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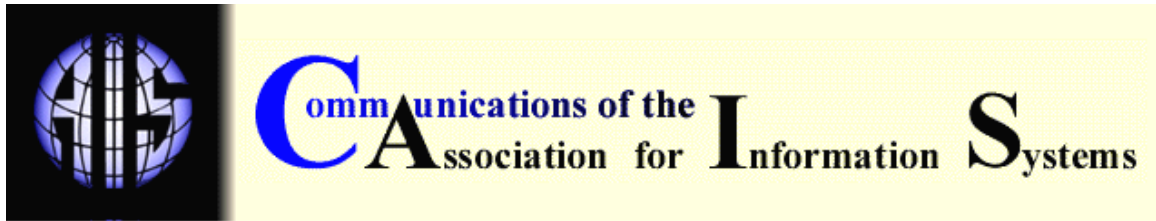
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INFORMATION SYSTEMS AND HEALTH CARE-VI: MEDICAL NOMOGRAMS WITH DECISION SUPPORT SYSTEMS: A CASE STUDY AND AN ENHANCED ARCHITECTURE

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ABSTRACT

Nomograms are used extensively in medical practice as decision aids to adjust treatment protocols based on knowledge gained from previous outcomes. In this paper, we describe a case study of a surgical nomogram system that was developed for estimating laser settings in refractive eye surgery. This system was developed in Microsoft Access with add-ins from Total Access Statistics. It is being used in one of the authors' surgical practice. Based on experiences with the system, we present an enhanced architecture for a nomogram server that can be used in other areas of medicine.

Keywords: nomograms, decision support systems, medical applications, case study, refractive eye surgery

I. INTRODUCTION

A nomogram is a graphical representation of a numerical formula. Typically, this graphical representation consists of several lines marked off to scale and arranged in such a way that by using a straightedge to connect known values (independent variables) on two lines an unknown value (dependent variable) can be read at the point of intersection with another line [Merriam-Webster Medical Dictionary, 2004]. Multiple straightedges are used with tie lines in-between for formulas with more than two independent variables. Hankins, in his classic lecture "Blood, Dirt and Nomograms," described the advantages of such nomograms [Hankins, 2004].

1. They allow for great economy of expression: the diagrams are much less cluttered than graphs with Cartesian coordinates.
2. A single nomogram can express all the parameters of a formula.
3. Because nomograms are read just by using a straightedge, they offer increased speed and accuracy,

Since the invention of nomograms more than a century ago, nomograms have been created and used in most areas of sciences and technology. Between 1923 and 1949 more than 1700 nomograms were created [Adams, 1950]¹. Given such a long history for nomograms, there are several variations in how they are used. Curvilinear contours are used to map relationships between key values as a guide for looking up unknown values when relationships are non-linear and cannot be reduced to a linear form. Sometimes decision-makers must perform a few computations to determine the value of the dependent variable in addition to using straightedges. Cardboard-based or other types of gadgets may be created that can be slid or rotated to marked gridlines to display values of dependent variables. Sometimes just the formula behind the relationship may be referred to as the nomogram.

In medicine, nomograms are generated and used extensively to adjust treatment protocols and counsel patients based on knowledge gained from previous outcomes [Eyeworld, 2004]. For example, at the Memorial Sloan-Kettering Cancer Center [2004], nomograms are used to predict outcomes for surgery and radiation therapy in prostate cancer, renal cell carcinoma, and sarcoma; to predict the chance of breast cancer's spread from the sentinel lymph nodes to auxiliary lymph nodes; to predict patient risk after surgery for gastric cancer; to help assess lung cancer risk of long-term cigarette smokers; and to assist physicians in predicting a patient's probability and length of survival after pancreatic cancer surgery. Dosing nomograms are used to guide the administration of drugs by predicting outcomes [Ariano et al., 2003, James et al., 2002, Massicotte et al., 2003]. Orthodontists use nomograms for calculating tensile strengths of materials and cardiologists use nomograms to access the geometry of the heart [Heesen et al., 1998]. Nomograms may also be hard-wired in devices like pacemakers for regulating the functioning of the heart and automated insulin pumps for diabetic patients. In Ophthalmology, surgical nomograms are used for prediction of outcomes in refractive (laser) eye surgery thereby guiding surgical parameters.

