Abstract:
The purpose of this study was to demonstrate the feasibility of using the sound transmission characteristics of bone as a diagnostic tool in orthopedics. This was done by analytically predicting the change in dynamic response of the human forearm due to changes in the bone material properties in various portions of the forearm. It is hypothesized that the response of a portion of the human body to a low-frequency (100 to 1000 Hz) sinusoidal force is an objective indication of the state of health of the skeleton in that portion of the body. Therefore, a change in the dynamic response of that portion of the body would reflect a change in the state of health of the skeleton. This points to the use of the dynamic response test as a diagnostic technique in orthopedics.

Since there has not been established a normal sound transmission characteristic which relates the physical parameters of the body to the dynamic response, it is anticipated that this diagnostic technique is more immediately applicable to detecting changes in the state of health of the skeleton. Such a technique could be useful in tracing the healing of a damaged bone as treatment is administered.

Predictions made by the analytical model indicate that this diagnostic technique may be more sensitive to bony changes in the skeleton than is roentgenography. In addition, measurement of the first natural frequency of a bone may be a more objective indication of the state of health of the bone than is a roentgenograph.

Limitations of the dynamic testing technique are, that bony changes in certain portions of a bone may be difficult to detect. In addition, the ability of this technique to detect a change in sound transmission characteristic is dependent upon the amount of change of the property.

It is anticipated that the research proposed will verify the hypothesis that the use of bone sound transmission characteristics is a useful diagnostic tool in orthopedics and that the dynamic response of a bone is an objective indication of its health.
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Date August 16, 1974
DYNAMIC TESTING AS A DIAGNOSTIC TECHNIQUE IN ORTHOPEDICS.

by

CLARK JOSEPH MOZER

A thesis submitted in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Mechanical Engineering

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The author acknowledges Dr. D. O. Blackketter for his guidance in preparing this thesis. He also acknowledges Dr. E. R. Garner for his assistance in the computer work. A special note of appreciation goes to the author's wife, Lani, for her help.
The purpose of this study was to demonstrate the feasibility of using the sound transmission characteristics of bone as a diagnostic tool in orthopedics. This was done by analytically predicting the change in dynamic response of the human forearm due to changes in the bone material properties in various portions of the forearm. It is hypothesized that the response of a portion of the human body to a low-frequency (100 to 1000 Hz) sinusoidal force is an objective indication of the state of health of the skeleton in that portion of the body. Therefore, a change in the dynamic response of that portion of the body would reflect a change in the state of health of the skeleton. This points to the use of the dynamic response test as a diagnostic technique in orthopedics.

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INTRODUCTION

This thesis has been written in the format outlined by the National Institute of Health for an application for research grant. The research done in preparing this paper was to demonstrate the feasibility of using the sound transmission characteristics of bone as a diagnostic tool in orthopedics. Research is proposed which will further develop this technique as a diagnostic tool and will experimentally verify its effectiveness.

The dynamic response of the human forearm to a low-frequency harmonic force has already been analytically predicted. This study predicted the change in response due to localized changes in bone material properties, as might occur with an osteolytic lesion. These analytical predictions of response changes provide the basis for the research proposal.
The objective of this research is to develop the use of bone sound transmission characteristics as a diagnostic tool in orthopedics. The objective is twofold:

1. Develop experimental techniques and equipment which will provide an objective indication of healing rate as treatment of the disorder is administered.

2. Develop techniques which may aid in early diagnosis of orthopedic disease.

A computer model which predicts the response of a human forearm to a low-frequency harmonic force, together with an experimental apparatus which measures the response of the forearm, have been developed at this university. This computer model has been used to predict the change in sound transmission characteristics of the forearm due to an osteolytic lesion. The results indicate that measuring the sound transmission characteristics of a bone, in this case, the forearm, to a harmonic force may be an objective indicator of the state of health of the bone. This research will confirm or refute these analytically predicted results.

Leukemia is an example of a malignant disease which may affect changes in the skeleton. Recent developments in chemotherapy have made it possible in many cases to rapidly place patients in remission. While in remission skeletal abnormalities as well as other symptoms of the disease disappear. In the case of these patients, the sound transmission characteristics of the bones may be an objective diagnostic indicator.
of the restoration of the bone matrix to normal.

