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# Quantification of the Bone Healing Process Using Information of B-Mode Ultrasound Image

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*Abstract*—**Ultrasound provides a promising non-invasive, safe, objective means of monitoring and quantifying bone healing. In this paper, the relationship between the ultrasound image intensity and the acoustic impedance was exploited to develop a quantitative measure towards assessment and monitoring of the bone healing process. Information theoretic criterion (KLD) was used to quantify the degree of bone healing using the intensity histogram of the callus region obtained from B-Mode ultrasound. Results from a pilot experimental study, show that the proposed method is capable of accurately quantifying the degree of bone healing.**

## I. Introduction

The identification of bone fracture healing onset, progress and extent is challenging in terms of clinical diagnosis [1-2]. In clinical settings, monitoring of the fracture healing process is typically conducted using manual assessment of the fracture site (manual stability, symptomatic pain, etc.) in conjunction with the evaluation of radiographic images in an attempt to determine the form and intensity of callus calcification. While these methods have been invaluable in the field of orthopedics, they are subjective in nature and largely dependent on the physician's expertise and clinical judgment. This potentially leads to discrepancy in clinical assessment, premature or delayed fixation removal, and/or untimely surgical and physical therapy intervention.

According to literature, various imaging techniques are currently used for monitoring bone healing in clinical practice [3-5]. These include X – ray radiographs, Computed Tomography (CT), Magnetic Resonance Imaging (MRI) and Vibratory devices [3-5]. Despite their clinical value, many of these imaging modalities have inherent limitations. For example, X-ray radiation exposure is potentially hazardous and considered unsafe, particularly in the repetitive testing involved in pathological cases, and for pregnant women and children. Furthermore, the healing process during the soft tissue (reparation) stage is difficult to visualize using radiographs, where the developing callus on the fracture site does not become visible until three to six weeks after fracture [3]. While an MRI scan can show signs of a stress fracture within 3-4 days of injury and are considered quite safe, MRI tests suffer from scarcity or unavailability in many small-scale hospitals, and relatively high cost, particularly for repeated tests [4]. CT scans, are quite useful for investigating cortical bone fractures and calcification of organs due to good contrast between tissues. On the other hand, the limitations of CT scans include the ionizing dose of radiation which also makes it not suitable for repeated tests, children, or pregnant women [10]. Vibratory devices also suffer from limitations related to increased signal damping and inaccuracies in locating the resonance frequency, rendering their potential application in bone healing monitoring complicated and impractical [5].

A review of literature reveals that ultrasound provides a promising non-invasive, safe, objective means of monitoring and quantifying the bone healing process, which has the potential to improve the current subjective clinical fracture assessment [6-9]. The main challenges cited in literature as reasons for ultrasound measurement difficulties that hinder its practical use stem from three different sources: 1) surrounding soft tissue, 2) variations in bone shape and size, and 3) inaccurate measurement due to probe separation [6-8]. This work combines theoretical and experimental techniques to overcome these challenges towards the quantification of bone healing during the various physiological healing stages of human bone.

In this study, the relationship between the ultrasound image intensity and acoustic impedance are exploited in order to develop a quantitative measure of bone healing. The proposed method relies on comparing the image intensity of healthy bone with that of the callus region around the fractured bone, which typically has higher acoustic impedance. Based on literature, two comparative methods are used: the image intensity mean and the Kullback-Leibler Divergence (KLD) [11]. The computational method is validated using materials with documented acoustic impedance, in addition to a clinical pilot study of four patients.

## II. Methodology

### A. Experimental System and Protocol

The experimental protocol (approved by the Institutional Review Board (IRB) Committee of the American University of Sharjah) is divided into four main stages as depicted in Fig. 1. These stages are: Image Acquisition, Image Database, Image Processing and Fracture Healing Level Quantification. In the image acquisition stage, the image of the fracture is collected using the portable commercial LOGIQ-e imaging system manufactured by GE [12-14]. The system includes Integrated Recording Keys that are used for remote control of Peripheral Devices. Six gain pods are used for sectional

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brightness adjustment of the image. The display screen has a resolution of (1024x768) pixels which allows a clear display on the screen [12-14]. The transducer which was used in this research work is a linear array operating at 5.0-13.0 MHz. In B-Mode, several parameters were used to enhance the quality of the image including the frequency, gain, edge enhancement, image depth, and dynamic range.

