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Multi Parameter Adaptive Neuro Fuzzy Inference System Model For Blood Oxygen Saturation Level Maintenance Of Ventilated Patients

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Abstract. Sustaining The Blood Oxygen Level Of Patients In Mechanical Ventilators Is A Serious Issue Faced By Physicians In Clinical Intensive Care Units. Even In Developed Nations, Health Care Specialists Are Manually Adjusting Various Mechanical Ventilator Parameters Periodically For Maintaining Oxygen Saturation. In Epidemic Conditions Where The Patient Number Increases Violently, Automation Of Ventilator Reduces The Risk And Effort Of Health Care Professionals. Real Time Maintenance Of Blood Oxygen Saturation Level In Pandemic Situations Can Only Be Made Possible By The Application Of Modern Machine Learning Assisted Artificial Intelligent Control Mechanisms. A Blended Model Using Multiple Adaptive Neuro Fuzzy Inference System (ANFIS) Is Developed Here To Predict The Inspired Oxygen Output Along With The Corresponding Ventilator Mode For Maintaining The Blood Oxygen Saturation Level Within Desired Limits Considering Real Time Patient Data And Ventilator Settings. Multiple ANFIS Output Of Inspired Oxygen And Mode Prediction Is Compared With Physicians' Decisions And It Is Found That The Developed System Output Shows A Very Low Error Of Devia- tion Of Less Than 5% From Physicians' Prediction. Also, This Method Improves The Speed Of Rule Development Compared With The General Fuzzy Inference Model.

Keywords: Blood Oxygen Saturation, Inspired Oxygen, Mechanical Ventilation, Artificial Intelligence, Adaptive Neuro Fuzzy Inference System

1. INTRODUCTION

Physicians Are Very Conscious In Keeping Up The Blood Oxygen Saturation Level (Spo_2) Of Critically Ventilated Patients In Intensive Care Units In The Range 95-100%. The Commonly Monitored Physiological Parameters To Get Spo_2 Within Desired Limits Are Continuously Monitored Pulse Oximetry Readings And Intermittent Arterial Blood Gas (ABG) Readings. Observing The Continuous Real Time Pulse Oximetry Readings Along With Occasionally Collected ABG Readings To Control The Flow Of Fractional Inspired Oxygen (Fio_2) Delivered By The Mechanical Ventilator In Real Time Can Be Possible Only By Intelligent Models. Continuously Monitoring Of Blood Oxygen Level And Its Mainte- nance Can Only Be Possible By Artificial Intelligence-Based Automation. Since Biological Systems Are Probabilistic In Nature System Modelling Can Be Done Only By Learning The

Existing System With Available Data. Hence For Maintaining Blood Oxygen Saturation Within Desired Level An Artificial Intelligent Model Of Ventilation Automation Must Be Developed.