Unlike most medical nomograms that do not change until new research indicates a need, surgical nomograms can change depending on several variables. Refractive surgical nomograms, for example, change relative to the surgical technique, the environment and individual patient characteristics [Soloway, 2001].

If surgical nomograms depend on such factors, how can surgeons develop and use such nomograms? One suggestion is that surgeons should start with pooled or group nomograms available in the literature and develop their own custom or personalized nomograms. To do so, the surgeon first records patient data, surgical data and the outcomes. Then, the data is analyzed to identify relationships and personal nomograms are constructed. If a computerized system is used for such an application, it should be able to store such data, manipulate the data and extract relationships between dependent variables and independent variables and display these relationships as nomograms. All these steps should be done in a user-friendly manner. In other words it should contain a database, a model base and a user-friendly interface. This alternative suggests the use of a decision support system.

We developed such a DSS, called VisionTracker, that is being used in one of the authors' surgical practice. After reviewing medical applications of decision support systems in the next section, we describe this surgical nomogram decision support system in Section III. Based on the experience with the system, an enhanced architecture for a nomogram server is described in Section IV. This architecture is generally applicable in other areas of medicine.

II. MEDICAL DECISION SUPPORT SYSTEMS (MDSS)

For parsimony, we call decision support systems used for medical applications Medical Decision Support Systems or MDSS. Over 200 reports of MDSS are reported in the National Library of

¹ A history of nomograms is given in Hanks [2004]

Medicine's Medline and the ABI/Inform Global databases. Given these large numbers, we restrict our literature review of accounts of MDSS to the past five years. Further we make a distinction between decision support systems for health care administration and decision support systems for medical applications and restrict our analysis to the latter. Decision support systems for health care administration are managerially oriented and focus on cost and other efficiencies where as MDSS are more physician-oriented and help in the identification and treatment of disease. Based on the type of decision support provided by MDSS, we categorize them into Diagnostic MDSS, Prognostic MDSS, Therapeutic MDSS, and Surgical MDSS. These systems are described in the following sub-sections:

DIAGNOSTIC MDSS

Diagnostic MDSS are decision support systems that help medical decision makers in identifying or determining the nature and cause of a disease or injury by evaluating patient history, examination, and review of laboratory data. Mangiameli et al. [2004] study model selection in medical diagnostic decision support systems. Using datasets on heart disease, liver disease, lung cancer, breast cancer, and cellular cancer they investigate the relative performance of different kinds of models and aggregates of models in medical diagnoses. They find that ensembles of models are more accurate than single models in their predictive ability. Rao and Turoff [2000] describe the architecture for a group decision support system that can be used by multiple physicians and other professionals for diagnostic decision-making. A system for automated retrieval of images to assist radiologist readings is described in Liu et al., [2000]. Saaty and Vargas [1998] describe the use of the analytical hierarchy process for medical diagnoses. In a study described by Yan et al. [2004], a medical diagnosis decision support system based on a hybrid genetic algorithm is used for diagnosis of five common heart diseases. Other systems for cardiac diagnosis include those of Hudson et al. [2004] and Ohlsson [2004]. Price et al. [2003] present a diagnostic decision support system for the classification of pre-invasive cervical squamous lesions and Cross et al. [2000] present one for breast lesions. A study by Swolin et al. [2003] shows that a decision support system together with a qualified morphologist, can generate leukocyte differential count reports of high quality. Vassilakis et al. [2002] developed a decision support system using artificial intelligence techniques for the classification and ultimately the diagnosis of epilepsies and epilepsy syndromes in children. Aspevall et al. [2001] use the grounded theory approach to structure the contents of a decision support system for urinary tract infections. Aronsky et al. [2001] discuss a diagnostic decision support system for patients with pneumonia.