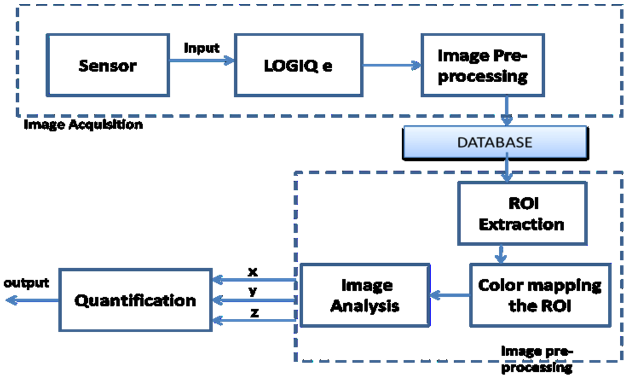


Fig. 1: Experimental System for the Quantification of Bone Healing

The images are referenced and transferred into a database for further processing and quantification. These images are then pre-processed to enhance the signal to noise ratio and select only the regions with intact bone and callus. In the last stage, quantification of extracted or cropped images using advanced digital image processing algorithms is performed with Matlab software.

The experimental procedure involved careful scanning of the fractured limb in order to obtain a clear view of the callus area. The output frequency of the transducer was adjusted for the detection of superficial vs. deeper structures. For example, high frequency (12MHz) was used for superficial surfaces, while lower frequency (8MHz) was used for deeper areas. In addition, the depth was also adjusted to enhance the clarity of the callus image. This is typically done by trial and error. The dynamic range, which reflects the difference between the highest and lowest pixel intensity values, should be high enough to detect the brightest region (bone), such that it forms a reference against which the callus intensity is judged. It is important to note here that the appropriate positioning for the patient's position is critical for proper assessment. This can be done by either seating the patient on a relatively high chair or on the side of the bed with his/her hand resting on a cushion facing the examiner.

### B. *Quantification Method*

Consider a random signal whose values are drawn from an underlying probability distribution $p_i$. The information associated with the amplitude is defined as:

$$I(i) = \log_2 \frac{1}{p_i} \qquad (1)$$

Where $I(i)$ is measured in bits. The average value (expected value) of the information content of a signal whose amplitudes are drawn from an underlying distribution $p_i$ is termed the entropy of that distribution, and as such is defined as:

$$H(p) = \sum_i p_i \log_2 \frac{1}{p_i}$$

Entropy may be explained as the minimum number of bits needed to code a signal whose amplitudes are drawn from a source with probability distribution $p_i$. If a different distribution $q_i$ is assumed, then a message originating from a source with distribution $p_i$ requires $H(p,q)$ bits to be encoded [11]

$$H(p,q) = \sum_i p_i \log_2 \frac{1}{q_i}$$

Where $H(p,q)$ is called the cross-entropy, and $H(p,q)>H(p)$. Thus, then the penalty in terms of the number of additional of bits required to code the message is given by

$$D(p\,||q) = \sum_i p_i \log_2 \frac{1}{q_i} - \sum_i p_i \log_2 \frac{1}{p_i}$$

$$= \sum_i p_i \log_2 \frac{p_i}{q_i} \qquad (2)$$

Where (2) is known as Kullback-Leibler divergence (KLD) and is measured in bits. The KLD as such offers a quantitative comparison of the difference between to probability distributions.

In the context of this paper, consider the intensity histogram taken from reference (bone) region and from a callus region, with amplitude histograms that follow distributions $q_i$ and $p_i$ respectively. The KLD can be used to quantify the level of healing. Callous regions that are close to being healed are similar to bone, and will thus lead to similar distributions for $q_i$ and $p_i$ and a low KLD value. Similarly, newly formed callous will have a distribution highly dissimilar to qi, leading to high values of the KLD.