The Fuzzy Inference Model Discussed In The Paper [1], Explained The Prominence Of Automation Of Mechanical Ventilator For Up Keeping The Level Of Oxygen In The Blood. In That Paper Only Single Output Prediction Is Considered. In Order To Reduce This Manual Rule Making Effort Machine Learning Supported Artificial Intelligent Model With Adaptive Neuro Fuzzy Inference System (ANFIS) Is Established. In The Present Work A Greater Number Of Patient Data Is Included And Blended ANFIS Output Of Inspired Oxygen And Ventilator Mode Prediction Is Done. Complex Human Systems Can Be Modelled More Accurately With Soft Computing Techniques Than Mathematical Modelling. Adaptive Neural Network-Based Fuzzy Inference System Used Here Is A Particular Type Of Artificial Neural Net That Built On Takagi–Sugeno Fuzzy Inference System Which Comes Under Statistical Machine Learning [2]. Nonlinear Modelling Capacity Of ANFIS Is A Boon To Researchers Working In Medical Automation. Y Gao And M Joo Worked In Adaptive Nonlinear Modelling Using Generalised Fuzzy Neural Network [3]. But The System Was Little Patient Specific An Its Robustness Must Be Checked. Also, In The Area Of Automation Of Mechanical Ventilation So Many Studies Are There Using ANFIS. Wang Et Al Proposed An Improved Data Driven Patient Model Named SOPAVENT (Simulations Of Patient Under Ventilation) Along With ANFIS Based Predictive System For ABG Values [4]-[5]. Kwok Et Al. Developed A Rule-Based Model With Adaptive ANFIS For Ventilator Automation [6]. But Here The Simulator Gave Poor Output And There Was A Need To Develop New Patient Model. Kwok Et Al [7] Proposed Another Hybrid Model Constituting Knowledge And Model Base. This Model Was Very Time Consuming And Needed The Use Of Neural Network Training Algorithms. Kwok Et Al [8] Proposed A Hybrid Model That Combined Linear Regression And A Nonlinear ANFIS Based On The Fundamental SOPAVENT Model By Goode Et Al. [9]. But These Model-Based Systems Were Only For Prediction And Had Only Constrained Degrees Of Freedom. The Intelligent Ventilator By SE Rees [10] Gave Another Approach Of Integrating Mathematical Pulmonary Gas Exchange Model With Acid Base Model. Here Also Model Based Approach Was Used. Since We Are Considering Human Beings, Combination Of Technology With Physiological Parameters Is Very Critical And Crucial. We Know That Machine Learning Is The Subset Of Artificial Intelligence Or Can Sometimes Be Used Interchangeably. Artificial Intelligence Uses Statistical Machine Learning Approaches To Develop Intelligent Systems [11]-[12]. Under Supervised Machine Leaning Comes Artificial Neural Networks, Support Vector Machine, Decision Tree, Neuro Fuzzy Systems Like Intelligent Modeling Techniques. N Bhagwat Et.Al. In 2019 Developed An ANN Model For Alzheimer Disease Clinical Score Prediction [13]. Here Artificial Intelligence Based Real Time System Learning Is Used For Modeling The Single ANFIS Predictive System.

Here We Are Developing An Innovative Model Of A Multi ANFIS Model To Predict Inspired Oxygen Supply (Fio_2) From The Ventilator Along With Different Ventilator Mode Variations For Achieving Desired Blood Oxygen Saturation (Spo_2) By Analysing Periodical ABG Values Along With Continuous Real Time Pulse Oximetry Readings. Section 2 Briefly Explains The Methods Developed For The Proposed System With The Platform Used. In Section 3 We Present The Theory Of The Proposed System Which Follows Section 4 That Describes Results And Discussions Which Shows The Predicted Output And Comparison Between The Predicted Systems With Doctors' Decision Making. We Conclude The Work In Section 5 Along With A Discussion Of Future Scope.

2. METHODS USED FOR MODEL CONSTRUCTION

Since The Work Concentrates On Human Beings Mathematical Modelling Process Is Challenging. Hence Artificial Intelligence Based Machine Learning Must Be Used For Modelling The System. For That Real Time Patient Data Samples Needed. And It Is The Main And Time Consuming Area Of The Research. The Work Flow Of The System Development Is Discussed Below.

2.1 Machine Learning (ML)

As Everybody Know It Is A Branch Of Computer Science That Develops Intelligence In Machines Copying Natural Intelligence Of Human Beings And Other Animals. Introducing AI In Medical Field Enhances The Space Of Development Of Algorithm That Mimic Human Ability Of Analysis And Interpretation Of Uncertain Medical Data. Wide Researches Are Going On Very Well Before In AI Based Medical Automation In Critical Care See The Ref- erence [14]. Amisha Et.Al. Clearly Explains The Modern Practical Applications Of AI In Medical Field [15]. Modern Aspect Of Artificial Intelligence For Statistical Modelling Is Machine Learning Which Develops Models Using The Data Collected [16]. Machine Learn- ing Enhances The Predictive Accuracy Of Medical System By Training The System With The Clinical Data Collected [17]. In That Paper Mechanical Ventilator Mode Prediction Was Carried Out Using Machine Learning Classification Algorithm. Here Only Ventilator Mode Prediction Is Carried Out. So In The Present Work A Blended Model For Combined Predic- tion Of Fio_2 Along With Ventilator Mode Is Carried Out Using ANFIS Blocks. Medical Data Collected Includes Certain And Uncertain Data Where Mathematical Modelling Is Not Pos- sible. Hence Come The Importance Of Machine Leaning Based Modelling. There Are Many Divisions Of Machine Learning- Supervised And Unsupervised. Here We Are Dealing With Supervised Neuro Fuzzy Inference System Under Machine Learning. Since It DevelopsModel By Learning Medical Data Using Neural Network And Solve Complex Problems Us- ing Fuzzy Logic Reasoning Ability.

