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EVALUATING THE ROLE OF CAPACITANCE TO DIAGNOSE BONE HEALING – A BASELINE STUDY

Kanika Gupta[1,*], Vikas Verma[2], Santosh Kumar[3], Girish Kumar singh[4]

[1]PhD, [3,4]Professor, Department of Orthopaedics, King George Medical University, Lucknow
[2]Associate Professor, Department of Orthopaedics, Integral Institute of Medical Sciences and Research, Lucknow

***Corresponding author**
Email: kanikajollyy@yahoo.co.in

ABSTRACT:
Background: *Bone is a biological semi-conductor therefore exhibits electrical properties. Till date no gold standard method is available for measuring bone healing in a fractured bone. Bone healing is dependent upon electrical properties of bone and an understanding of these properties for diagnosing bone union. Capacitance is one such property. The objective of the study was to measure changes in capacitance in different parts of the bone as the fractured bone heals and construct validate capacitance against Radiographic Union Score for Tibia (RUST) score*
Methods: *This pilot study was undertaken on 30 patients of compound fracture both bone of leg treated by insulated external fixators permitting measurement of capacitance from the bone without noise from the soft tissue. Capacitance at different point time was measured in different segments of the fractured bone and construct validated against RUST score. Capacitance across the fracture site at week 2 predicted RUST scores at 20 weeks with a sensitivity of 90%, specificity of 71%, and positive predictive value of 41% and Negative predictive value 83%.*
Conclusion: *The trend of increasing capacitance and its sudden fall as the bone unites confirms that bone does behave like a capacitor. Capacitance varies as the bone heals. Capacitance is significantly different in different segments of the bone. Capacitance across the fracture site may be used to predict RUST score at week 20. However unstable readings of capacitance in some patients make the process difficult.*

INTRODUCTION

Bone is a biological semi-conductor, and therefore displays a combination of many electrical and magnetic properties such as resistance, impedance, conductance, dielectric permittivity, specific capacitance and inductance[2]. These are generated due to piezoelectric[3] and junctional diode effects[1]. Till date no gold standard is available for measuring the rate of fracture healing[4]. Bone healing is also dependent upon electrical properties of bone and therefore, for diagnostic purpose it is necessary to understand and characterize these properties in different parts of the bone[2]. Monitoring of difference in electrical properties of marrow, cancellous and cortical parts are necessary for developing diagnostic procedure by electrical parameters.

A transverse fracture in a bone would result in the fractured bone to behave like a capacitor as the parallel surfaces of the 2 segments (behaving as plates with charges) are separated by an area (A) filled with dielectric material i.e. blood and marrow whose electrical permittivity is $\mathcal{E}_0$. As the fracture heals the gap between the two surfaces reduces and becomes zero till union takes place. Capacitance is measured by the formula $C= \mathcal{E}_0 A/d$, d being the distance between the two plates. As capacitance is inversely proportional to distance between the two surfaces, it was hypothesized that with union capacitance should increase and when the bone unites it should become zero as the two surfaces would come in contact resulting in conduction of charges from proximal to distal fragment resulting in the whole bone to act as a conductor. These theories may result in development of capacitance as a diagnostic tool for predicting delayed unions early and not after 16 weeks (according to current clinical practise).

METHODOLOGY

30 patients 12-70 years of age with compound fracture both bone leg, Gustillo Grade I&II, to be treated by external fixators were enrolled in the study. As electrical potentials generated in fractured bone (<=6 mV) can be masked by much higher potentials (>6 mV) generated in the damaged surrounding muscle[8] showing a need for a method to measure bio-potentials from the bone that exclude the skin and soft tissue[9]; therefore, fractures were fixed by Insulated external fixatores insulated by Besphenol F, a derivative of epoxy[2] which has been used to insulate the wire of the pacemaker since 1977[5]. These fixators rendered three segments: one normal proximal segment (AB), one normal distal segment (CD) and one fractured segment (BC) as shown in Figure 1:

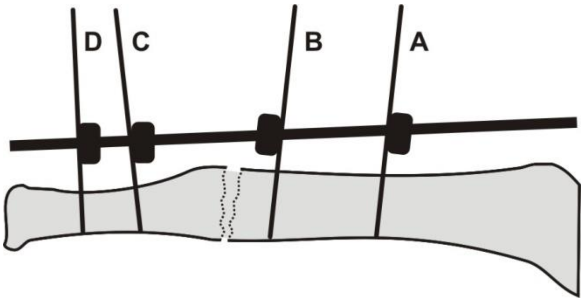

Fig 1: Diagrammatic representation of the Setup

Patients were followed up at day 1 after intervention, week 2, week 4, week 6 and week 8 for measuring capacitance. Capacitance of fractured segments and the two normal segments were compared with each other. Capacitance at various weeks was also compared with that of Day 1 after the intervention. Since there is no gold standard for diagnosing union, we used RUST score for union and delayed union. RUST Score of 9 and above was observed as that of normal union and below 9 was of Delayed union. We construct validated capacitance at different times of bone healing against RUST score to obtain the sensitivity and specificity at various (values of electrical parameters). Best cut off were decided by having the largest sum of sensitivity and specificity values. This provided electrical parameters at various time intervals suited for the diagnosis of delayed and normal unions.