Although leukemia is presented here as an example of a disease where bone sound transmission characteristics would be useful in diagnosis, obviously there are other orthopedic disorders to which this technique could be applied as an objective diagnostic tool.
BACKGROUND

As a part of this background review, a bibliography of medical literature reviewed is presented in Appendix I.

The need for an early diagnosis in malignant disease is well established. Due to the recent advances in chemotheraphy in the treatment of leukemia, there is an even greater urgency to reach an early diagnosis of hematologic malignancy (1). In an article published in late 1972, Van Slyk (1) states that from a study of 159 children who have survived more than 5 years after diagnosis, it is estimated that over 50 per cent will have normal life spans.

Leukemia is an example of a malignant disease which may present with bone pain and associated osteolytic lesions. B. A. Chaubner (2) points out that in the case of patients with chronic granulocytic leukemia, bone pain suggests an underlying osteolytic process. This process can take place without radiologic changes or hematologic evidence of blastic transformation. In other words, certain bone lesions may not appear on a radiograph, particularly at an early state of the disease. However, it is precisely at this early stage of development in a malignant disorder that the diagnosis is critical. Also critical is having an objective means of evaluating the effects of therapy.

The percentage of the patients who have leukemia who experience bone changes varies. Silverman (3) found bone changes in 70 per cent of the children in his study. Thomas (4) found lesions in 90 per cent
of the children he studied and in 57 per cent of the adults. In a more recent survey, Aur (5) found bone changes in 21 per cent of the children. Aur used more strict criteria in determining whether the bone was affected by leukemia, which accounts for the substantially lower percentage in his findings.

The specific lesions which occur in leukemia are varied, depending primarily on the age of the patient and on the state of advance of the disease. They are, briefly, generalized rarefaction of the skeleton, radiolucent transverse bands occurring in the metaphysis of long bones (occurring primarily in children), osteolytic lesions, and cortical and periosteal lesions (4). Thomas (4) found that the osteolytic lesions were very common in both children and adults with leukemia. That the lesions may cause severe bone destruction is illustrated by the cases of vertebral compression reported (6, 7).

The bony changes that occur in leukemia may disappear during remission (1). Bone pain associated with these changes also disappears during remission (4, 1). It is interesting to note, however, that during remission bone pain may disappear and the function restored without improvement in the radiographs (6). This suggests that remission of the leukemic process is not necessarily related to radiologic evidence. It has also been established (5) that bone pain is not necessarily related to roentgenographic findings. These facts suggest the need for a more objective measure of bone property changes than the roentgenographs provide in order to monitor the leukemic process in the
bone.

A substantial amount of work has been done in recent years on in-vivo non-destructive testing of bones. Techniques for measuring the response of bone to a low-frequency harmonic excitation have been developed by Jurist (8) and at this university (10, 11, 12). Jurist (9) has applied his measurements of tibial resonant frequency as a diagnostic technique in measuring the strength of fracture unions. He found that this technique shows promise as an accurate indicator of fracture healing.

At this university, Matz (10) made a parametric study of the effects of different physical parameters on the low-frequency vibration response of the forearm. The four physical parameters Matz measured were ulna length, fleshiness, bone size and muscle development. All of these parameters were found to affect the sound transmission characteristics of the forearm. Matz's work is particularly important, because his work can help explain variations from an average response for a large population. There has not been established a "normal sound transmission characteristic" which relates the physical parameters of the subject's forearm to the dynamic response.

E. R. Garner (11) used Matz's experimental apparatus to obtain the response of the forearm of a 34 year old male. He then mathematically modeled the forearm, using the finite element technique, in terms of eight macroscopic biological properties of the flesh and bone in the arm. By adjusting these properties until the analytical response from his model matched the experimental response from Matz's apparatus,
Garner determined the macroscopic biological properties of the flesh and bone of the forearm of the subject. Garner's modeling technique enables the investigator to predict changes in the response of the forearm due to changes in the physical properties of the arm.