2.2 Data Collection

After Getting Consent From The Scientific And Ethical Authorities, Records Of Data Including Real Time Pulse Oximetry Readings, Arterial Blood Gas Values Together With Mechanical Ventilator Settings Of Patients In The Period Of December 2017 To January 2021 Were Taken. This Study Was Approved By The Institutional Ethics Committee, ASTER MEDCITY, KOCHI, KERALA (Ref No: AM/EC/79-2018). Expert Advices Like Decisions Of Doctors, Respiratory Therapists Etc. Also Were Collected. Continuous Observation And Regulation Of Blood Oxygen Saturation Is Very Essential During Weaning Time. Hence Da- ta Samples Of 75 Ventilated Subjects In One-Hour Duration Were Collected Until They Were Extubated Statistical Examination Was Done For Finding Out The Most Correlated Patient Physiological Parameter With Fio_2. After Pair Wise Analysis It Was Found That The Most Correlated Variables In ABG Analysis Were Partial Pressure Of Oxygen- PO_2(Mmhg), Partial Pressure Of Carbon Dioxide- PCO_2(Mmhg), Bicarbonate Concentration- HCO_3(Mmol/L) And Also Ph Value In Blood. These ABG Values Corresponding To The Real Time Pulse Oximetry Readings (Sao_2) Were Considered As Inputs Of The Proposed System. The Inspired Oxygen (Fio_2) Along With Mechanical Ventilator Mode Changing WasThe Output Of Multi ANFIS Model.

2.3 *Adaptive Neuro Fuzzy Inference System (ANFIS)*

In The Area Of Artificial Intelligence Based System Modelling Adaptive Neuro Fuzzy Inference System Was Established To Compromise Between The Interpretability Of Fuzzy System And Mapping Accuracy And Speed Of Neural Network [18]. Either Fuzzy Or Neural Network Acts As Input To Each Other. Here Data Driven Learning Capacity Of Neural Network Was Used To Develop Fuzzy System. The System Could Be Initialized With Or Without Knowledge In Fuzzy Rule Developing. A Wide Variety Of ANFIS Architecture Were Developed By Researchers For Different Applications. Jang J.S.R Proposed An Architecture Of ANFIS And Suggested Some Of Its Promising Applications [19]. In 2015 Walia Et Al Presented An ANFIS Architecture With A Learning Method Behind It And Their Survey On ANFIS Applications Showed Clearly Its Importance In Clinical Decision Making [20]. Accurate Decision-Making Ability Of ANFIS Makes It Important In Clinical Decision Making. In 2008, L Prathiban And R Subramaian Proposed A System For Heart Disease Prediction Using Neuro Fuzzy Along With The Features Of Genetic Algorithm [21]. Yadollahpour A Et Al Designed An ANFIS Decision Support System Using MATLAB To Predict Glomerular Filtration Rate Variations [22]. Rahul Deb Das And Stephen Winter Developed A Multilayered ANFIS For Transport Mode Prediction [23]. ANFIS Is Used To Model Biological Systems Which Are Non-Linear, Uncertain, Complex And Dynamic. From The Wide Literature Review We Came To A Conclusion That The Fast, Accurate And Time Saving ANFIS Predictions Will Help The Physicians For Effective Decision Making And It Efficiently Controls Inspired Oxygen In Real Time. Here Two ANFIS Blocks Were Used To Develop A Multi Input Output System Using MATLAB. Testing Of The Output Was Undertaken And ErrorOf Deviation Also Calculated.

1 *Theory Of The Proposed System*

Commonly Mechanical Ventilators Are Used To Deliver Oxygen To Patients In Intensive Care Units And The Delivered Oxygen Is Represented As Inspired Oxygen (Fio2). It Is A Challenging Task Even For An Expert Clinician To Select The Appropriate Ventilator And Corresponding Modes. Training Medical Staff To Handle Ventilators Is Also A High-Risk Job Because They Are Dealing Human Life. The Clinician Or Respiratory Therapist Must Know When And There Any Change In Mode Is Needed. Based On The Patient Physical Status I.E. Abgs, Pulse Oximetry Readings, Level Of Consciousness, Body Weight And Muscle Strength, Ventilator Regulates Parameters Like Rate, Depth, Inspired Oxygen (Fio_2). The Method Of Breath Supply And The Type Of Birth Used In Ventilators Establishes The Different Ventilator Modes [16]. Here We Are Developing Multi Input Multi Output System For Inspired Oxygen Prediction With Mode Variation For Getting Required Blood Oxygen Saturation. Fig.1 Shows The Proposed Work Flow Of Multi ANFIS Or MANFIS For In- spired Oxygen Prediction And Mode Selection. Here Two ANFIS Blocks Named 1 And 2 Are Trained Separately With Same Input Parameters. ANFIS 1 For Fio_2 Prediction And ANFIS 2 For Ventilator Mode Prediction. Their Outputs Are Stored In Strings And It Is Im- ported To Simulink Page For Testing.