PROGNOSTIC MDSS

Prognostic MDSS are decision support systems that help decision makers with predictions of the probable course, outcome, or the likelihood of recovery from a disease. Walczak et al. [2003] use neural networks to predict the length of stay of patients and the injury severity in two distinct patient populations: pediatric trauma patients and patients with acute pancreatitis. Even though they focused their attention on the cost implications of the length of stay and injury severity, we include this application in our review because their system can also be used to counsel patients about these factors. Sefion et al. [2003] and Kuilboer [2002] present systems for control of asthma. A decision support system in the Belgian Nuclear Research Center is used for prognosis of possible radiological consequences after an accidental release of radionuclides [Rojas-Palma et al., 2003]. Iliffe [2002] discusses the design and implementation of a decision support system for the management of dementia syndromes in primary care.

THERAPEUTIC MDSS

Therapeutic MDSS are decision support systems that help decision makers in decisions regarding treatment of disease or disorders by remedial agents or methods. Pain et al. [2003] describe decision support systems that can be used for prescribing drugs. They interview several physicians and other medical professionals and report that the participants welcomed the idea of

technology assistance in prescriptions and thought that such systems would reduce preventable medical errors that cause about 1500 deaths per year in New Zealand. Parker [2002] describes how advances in clinical decision support systems and other technological innovations like bar coding, robotics, and wireless technology are being used in medication administration and prescription and how they result in reducing medication errors. Moustakis and Vassilis [1995] use a system with a case-based decision modeling architecture for therapeutic decision-making for maldescensus testis. The decision support system reported by Short et al. [2003] incorporated the findings of 960 Markov models examining the decision to prescribe aspirin in the secondary prevention of stroke. A computerized decision making system was as effective as skilled clinicians in achieving pregnancy by using ovarian stimulation with FSH. Systems for managing pain are described in Huang et al [2003] and Knab et al. [2001]. A decision support system for the management of accidental mushroom and plant poisoning is presented by Zotti et al [2001]. Del Fiol et al. [2000] discuss the development and evaluation of a decision support system prototype that helps with the prevention of adverse drug events by detecting drug-drug interactions in drug orders. Hernando et al. [2000] developed a system called DIABNET that aids doctors with therapy planning in gestational diabetes. On a negative note, Bennett [2003] finds that just the use of a prescribing decision support system does not ensure patients' adherence to medication.

SURGICAL MDSS

Surgical MDSS are decision support systems that assist in decision-making regarding treatment of injury, deformity, and disease by instrumental means. It is worthwhile to mention here that Surgical MDSS are different from systems for computer-assisted surgery. There is a wealth of knowledge and research in systems based on robotics, vision, and other advances to help in surgery. Our focus here is on decision support provided to aid surgical decision-making and not instrumental support as provided in computer-assisted surgery. Other than our system that we describe in the next section we find only one such application in the literature. Krol and Reich [2000] developed computer algorithms and decision support systems to detect critical conditions during surgery, and alert anesthesiologists in the operating room. Their system detects conditions during surgery such as light anesthesia or unstable blood pressure based on hemodynamic data like the heart rate, mean arterial pressure, and systolic arterial pressure.

III. VISIONTRACKER: A SURGICAL MDSS

VisionTracker is a surgical MDSS that was designed to help surgeons develop their own nomograms for analyzing and predicting refractive surgery outcomes thereby enabling them to adjust treatment protocols in LASIK refractive surgery. It is being used in one of the authors' surgical practice since 2001. VisionTracker was developed in Microsoft Access 2000 and Total Access Statistics 2000 for Windows personal computer systems. In this section, we first describe the LASIK surgical procedure and surgical nomogram development in general. Then, we describe the components of the VisionTracker Surgical MDSS and their usage. We discuss its limitations in the final sub-section.

THE LASIK SURGICAL PROCEDURE

LASIK is a surgical procedure intended to reduce a person's dependency on glasses or contact lenses. LASIK is an acronym for Laser-Assisted In Situ Keratomileusis [Lasik Eye Surgery, 2004]. It is a procedure that permanently changes the shape of the cornea, the clear covering of the front of the eye, using an excimer laser. A knife, called a microkeratome, is used to cut a flap in the cornea. A hinge is left at one end of this flap. The flap is folded back revealing the stroma, the middle section of the cornea. Pulses from a computer-controlled laser vaporize a portion of the stroma and reshape it. The flap is then replaced. A list of FDA approved lasers is available at its Website [Lasik Eye Surgery, 2004].