At this university Harrigan (12) developed improved instrumentation and procedures for determining the response of the forearm to a low-frequency harmonic excitation. He determined four configurations of the apparatus which will provide reliable test data. The four configurations which Harrigan found have frequency deviations of less than 8 per cent. Three of these configurations had frequency deviations from the first bending natural frequency of less than 5 per cent. Thus, Harrigan greatly improved the accuracy with which the first natural frequency of the forearm can be measured.
RATIONALE

Presently, detection of orthopedic disorders is done largely by X-ray. In a large number of cases this is the only diagnostic tool necessary. However, Snider (15) has estimated that a 30 per cent reduction in roentgenographic bone density is necessary to detect any change in the resulting X-ray negative. Thus, with the present diagnostic means, there is room for a great deal of bone damage before the disorder can be readily detected roentgenographically. It seems that there exists a need for a more sensitive diagnostic tool for measuring the integrity of bone.

The bone lesions which occur in leukemia reduce the density and therefore the bending stiffness of the bone matrix. It would be desirable to be able to accurately detect these changes in the structural properties of the bone. One way of doing this is by exciting the bone with a sinusoidal force (a vibration) and then detecting the response of the bone to the input force. The response of the bone will indicate the structural properties (sound transmission characteristics) of the system.

For a continuous system, such as the human forearm, there are an infinite number of natural frequencies of vibration and associated mode shapes (13). Generally the first natural frequency of a system is readily detectable experimentally. Briefly, this is the lowest frequency of excitation at which the amplitude of the response of the system has a maximum. At higher natural frequencies the damping which
is present in every real system, and which is very predominant in biological systems, attenuates the displacement of the system to the point where the response is unnoticeable. It is therefore expected that in the measurement of the dynamic response (sound transmission characteristics) of bone, the first and possibly, the second natural frequencies will be observed. These natural frequencies and natural modes are functions of the structural properties (bending stiffness) and inertial properties of the system. Therefore, the dynamic response (sound transmission characteristics) of a system with a given geometry and mass distribution will determine the structural properties of the system. It is precisely these structural properties which indicate the health of the skeleton, which is essentially a structural frame. In the case of leukemia, the state of health of the skeleton may be related to the state of advance of the malignancy.

In the case of a simple beam an analytical prediction of the response of the system presents no problem. However, an analytical prediction of the response of a complicated biological system is a formidable problem indeed. E. R. Garner has used a numerical approximation technique, the finite element method, to approximate the response of the forearm of a 34 year old male to a sinusoidal input force. Garner's work is presented in full in Reference (11).

Garner found that a reduction in both the hydrostatic and deviatoric stiffness of bone would result in a lower first natural frequency for his modeled system. As he points out, this is to be expected since
generally a reduction in the stiffness of a structural system will lower the natural frequency of the structure. Garner found that the response was much more sensitive to changes in deviatoric stiffness than to changes in hydrostatic stiffness. Thus, Garner's model predicts that in the case of generalized rarefaction of bone, which would presumably reduce the stiffness of the bone, the first natural frequency of the bone would be reduced. Note that a generalized rarefaction of bone is one of the effects that leukemia has on both adult and juvenile patients.

To examine the predictions of the modeling technique further, the total (hydrostatic and deviatoric) stiffness of a section of bone three inches long approximately midway between the wrist and the elbow of both the radius and the ulna was reduced from zero to fifty per cent of the normal stiffness as determined by Garner. The first natural frequency of this analytically modeled forearm was then predicted. A summary of this procedure is presented in Appendix II. It was found that the peak amplitude of the response reduced linearly with the reduction in bone stiffness (Figure 1). Figure 2 shows the expected change in response of the arm due to a 50 per cent reduction in stiffness in this localized area. Note that the amplitude of the response has reduced slightly and the first natural frequency has moved from 480 Hz to 400 Hz. The bandwidth, B, measured at 75 per cent of the peak amplitude of each curve was increased slightly from 220 Hz to 235 Hz. It is therefore expected that on the basis of these analytical
FIGURE 1. Change in First Natural Frequency Due to Stiffness Changes

SLOPE = -16Hz/10% REDUCTION IN STIFFNESS

PER CENT CHANGE IN BONE STIFFNESS IN SHAFT
FIGURE 2. The Expected Change in Response Due to a 50 Per Cent Reduction in Stiffness in the Shaft
results, a similar shift in the response curve would occur for a patient with a similar lesion.

To further anticipate the results of lesions in different locations in the arm, the total stiffness of a 1-1/2 inch long section of the forearm located in the wrist was reduced from zero to 50 per cent below the normal value. In this case, however, there was a negligible shift in the frequency response curve. This was not particularly discouraging, since in the case of the first natural bending mode of a system such as this, this is the expected result. In this system the mid-section of the beam is bent more than the end-sections, therefore a change in the structural properties in the mid-section of the beam would affect the response more than a similar change in the end sections of the beam. One of the limitations of the dynamic testing method as a diagnostic technique is that the location of the lesion may be critical to the detection.