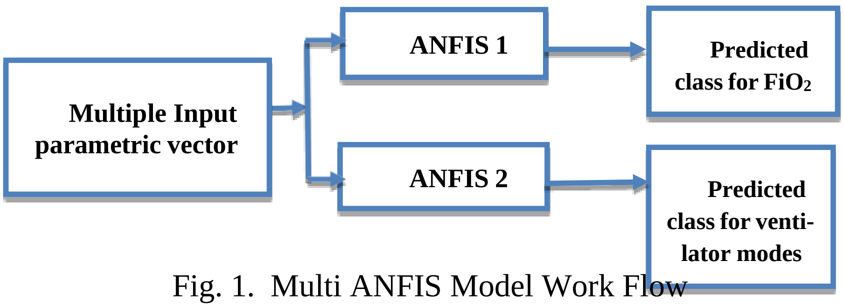

Fig. 1. Multi ANFIS Model Work Flow

Here Patient Blood Gas Parameters Are Taken For Modelling And Inspired Oxygen FromThe Ventilator That Has Been Applied To The Patient Is Predicted With Ventilator Mode Setting. Neuro Fuzzy Network Here Used Is A Triple-Layer Feed Forward Network

Grounded On Takagi–Sugeno Fuzzy Inference System Using MATLAB R2021a. For Each ANFIS Block Separate Training Is Done And Each Output Is Stored In A Cell Array And Is Called Simultaneously In Simulink Simulation Mode For Testing. The Primary Layer Is The Input Layer With Five Input Variables PCO_2 (Mmhg), PO_2 (Mmhg), HCO_3 (Mmol/L), Ph And Oximetry Reading Sao_2. The Output Layer Is The Third Layer And It Is The Predicted Inspired Oxygen (Fio_2 (%)). Considering The ANFIS Model, The Middle Layer Or Second Layer Symbolized The Fuzzy Rules. The Controlled Output Variable Viz. Inspired Oxygen (Fio_2) Constitutes The Third Layer In The First ANFIS 1 Block Where As In The Second Block ANFIS 2 Ventilator Mode Is Taken As The Output Variable Considering The Input Parameters Remain Unchanged. The Learning Ability Of Neural Network Converts The Input Information Into Fuzzy Rules. Error Was Calculated By Comparing The Predicted Output With The Input. The Weight Values Were Adjusted Between The Network Layers With Respect To The Predicted Error. The Data Samples Used Here Are For Developing Fuzzy Neurons. After That Weights Are Used To Induce Fuzziness Into The Network. There After Learning Algorithms Are Developed For Weight Adjustment. Output Is Predicted Using Another Set Of Data Sample Other Than That Used For Learning.

Table 1 Given Below Shows The Input Output Parameters For ANFIS 1 And ANFIS 2. The Common Input Parameters For Both ANFIS Blocks Are Ph, PCO_2 (Mmhg), PO_2 (Mmhg), HCO_3 (Mmol/L), And Pulse Oximetry Reading Sao_2. These Are Selected From Va- riety Of Parameters By Statistical Analysis [1]. Output Parameter Of ANFIS 1 Is Inspired Oxygen And Of ANFIS 2 Is Different Ventilator Modes. Here The Commonly Used Six Ventilator Modes Like Assist Control Modes Involving Pressure Control (ACPC), Assist Control Modes Involving Volume Control (ACVC), Average Volume-Assured Pressure Sup- port (AVAPS), Bi-Level Positive Airway Pressure BIPAP, Continuous Positive Airway Pressure Ventilation With Pressure Support (CPAP/PS), And Synchronised Intermittent Mandatory Ventilation With Volume Control (SIMVVC) Are Used For Modelling. The Modes Were Given Numbers Counting From 1 To 6 For Converting The Analysis Into Re- gression Problem For ANFIS 2 Model.