Ethical clearance was given by the Research committee of King George's Medical University, Lucknow-UP, India.

RESULTS

Patient Characteristics:

The mean age of the patients was 42.83±13.83 years. All were males. 66.66% patients had fracture in the proximal portion of the diaphysis of tibia. Patients reported after mean 2.23±.33 days after injury and were surgically managed after 14.7±8.08 days after the injury. 60% patients were referred patients. The mean circumference of the wound was 24.98±28.11 centimeters. 56.67% wounds were circular, 16.67% were oval, 20% were punctured and 6.6% were irregular in shape. The mean distance of the wound from the ankle was 11.9±7.1 centimeters. The wounds of the 20 patients were contaminated by dirt. 10 patients had comminuted fractures. The fibula of all 30 patients was fractured. Pus was present in 60% of the patients. The mean haemoglobin was 10.3±2.12 gram%. Mean TLC count was 7595±2325 cells/mm^3, polymorphs 67.8±6.4 cells/mm^3, Lymphocytes 29±6.6 cells/mm^3, Eosinophils 4±14, Monocytes 0.87±1.38. Mean length of proximal normal segment of Tibia was 7.45±1.82 centimeters and was 8.07±2.25 centimeters for the distal normal segment. Mean length of fractured segment of Tibia was 9.07±3.20.

Diagnostic assessment of capacitance across the fracture site to predict a RUST Score above 9:

Capacitance at week 2 predicted RUST score at week 20 with a sensitivity of 90%, specificity of 71%, and positive predictive value of 41% and Negative predictive value 83%. Capacitance at week 8 predicted RUST score at week 20 with a sensitivity of 70%, specificity of 94%, and positive predictive value of 94% and a Negative predictive value of 88%. Table 1

Capacitance at week 2 correctly predicted union in 90% cases and delayed union in 71 % cases. The precision rate for a positive on test for normal union was 41%. The precision rate for a negative test result (delayed union) is 83%. The likelihood of positive diagnosis is minimal for capacitance at week 2 (+LR=1.54). The likelihood of wrong diagnosis is less (-LR=0.86). Table 1

Table 1: Diagnostic assessment of electrical capacitance predicting RUST Score above 9 at week 20

	Capacitance > 2.14E-03 micro farad at week 2	**Capacitance > 2.14E-03 at week 8**
Sensitivity	0.90	0.70
Specificity	0.71	0.94
Positive Predictive Value	0.41	0.94
Negative Predictive Value	0.83	0.88
(+) likelihood ratio	1.54	14.8
(-)Likelihood ratio	0.86	0.13
True Positives	9	7
True Negatives	5	8
False Positives	2	0 (0.5)
False Negatives	1	3

Capacitance at week 8 correctly predicted union in 70% cases and delayed union in 94% cases. The precision rate for a positive on test for normal union was 94%. The precision of a negative on test (delayed union) is 88%. This is better than capacitance at week 2 therefore for further analysis Capacitance at week 8 was used. The likelihood of positive diagnosis is high for capacitance at week 8 (+LR=14.8). The likelihood of wrong diagnosis is more significantly less (-LR=0.13) as compared to capacitance at week 2 (-LR=0.86). Capacitance could be recorded in only 17 cases at week 2 and 18 at week 8 due to unstable readings. As capacitance at week 8 was found to have more predictability that capacitance at wee 2, therefore further analysis was undertaken with capacitance at week for understanding the behaviour of bone as a capacitor.

A comparison of capacitance at week 8 in proximal and distal segments is shown in Table 2.