The effect of changes in density in the forearm was also investigated. It was found that a decrease in density either generally or locally increased the amplitude of the response slightly and the resultant first natural frequency was greater than that of the normal system. Figure 3 shows the shift in response due to a 50 per cent decrease in density of a 3 inch long section of the forearm at midshaft. The first natural frequency changed from 480 Hz to 560 Hz and the bandwidth of the first natural frequency increased from 220 Hz to 295 Hz.
FIGURE 3. The Expected Change in Response Due To A 50 Per Cent Reduction in Density in The Shaft
Similar to the analytical results for reduced stiffness, there was little change in the response of the arm for density changes in a localized region near the wrist.

A bone lesion which reduces the roentgenographic density of the bone will affect the dynamic response (sound transmission characteristics) of the bone in two ways. It reduces the size and/or number of bone trabeculae and therefore reduces the stiffness of the bone. As can be seen from Figure 2, this has the effect of broadening the response curve and shifting it to the left. The lesion also decreases the density of the bone by replacing the more dense bone (2.3 gm/cm$^3$) (14) with fluid which has a density close to that of water (1 gm/cm$^3$). This has the effect of shifting the response curve to the right, as shown in Figure 3.

In view of these two effects, the question becomes, "How is the overall response changed due to the lesion in the forearm?" A total loss of bone in a localized area would result in a 57 per cent reduction in density in that area due to the replacement of the bone by fluids. This would also result in a 100 per cent loss in stiffness in the bone; since the fluids have essentially no stiffness. It is therefore anticipated that the response curve shift will be dominated by the reduction in bone stiffness rather than the reduction in density, and the response curve is expected to shift to the left. It is also expected that the bandwidth will generally increase, however, this is greatly affected by the damping characteristics of the flesh.
This variable of flesh damping makes it difficult to anticipate the change in bandwidth.

In summary, it is easily seen that there are many factors which may affect the sound transmission characteristics of a biological system. It has been found that bone stiffness and bone density do affect the response and it is anticipated that bone stiffness will have a dominant effect. It has also been found that the ability to detect these lesions by changes in the dynamic response is dependent upon the location of the lesion, the severity of the change in properties of the bone, and on the amount of bone affected (size of the lesion).
SPECIFIC AIMS

The specific goals which are necessary to develop the use of bone sound transmission characteristics as a diagnostic tool are:

1. Determine the usefulness of the new diagnostic technique as a means of tracing the state of health of the bone matrix. Compare the response tests with roentgenographs to aid in the evaluation of the technique. These roentgenographs will be used to correlate the changes in the dynamic response of bones of the human body to verified changes in the bone structure in those regions.

2. Develop the necessary apparatus to obtain the dynamic response of the lower leg. Standardize experimental procedures for obtaining the dynamic response of the forearm and lower leg to a harmonic force input.

3. Continue verification of the repeatability of the experimental technique by testing a group of healthy individuals over a four-month period.
METHOD OF PROCEDURE

1. Experimental Procedures

The equipment which will be used to obtain the steady state response of the forearm will be essentially that developed by Harrigan (12) at this university. A small transducer transmits a harmonic low-frequency, low-amplitude force from an electrodynamic shaker to the styloid process of the ulna. The response of the forearm is detected by a piezo-electric accelerometer which detects the acceleration of the forearm at the point of contact and converts the mechanical movement to a voltage. The signal from the accelerometer is then amplified and is plotted on the abscissa of a graph while the frequency of the harmonic force is plotted on the ordinate. A schematic of this is shown in Figure 4. The wave analyzer in Figure 4 both generates the frequency of the input force and changes the signal from the charge amplifier to DC.

The positioning fixture for obtaining the response to the forearm is shown in Figure 5. The spring-loaded input transducer, which transmits a constant harmonic force to the styloid process from the electrodynamic shaker is shown. The response transducer in Figure 5 is positioned about halfway between the wrist and elbow.