Table 1. Input Output Parameters

Input Parameters Common For ANFIS 1 & ANFIS 2	Output
Ph	
PCO_2(Mmhg)	Fio_2 (%) For ANFIS 1
PO_2(Mmhg)	
HCO_3(Mmol/L)	Ventilator Modes For ANFIS 2
Sao_2 (%)	

3. RESULT

We Cannot Display Patient Data Here, Since It Is Very Confidential Real Time Medical Data. Common Data Samples Were Taken For Both The Models. Only The Output Parameter For The Model Varies I.E. Fio_2 Variations And Mechanical Ventilator Mode Variations. The Result Of The Work Is Discussed Below:

The Output Developed For ANFIS 1 Is Displayed By Fig. 2. The Figure In Cooperated- Data Samples Used, The Root Mean Square Error (RMSE) Value Got For ANFIS 1 Model That Is 0.000089, ANFIS 1 Structure Developed, One Sample Membership Function Of The Input, Say Ph Value In Arterial Blood Gas Analysis Among The Five Inputs Listed Above, Output Membership Function I.E. Fio_2 And Finally The Rules Developed For First ANFIS That Is Rule Viewer. The Rules Here Are Created By The Learning Capacity Of Neural Network, For Example The Standard Range Of Ph Is 7.35 To 7.45. Reduction Of Ph Beyond 7.35, ThePatient Turned Out To Be Critically Acidotic And Fio_2 Must Be Increased. In That Situation By Analysing The Data, ANFIS Model Creates Rules For Appropriate Inspired Oxygen Prediction For Ventilated Patients.