Table 2: Comparing values of capacitance for proximal and distal segments

Time interval	Mean in proximal segment in micro farad (variance)	Mean in distal segment in micro farad (variance)	p-value (2-tailed)
Day 1	0.014 (0.03)	0.20 (0.07)	0.48
Week 2	3.99 (283.9)	1.73 (39.31)	0.59
Week 4	3.62 (30.23)	0.23 (0.14)	0.01*
Week 6	11.54 (1046.54)	0.07 (0.02)	0.16
Week 8	9.22 (819.03)	0.16 (0.03)	0.34

***Statistically significant (p<0.025)**

The difference in the mean capacitance at week 8 in the proximal segment at day 1, week 2, week 6 and week 8 was not statistically significant. However statistically significant difference was observed between the proximal segment and distal segment at week 4 ($p<0.025$). An important observation of our study while measuring capacitance is unstable readings which lead to loss of data. At day one the stable readings were recorded in 19 patients out of 30. At week 2 stable reading were recorded in 19 patients from the proximal segment and in 16 patients from the distal segment. At week 4 stable reading were recorded from proximal segment in 21 patients and in 19 patients from the distal segment. The number of patients with stable values at 6th week was 17 from proximal and 13 from distal segments. It further reduced to 10 for proximal and 8 for distal segment at week 8.

Comparison of capacitance in proximal segment and fractured segment is shown in Table 3

Table 3: Comparing means of Capacitance of proximal segment and fracture segment at different points of time:

Time	Mean capacitance of proximal segment in micro Farad (variance)	Mean capacitance of Fractured segment in micro Farad (variance)	p-value (2-tailed)
Day 1	0.132 (0.03)	0.162 (0.17)	0.73
Week 2	0.069762014 (0.02)	0.449871458 (2.07)	0.35
Week 4	2.29 (27.87)	3.88 (157.26)	0.51
Week 6	9.54 (978.8)	4.77 (202.6)	0.65
Week 8	0.17 (0.05)	0.61 (2.64)	0.41

***Statistically significant (p<0.025)**

No significant difference in capacitance was found between the normal proximal segment and fractured segment at any point of time.

Comparison of capacitance in distal segment and fractured segments is shown in Table 4.

Table 4: Comparison of means of capacitance between normal distal segment and fracture segment at different points of time:

Time	Mean capacitance of Distal segment in micro Farad (variance)	Mean capacitance of Fractured segment in micro Farad (variance)	p-value (2-tailed)
Day 1	0.14 (0.04)	0.24 (0.23)	0.56
Week 2	0.08 (0.02)	0.55 (2.51)	0.34
Week 4	0.093 (0.05)	0.091 (0.05)	0.98
Week 6	0.01 (0.00079)	0.03 (0.01)	0.34
Week 8	0.104 (0.01)	0.08 (0.01)	0.12

***Statistically significant (p<0.025)**

There is no significant difference in means of capacitance between proximal segment and fractured segment at any point of time.

Comparison of capacitance in fractured segment (at various weeks as the fracture heals) with that of day 1 are shown in table 5.

Table 5: Comparison of means of Capacitance at weeks 2,4,6 and 8 with mean at day 1:

Time of Follow up	Time of Follow up	Mean Capacitance (variance) micro Farad	p-value
Week 2	0.15 (0.16)	0.38 (1.40)	0.28
Week 4	2.13 (45.94)	3.54 (144.35)	0.37
Week 6	0.0054 (8.23)	0.47 (1.91)	0.30
Week 8	0.10 (0.14)	1.45 (1.08)	0.03

***Statistically significant (p<0.025)**

There is no statistically significant difference in Capacitance at week 2, 4, 6 & 8 when compared with Day 1

DISCUSSION

Capacitance has been reported in bone but only in in-vitro studies. This is the first study of its kind on live patients as the fracture heals. This is the first step towards generating the baseline data for understating the electrical atmosphere of bone in terms of capacitance. Capacitance was measured till week 8, the time at which the bones did not unite but were in the process of uniting or going into delayed union. Drilling of holes to put the shanz pins of the external fixator raises the possibility of bone around the drill hole to act as a capacitor, which if true would result in capacitance in proximal and distal fragments, a positive observation of this study. As the fracture heals gap reduces and capacitance increases. Unstable readings were observed during measurements that lead to significant loss of data. Specific capacitance has shown to be related with mineral content and density of bone[6]. Capacitance is also dependent upon moisture content[7].We were unable to perform these tests as it required in-vitro study which was ethically not possible on patients. However in this study it was observed that a significant difference existed at week 4 between proximal and distal segments confirming that moisture content, mineral content and density of marrow changes affect capacitance. This study showed that measurement of capacitance is possible and can be used for predicting Delayed unions at week 8. As the sample size was less, further research with sophisticated instruments is required which may even increase the prediction properties of capacitance at week 2.

CONCLUSION

The trend of increasing capacitance and its sudden fall as the bone unites confirms that bone does behave like a capacitor. It can also be used for predicting delayed unions early. However a further study with a larger sample size and in which patients are followed till closure of fracture gap is required. Also a better circuitry may solve the problem of unstable readings.

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