Harrigan also determined four configurations of the test apparatus which will provide reliable data. One of these configurations will be chosen to obtain the response of the forearm. Slight modifications
FIGURE 4. SCHEMATIC OF INSTRUMENTATION
FIGURE 5. ARM POSITIONING FIXTURE
of the apparatus will be made in order to improve the repeatability of the response. Since extensive testing of the forearm has already been done at this university, the problems associated with this phase of the research should be minimal.

Thomas (4), et. al., reported that a significant percentage of bone lesions in leukemia occur in the tibia and fibula, more so than in the radius and ulna. It is therefore necessary to develop a positioning fixture to obtain the response of the lower leg. This does not involve additional instrumentation, as the same instruments used in testing the forearm will be used to test the leg. (Figure 4) Some preliminary testing of the leg has been done at this university and the results indicate that the response of the leg to a harmonic force is readily obtainable and that the response is reliable andrepeatable.

2. Verification of Experimental Repeatability

The response of both arms and legs of 50 normal healthy individuals will be obtained. These individuals will be grouped into 5 groups of 10 subjects according to their ages, as shown in Table 1. The subjects will be examined for any physical abnormality in the limbs tested prior to the test period. The subjects will be tested twice a month for four months and their physical condition will be monitored throughout this time. These data will indicate the repeatability of the technique for a given patient and will also provide some basis for establishing the
TABLE I

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expected normal response of a limb. The ulna length or tibia length, bone size, muscle development and fleshiness of the limb will also be recorded at the beginning of the four-month test period. Since Matz (10) has investigated the effects of these parameters on the response of the forearm, this information should be very useful in explaining variations from the average response. It may also lead to identification of a mean. Standard statistical techniques will be used to determine the repeatability of location, peak amplitude, and bandwidth for each individual, as well as for the groups.

3. **Evaluation of Diagnostic Technique**

Approximately 50 people who are affected by bone lesions in the forearm or lower leg will be tested and X-rayed to determine whether this technique can be useful in the diagnosis of osteolytic disease or in the tracing of healing of the disorders. It is anticipated that some of the patients will have leukemia or some other orthopedic disorder such that they will be undergoing chemotherapy or some other
treatment. These patients will be tested twice a week while they are undergoing treatment to determine if the diagnostic technique will record the anticipated change in dynamic response of the limb due to the change in stiffness and mass properties of the bone. Correlation will be made between these changes in the dynamic response of the limb and the changes in the roentgenograph. These correlations will allow an evaluation of dynamic response testing as a diagnostic technique in terms of bone changes verified by roentgenograph. Comparison of the results of the response tests of the patients affected by bone lesions and the healthy subjects should also indicate the usefulness of the dynamic response of the limbs as a diagnostic tool.

Based on the finite element model predictions presented earlier in this paper, there are some problems anticipated in this study. The shift in the response curve of an individual depends upon the location of the bone lesion and on the severity of the bone damage. Severity of bone damage includes the volume of bone affected (size of lesion) and the degree of bone destruction in that volume. It was found, for example, that a lesion in the area of the wrist may be difficult to detect. Also, a less severe lesion which reduces the bending stiffness in the bone a relatively small amount will be harder to detect than a lesion which greatly affects the bending stiffness of the bone.

Comparisons of responses of abnormal and normal limbs on the same subject will also provide a good indication of the ability of this diagnostic tool to trace changes in the bone matrix as treatment is
administered.
SIGNIFICANCE

In some cases the use of roentgenographs as an objective indicator of the state of health of the skeleton is unsatisfactory. It is anticipated that the proposed research will provide a more objective means of measuring the change in strength of the bone matrix as a patient undergoes therapy. The research will also indicate the feasibility of using bone sound transmission characteristics as a tool for earlier diagnosis of orthopedic disorder. Thus, this research may provide a new diagnostic tool for indicating the effectiveness of treatment of orthopedic disorders.

It is expected that this technique will be more sensitive to some skeletal changes than is radiography. It is necessary for a 30 percent reduction in roentgenographic density to occur before a lesion can be observed roentgenographically. Harrigan has developed instrumentation which will detect the first bending natural frequency of the forearm to within 5 per cent. A comparison of the two techniques is shown in Figure 6. It can be seen that for a 3 inch lesion located midshaft in the forearm, the diagnostic resolution has been improved from within 30 per cent to within 20 per cent of normal bone density. This estimate is somewhat conservative, as Harrigan achieved better results than this with two configurations, within 3 per cent of the first bending natural frequency.