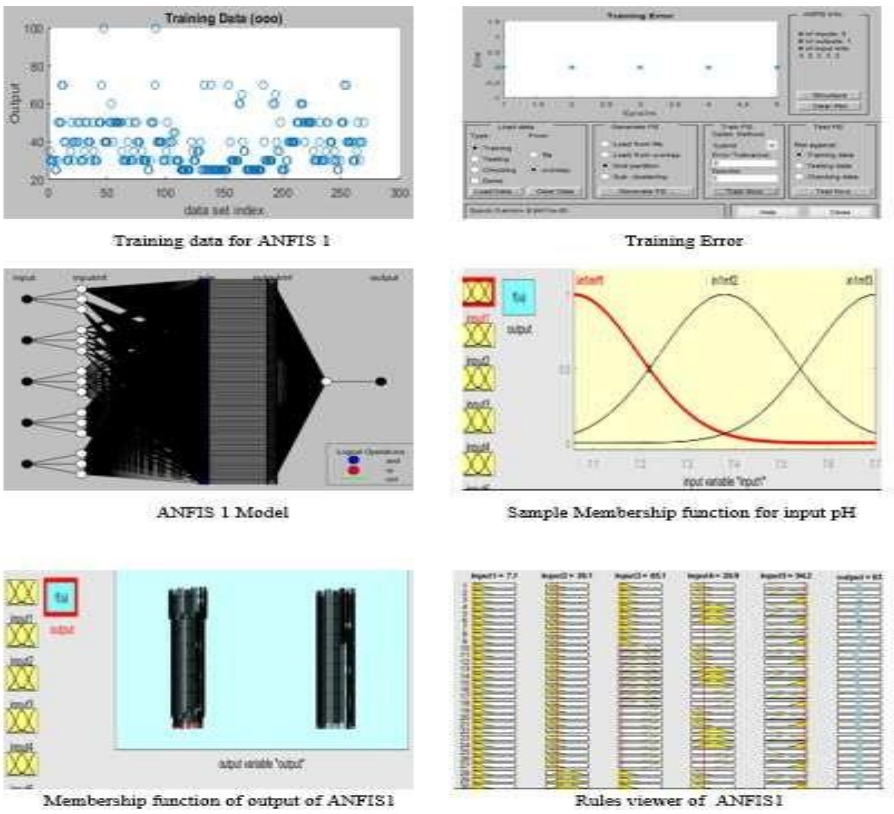

Fig. 2. ANFIS1 Model Characteristics

In Fig. 3, Similar Representation Of The Regressive Output Of Second ANFIS 2 Block Is Displayed, Which Shows A Minimal Training RMSE Of 0.000067. Input Parameters Are Common For Both Models And In The Second ANFIS 2 Model, The Predicted Output Was Ventilator Mode Whose Membership Function Also Displayed In Fig. 3. The Generated Out-put File Is Stored In An Array In And With The Help Of Graphical Interface In SIMULINK 2021, The Testing Of The Exported Fuzzy Inference System File (FIS File) Of The Multi-Input Multi Output Model Was Done Using The Remaining 25% Data For Both ANFIS 1 And ANFIS 2 And A Combined Output Of Fio_2 With Mode Is Generated. Every Tested Data Output Was Compared With The Three Clinicians' Decisions [1]. The Percentage Error Cal- culated Between The Average Of Three Physicians' Decisions And Tested Output For 30 Data Sets Is Found To Be 0.463 Percentage.

Table 2 Shows The Predicted Inspired Oxygen Values By MANFIS Model Corresponding To Three Doctors' Suggestions For A 3 Sample Data Sets. The Graph In Fig. 4 Shows Compari-son Of Multi ANFIS Fio_2 Prediction Along Ventilator Mode Changes With Three Doctor's Predictions- D1, D2 And D3 For 30 Data Samples.

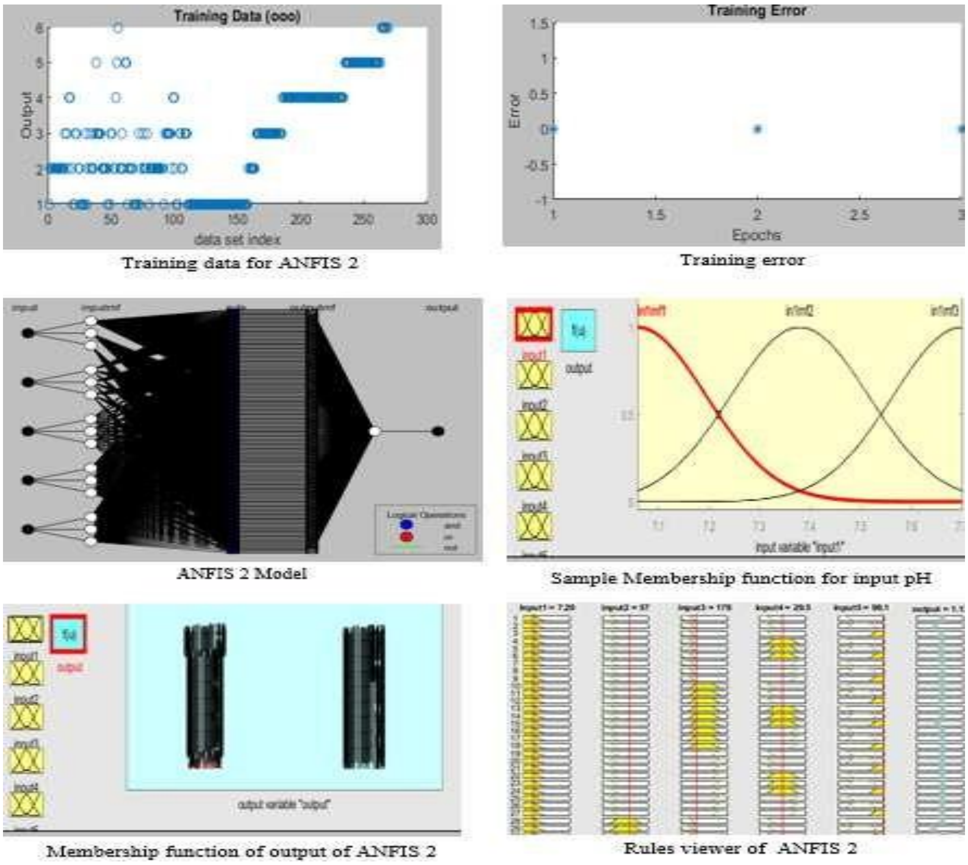

Fig. 3. ANFIS 2 Model Characteristics

Table 2 Comparison Between Systems Predicted Fio_2 With 3 Physician's Decision

Samples	D1	D2	D3	Proposed Fio_2
1	65	65	70	67
2	60	60	60	58
3	55	55	50	55
4	40	50	45	45
5	70	65	70	68