## III. RESULTS and DISCUSSION

Before using the Kullback-Leibler Divergence (KLD) method on biological materials, the proposed method was first tested and calibrated using known materials with documented acoustic impedances, such as marble, brick and Plexiglas. These materials were compared to aluminum, which has relatively high acoustic impedance of 17.33 MRayl, and as such serves as a reference material. The KLD of these different materials was obtained and tabulated in Table 1.

Table 1: Experimental Results for System Verification

| Materials | Acoustic impedance (MRayl) | KLD |
|---|---|---|
| Aluminum | 17.33 | NA |
| Marble | 10.5 | 0.6033 |
| Brick | 7.4 | 2.5780 |
| Plexiglas | 3.1 | 6.2592 |

It can be concluded that materials with relatively close acoustic impedance to that of the Aluminum such as marble will have low value of KLD. As the acoustic impedance of the material decreases, the KLD will increase accordingly. Therefore, the acoustic impedance and KLD values have an inversely proportional relationship.

The pilot study consisted of four patients. As a representative case, only the results for one patient (termed patient A) is presented in this paper. Patient A is a three year old girl scanned three weeks following the fracture.

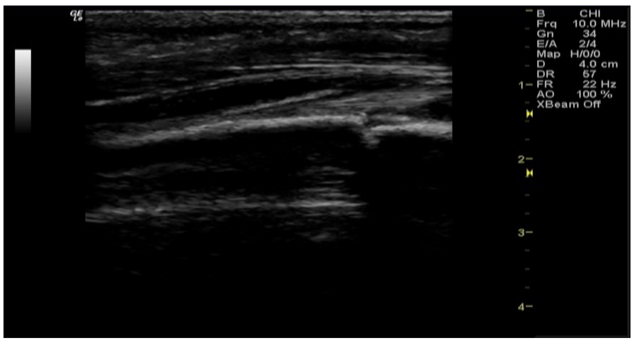


Fig. 2: Ultrasound Image of Patient A Obtained Three Weeks After Fracture

The ultrasound image of patient A is shown in Fig. 3. From this image, it is clear that the bone and callus can be easily visualized. The dynamic range of the image was adjusted to enhance the visualization of the callus region and differentiate it from the bone region. The grayscale color map was also modified to include brighter colors in order to distinguish between different tissue such as fat, bone and callus as shown in Fig. 3.

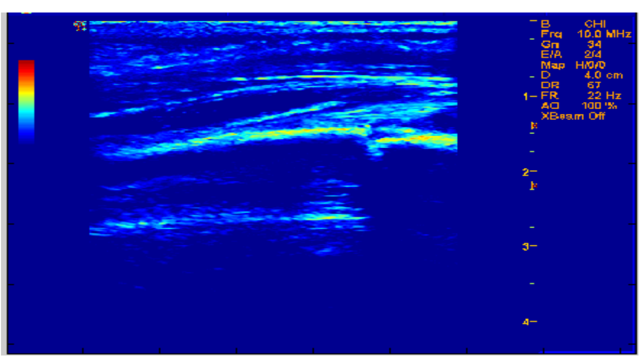

Fig. 3: Color map Ultrasound Image of Patient A

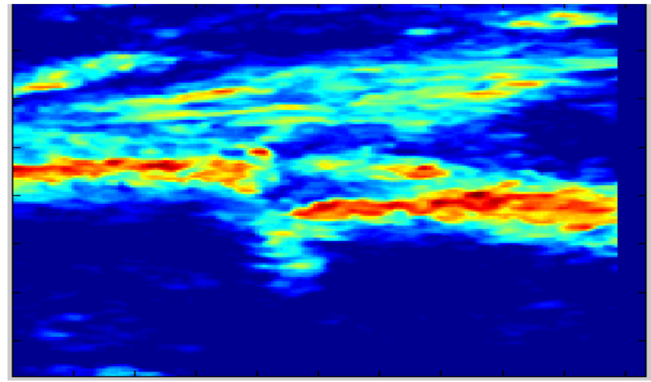

Fig. 4: Magnified Region of Interest around the Fracture Area

The red color in the images is a good representation of the object density; bone has more red color than callus which indicates that bone is denser than callus as shown in Fig. 4. For statistical analysis, relevant regions must be extracted in order to compare callus and bone image intensity mean against the KLD value.