A further important advantage of this diagnostic tool is that it provides a more objective measurement of the strength of a bone than
Figure 6: Anticipated improvement in diagnostic resolution.
is currently available. This technique directly measures the bending stiffness of the bone, whereas roentgenograms provide only a subjective indication of the strength.

This diagnostic tool should have application as an immediate indication of the effectiveness of treatment in the case of orthopedic disorder. It could be used, as Jurist has shown (9), as an indicator of the strength of fracture unions. It has been shown in this proposal that the technique may also be useful in demonstrating changes in bone health due to treatment of osteolytic lesions.
BIBLIOGRAPHY


APPENDIX
APPENDIX I

Discussion of Medical Literature


   The report states that early bone involvement in leukemia is not a useful prognostic indicator. A much lower incidence of bone changes was found in this report due to stricter criteria for inclusion into the affected group.


   Two case studies are presented, both of which had roentgenographic findings of skeletal effects and accompanying bone pain. Both cases were adult. Most of the cases of bone changes have been of chronic lymphocytic leukemia.


   A case report of a patient with acute leukemia is presented. The patient experienced compression fracture of a vertebra as well as an osteolytic lesion midshaft in the ulna. Diffuse rarefraction of the axial skeleton was present.


   Two case studies of adult patients with leukemia and hypercalcemia. One of the patients experienced bone pain and showed
a radiolucent area in one rib. Radiotherapy relieved the pain, but the lesion remained unchanged. Later roentgenograms showed no abnormality.


The report presents a case history of an eight year old girl with leukemia. It also outlines the aspects of treatment of leukemia and details some of the methods of treatment.

Although the article does not deal with the bony changes which occur in leukemia, it provides insight into the methods of treatment and the prognosis.


The article reports six case studies of patients with CGL. He states that bone pain may occur without radiologic changes in the bone. This suggests an osteolytic process.


The author states that the radiographs are of diagnostic value, especially in the case of impending relapse. Changes in the jaw were demonstrable in 62.9 per cent of the children with active leukemia. Some of the changes found were subtle.

Five case studies are presented of children who presented with arthritis. Two of the cases had roentgenographic changes in their bones, while another patient experienced a collapsed vertebra.


The frequency of bony changes occurring in a particular bone for a study of 85 adults and children is presented. A short discussion of the osseous changes which occur in leukemia is presented, as well as a number of roentgenographs of lesions.


Hypocalcemia was detected in 10.4 per cent of a study of leukemic children. This complication resulted in the death of 5 of the 16 patients in the study. This complication is not related to bone lesions.


Case studies of six adults with smoldering acute leukemia, a variation of acute granulocytic leukemia, are presented. One patient had a lytic lesion of the femur and tibia, which became larger as the disease progressed.

A case history of an adult with acute leukemia is presented. The patient experienced pathological fractures of the clavicle and rib as well as osteolytic lesions of the skull, femur, pelvis and ribs.


A case study of a thirteen year old boy with undifferentiated leukemia and hypercalcemia is presented. The author refers to (4) above and states that it is generally thought that hypercalcemia is a result of the destruction of bone by the leukemic cells. The patient showed marked osteoporosis, a telescoping fracture of the left distal femur, and compression of some vertebral bodies.


This report gives four cases of leukemic involvement of the spine. The axial skeleton is not usually affected in children with leukemia. The report points out that the disappearance of back pain and return of function is not related to improvement in the radiographs.
This report is a study of roentgenographic results of children under one year old. Roentgen changes are presented for the chest, abdomen, and urinary tract and are noted as well as for the skeleton. Some of the bone changes were due to nutritional problems rather than leukemia.


The report is an extremely comprehensive review of the literature to 1948. It describes the lesions found, including osteosclerosis, which was not found in most other more recent studies.


In this review, 47 per cent of the children studied had osseous abnormalities attributable to leukemia at the time of diagnosis. The osseous changes reported are similar to the changes reported in other articles. Two case studies are presented as well as several photographs of skeletal abnormalities.


This report is a very comprehensive pathological and roentgenographic study of the skeletal lesions in leukemia. Incidence and
site of the lesions are presented and detailed descriptions of
the lesions are given.

19. Van Slyk, E. J., "The Bony Changes in Malignant Hematologic
Disease," Orthopedic Clinics of North America, 3: 733-734,
November, 1972.

