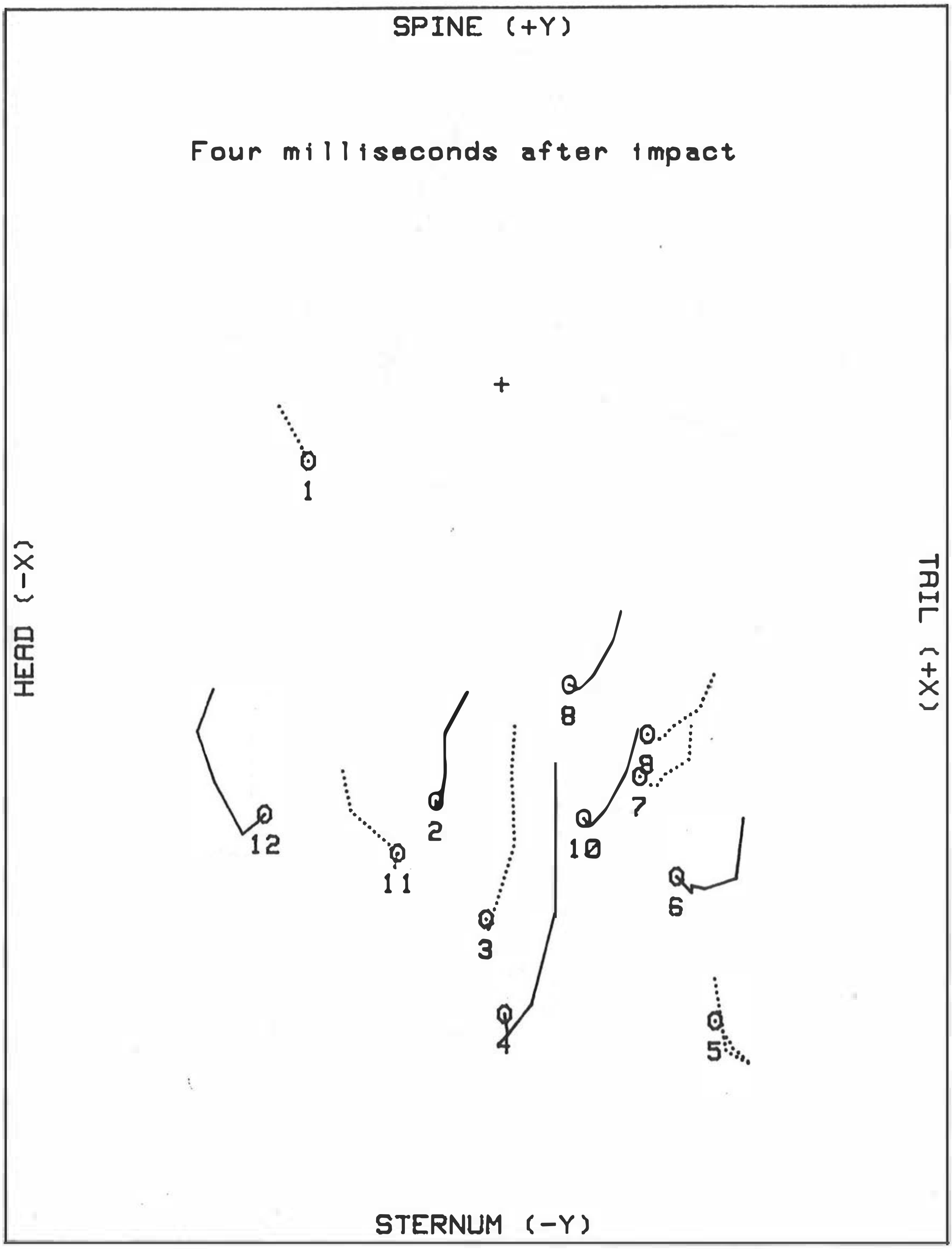


Fig.3 Schematic layout of equipment



Trial:21/80 Ball movements relative to ball 0,(+)

Fig.4 Analysis of X-ray data for ball movement