Next, the histogram of extracted regions of interest for both callus and bone are shown in Figs. 5 and 6.

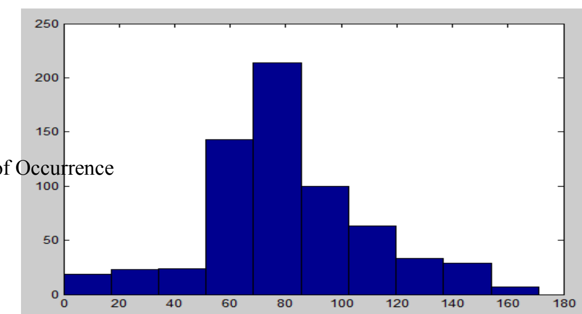


Fig. 5: Histogram of Extracted Callus (Patient A)

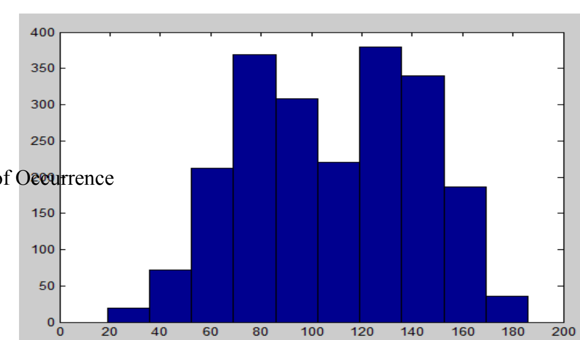


Fig. 6: Histogram of Extracted Bone (Patient A)

Table 2: Quantitative Healing Parameters of patient A data

| Time since the fracture day | 3 Weeks | 5 Weeks | 9 Weeks |
|---|---|---|---|
| Callus Mean | 84.0 | 72.2 | 84.0 |
| Bone Mean | 106. 8 | 111.0 | 106.9 |
| KLD | 12.9 | 9.2 | 1.1 |

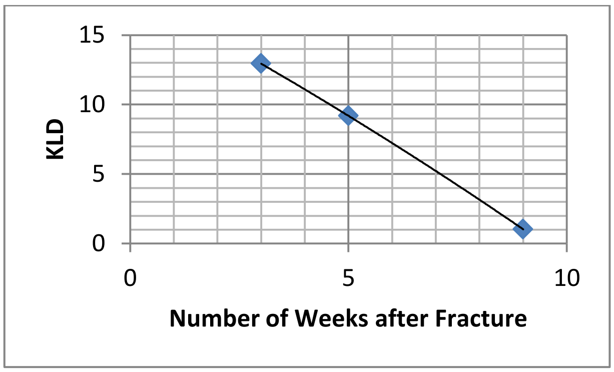


Fig. 8: KLD for Patient A at 3 weeks, 5 weeks and 9 weeks after fracture

A similar procedure was performed after 5 and 9 weeks. The quantification results are shown in Table 2 and Fig. 8. It can be seen that while the mean values of the bone and callus region do not exhibit a pattern that reflects the healing process. On the other hand, the KLD shows a consistent decrease in value that is representative of the healing process.

## IV. Conclusion

This work combines theoretical and experimental techniques based on pulsed mode ultrasound technology towards the quantification of the physiological bone healing process. Exploiting the relationship between ultrasound image intensity and acoustic impedance, information theoretic criterion (KLD) was successfully used to quantify the degree of bone healing using the intensity histogram of the callus region obtained from B-Mode ultrasound. An experimental pilot study was used to validate the applicability of the KLD-based measure for the quantitative assessment and monitoring of bone healing in a clinical setting.


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