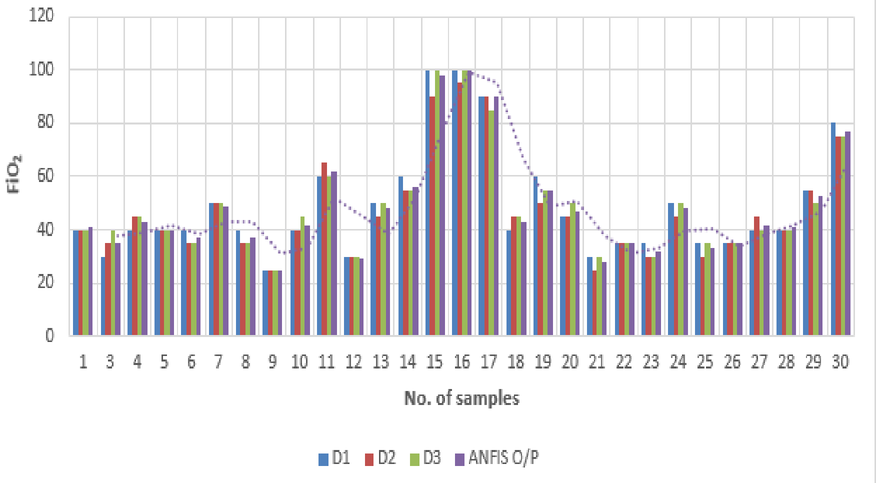

Fig. 4 Predicted Value Comparison With Doctors' Decision

4. DISCUSSION

The Fuzzy Model For Inspired Oxygen Developed Was Accurate But The FormationOf Rules Was Somewhat Tedious And Time Consuming [1], Since It Needs So Much Human Effort And Suggestions From Experts. S. M. Analin Proposed A Nonlinear Predictive Con- trol Using Neural Network For Spontaneous Breathing. The Model Developed Was Not Pa- tient Specific And The System Developed Was Only Suggestive [24]. Then The Next Choice Here Was Machine Learning Supported Artificial Intelligence Based Adaptive Neuro Fuzzy Method. Using Large Amount Of Patient Data Including Blood Gas Analysis, Pulse Oximetry Readings And Also Relevant Mechanical Ventilator Settings The Intelligent Model Is Developed. Here Multiple ANFIS Block Are Used For Inspired Oxygen And Mode Prediction. It Is Found That Every Model Functioned Efficiently Only With Large Variety Of Data Samples. Real Time Readings Of All Possible Respiratory Failure Patients Were Incorporated. Periodical ABG, Pulse Oximetry And Ventilator Settings Were Considered With Ethical Approval. These Data Samples Were Given As Input To The Neuro Fuzzy Software In MATLAB. The Model Developed Was A Three-Layer Neural Network With Input, Output And A Middle Layer. The Output Of ANFIS 1 Is Amount Of Inspired Oxygen And ANFIS 2 Is Variation Of Modes. Using The FIS File Exported To Simulink Model, Remaining New Patient Data Was Tested And Got An Error Of Deviation Much Less Than Typical Accepted Limit Of 5%, Even If Considering The Uncertain Behavior Of Human Body.

5. CONCLUSION AND FUTURE WORK

Here An Intelligent Predictive System Is Developed To Reduce The Effort Of Clinicians To Handle Mechanical Ventilator During Epidemic Conditions. For That ArtificialIntelligence Base System Modelling Is Done With Statistical Machine Learning Techniques. An Adaptive Neuro Fuzzy System For Multiple Output Was Developed To Forecast The Amount Of Inspired Oxygen With Mode Variation For Ventilated Patients With Real Time Data. Multi ANFIS Model Developed Here Reduced The Time Consumed For Developing Complex Fuzzy Rules With Increase In Data And It Was Found That Adaptive Neuro Fuzzy Model Developed Here Can Be Used As A Suggestive Mode To Clinicians Because Of Its Low Training Time And Low Percentage Of Deviation With Doctors' Decision. Going Into Future Research, Computer Assisted Medical Automation Using Deep Learning Is The Most Interested Tool For Maintaining Sao_2 [25]-[27][28][29]. We Are Now In The Developing

Stage Of A Multiple Input Multiple Output System By Combining Multiple Ventilator Parameters Along With Inspired Oxygen Output Using Deep Learning Technology.

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