Outcomes achieved in correcting vision induced by this and other refractive surgeries vary according to such factors as the surgical technique, the environment, and individual patient

characteristics [Soloway, 2001]. An important element relating to the surgical technique is the amount of corneal hydration before and during the ablation (removal of the tissue by the laser). How much irrigation is used during the lamellar cut? Is accumulated moisture removed during the laser treatment? How much time elapses between creation of the flap and the ablation? Environmental factors that can affect outcomes include the temperature, humidity, and altitude of the laser center, and the amount of particulate matter created by plumes. Among the patient characteristics that influence outcomes are: higher refractions (both spherical and cylinder); larger optical zones; and advanced age. For example if a physician adjusts the laser to correct a spherical equivalent of $7.0D^2$, a correction of $7.5D$ may be obtained in actuality. So the physician should have used a setting lower than $7.0D$ to achieve an actual correction of $7.0D$. The relationship between the laser setting and the achieved correction can be modeled as a nomogram and subsequently used for decision-making regarding the setting to use. Previous outcomes are used to generate a formula that can help predict future results to continually improve outcomes.

To develop a personal nomogram, a physician first standardizes as many factors as possible before, during, and after the surgery. Factors that should be standardized include system elements, patient factors, refractive factors, operative technique factors and post-op factors. For the system elements, the refraction should be accurate to $0.25D$ and laser calibration should be accurate to within $0.25D$. It is important that the surgeon's technique be standardized as much as possible because variation in the technique is known to contribute to a difference in outcomes of as much as $1D$. Patient factors that are contraindications to surgery are pregnancy, uncontrolled glaucoma, ABM, autoimmune disorders, unstable refractive error – diabetes, keratocornus and the thickness of cornea. Care should be taken to ensure that incorrect refractions are not used; errors in transposition are not committed; that the lenticular vs. corneal astigmatism are differentiated; and the correct eye is being treated. Elements to be standardized during the operative procedure include the ring size, flap thickness, hydration of cornea, duration of procedure, wiping or not wiping bed, hertz rate, cooperation of patient, and pupil fixation. Physicians, nurses and technicians should cross check calibration and refractive data entry. Also a marking axis should be used as a visual reference at the time of surgery to ensure proper setting of astigmatism. Once all the elements are standardized as much as possible this system can be used. We describe this system using the classic Sprague and Carlson's [1982] framework of decision support system components in the following sub-sections.

THE DIALOG MANAGEMENT SYSTEM

The user interface for VisionTracker was developed using user-centered design principles. The system presents all the patient data on a main screen that mimics paper charts that physicians are familiar with (Figure 1.). Keyboard accessibility played an important role in the design of the system. Patient data can be entered quickly by using the tab key to move from field to field. The system is set up for multiple users, and many drop-down boxes and wizards help facilitate functionality. The main screen offers seven tabs to provide direct access to various forms within the program. Refractive information can be represented in two ways:

1. minus cylinder format and
2. plus cylinder format.

Some surgeons are comfortable with using the minus cylinder format whereas others are comfortable working with plus cylinder format. In accordance with user-centered design principles, the system does an automatic conversion from one form to another so that the data is in a format most preferred by the user. The first three tabs are for exam data entries, nomogram

² D refers to Diopter throughout this paper. Diopters measure the refractive power of a lens and are equal to the reciprocal of the lens' focal length in meters

calculations, and surgery data entries in the minus cylinder format and the next three for the same in plus cylinder format. The seventh tab is for report generation and other utilities. Data entered in the (-) Exam Data Entry form is automatically converted into values in the (+) Exam Data Entry format and vice versa. Similarly conversions occur on the other forms.

After physicians or technicians examine a patient, the data is entered in the exam data entry form for that patient as shown in Figure 1. The exam data entry form is divided into two parts with similar data fields. The left part is for the right eye data and the right part is for the left eye data.