The report alerts the reader to changes observed in malignant
blood disease. The lesions are described in some detail. The
article urges early diagnosis in view of therapeutic advances.

20. Willson, J. K. V., "The Bone Lesions of Childhood Leukemia, A

Willson discusses four types of lesions which occur in leukemia.
Emphasis is placed on the occurrence of transverse metaphyseal
line as being of diagnostic significance. He states a need for
roentgenograms of long bones when leukemia is suspected in children.
APPENDIX II

Modeling the Bony Changes With the Finite Element Model

The finite element model and associated material properties used in this study to anticipate the changes in response of the forearm where the same as those developed by Garner (11). A detailed development of this work is described in Reference (11). The purpose of this Appendix is to describe the changes made to the finite element model to generate the anticipated changes in response due to an osteolytic lesion.

Since an osteolytic lesion only affects the bone material properties in a localized area, it was necessary to change the effective mass and stiffness of only those elements which were to undergo osteolytic changes.

To accomplish this, it was first necessary to build the entire finite element model of the forearm (See Figure I-1). This procedure generated the total model mass array, the bone stiffness array, and the flesh hydrostatic and deviatoric stiffness arrays. The matrix equation which then could be solved for the normal response is given by

\[ (-\omega^2 M + j\omega E_b K_1 + j\omega E_3 K_2 + j\omega E_4 K_3) P = F \]  

where

\[ \omega \]  = the frequency of the forcing function
\[ j \]  = the square root of minus one
\[ M \]  = model mass matrix
\[ K_1 \]  = bone stiffness matrix
\[ K_2 = \text{flesh deviatoric stiffness matrix} \]
\[ K_3 = \text{flesh hydrostatic stiffness matrix} \]
\[ E_B = \text{function of bone material properties} \]
\[ E_3 = \text{function of flesh material properties} \]
\[ E_4 = \text{function of flesh material properties} \]
\[ P = \text{vector of unknowns corresponding to the response} \]
\[ F = \text{forcing function vector} \]

Since it was desired to change only the mass and stiffness of the bone elements which were considered to be affected by the bony change, it was necessary to construct partial bone mass and stiffness arrays which contained only stiffness and mass terms for the affected elements (Figure I-1). These partial arrays were designated \( M_{BP} \) and \( K_{BP} \) as the partial bone mass and stiffness arrays, respectively. This process was done using the same program which constructed the total bone mass and stiffness arrays, but which was only allowed to build the mass and stiffness arrays for the designated elements.

The total bone mass matrix and the bone stiffness matrix were then modified by subtracting a percentage of the partial bone mass and stiffness arrays from the original bone mass and bone stiffness arrays. The equations are given by

\[ M_B^1 = M_B - \Delta p M_{BP} \]
\[ K_B^1 = K_B - \Delta p K_{BP} \]
where

\( M_B \) is the total bone mass matrix

\( K_B \) is the total bone stiffness matrix

\( \Delta p \) is the per cent change in material property

\( M_{Bl} \) is the bone mass matrix of the affected bone

\( K_{Bl} \) is the bone stiffness matrix of the affected bone

The reduced bone mass and stiffness arrays \( M_{Bl} \) and \( K_{Bl} \) correspond to the mass and stiffness arrays for the bones which were affected by the osteolytic lesion. These were substituted into Equation 1-1 for the total bone mass and stiffness arrays to complete the formulation of the problem. The equation was then solved for \( P \) by matrix inversion, and the vector \( P \) then transformed to nodal displacement to obtain the system response.

Figure 1-1 indicates the sequence of programs in this procedure.
BUILD FINITE ELEMENT MODEL

MODEL MASS ARRAY

BONE STIFFNESS ARRAY

FLESH HYDROSTATIC STIFFNESS ARRAY

FLESH DEVIATORIC STIFFNESS ARRAY

BUILD THE PARTIAL BONE MASS AND STIFFNESS ARRAYS

PARTIAL BONE MASS AND STIFFNESS ARRAYS

MODIFY THE BONE STIFFNESS AND MODEL MASS ARRAYS

MODIFIED MODEL MASS ARRAY

MODIFIED BONE STIFFNESS ARRAY

GENERATE SYSTEM RESPONSE

FIGURE I-1
MODIFICATION OF FINITE ELEMENT MODEL RESPONSE