If a data entry form was used for one eye at a time, it could cut the complexity of the underlying table and subsequent programming considerably. The tradeoff was a visual design vs. programming complexity. The decision taken gives the user a presentation with which they are most comfortable. The data entry form for the right eye is shown in Figure 2. The fields on this form include the date of the exam, the distance vision and near vision without correction, whether this is a pre-operative exam or post-operative, whether this is the first surgery or an enhancement, and refractive data with glasses, automated, manifest and cycloplegic. Also, the manifest vertex distance, cycloplegic vertex distance, the pachymetry, the keratometry and the topographic steep axis are input. The cycloplegic refractive data is important for a pre-op exam

Refractive Surgery Evaluation Data Entry Form

Patient ID: 001085 Last Name: EYEPATIENT FI: L MI: K DOB: 3/16/54 Sex: F MD: NFW Best Eye: OD

Exam Data Entry | Nomogram Calculations | Surgery Data Entry | Exam Data Entry | Nomogram Calculations | Surgery Data Entry | Reports

RIGHT EYE

Date: 7/23/98 No Correction: Dist: 20/400 Near: 20/400

PRE-OP EXAM? ☒ RSxSequence# 1

	Sphere	Cylinder	Axis	AddRx	Dist. VA	Near VA
GLS	-9.000	-.750	80			
AR						
MR	-9.000	-.750	80		20/15	20/20
CR	-9.250	-.250	50		20/15	

	MVD	PACH	IOP	K's	Flat	Steep	S/Axis	C	TS/Axis
CVD		613	18		46	46.37	77		

LEFT EYE

Date: 7/23/98 No Correction: Dist: <20/400 Near: 20/400

PRE-OP EXAM? ☒ LSxSequence# 1

	Sphere	Cylinder	Axis	AddRx	Dist. VA	Near VA
GLS	-9.500	-1.000	87			
AR						
MR	-9.500	-1.000	87		20/15	20/20
CR	-9.750	-.750	80		20/20	

	MVD	PACH	IOP	K's	Flat	Steep	S/Axis	C	TS/Axis
CVD		641	18		46	46.25	145		

Record: 1 of 9

The identification number is the patient's six digit chart number.

Figure 1. The User Interface

	Sphere	Cylinder	Axis	AddRx	Dist. VA	Near VA
GLS	-1.000	-2.500	70	0.000	20/25	20/25
AR	-1.250	-2.750	65			
MR	-1.000	-2.500	65	0.000	20/20	20/20
CR	-1.250	-2.250	70		20/20	

MVD	PACH	IOP	K's	Flat	Steep	S/Axis	C	TS/Axis	V
14									
16	547	17		44.5	45.62	147		146	

Figure 2. The Examination Data Entry Form

and the manifest refractive data is important for the post-operation exam. The cycloplegic pre-op data is the desired correction and the manifest post-op data is the final outcome. Comparison of these values results in the construction of the nomogram. We discuss this process subsequently in the modelbase sub-section. As mentioned previously, data entered in minus cylinder format is automatically converted to plus cylinder format and vice versa. The system also contains data validation features.

Surgery Date	LSurgAge	Procedure	SURG #
7/12/00	51	LASIK	1

	Sphere	Cylinder	Axis	LLCSSE	RxGoal	AdjVal
LCS(+)	-5.220	+1.000	110	-4.720		
LCS(-)	-4.220	-1.000	20	-4.720		

Pach	Flap	KAbID	PostAbID	KLf	Keratome
489	160	66	263	423	2801

Temp	Humidity	HzRate	Location	Excimer Used
71	60	10	Sartori/CF	VisxStar

Figure 3. Surgery Data Entry Form

The surgery data entry form is shown in Figure 3. Based on the current date, the age of the patient is calculated and displayed. Other data entry fields include the type of procedure performed by the surgeon, whether this is the first surgery or an enhancement, the laser correction settings in both minus and plus formats, the patient data and the environmental conditions like the humidity, the location, the hertz rate and excimer used. This form also provides fields to store data about any complications that may arise and for comments. The laser correction setting spherical equivalent is the attempted correction and the cycloplegic spherical equivalent during the pre-op exam - manifest spherical equivalent in the post-op exam is the achieved correction.

THE DATABASE MANAGEMENT SYSTEM

Data is stored in three primary tables in this Microsoft Access 2000 based system. The data model is shown in Figure 4. The patient data is stored in the tblPatientInfo, the examination data

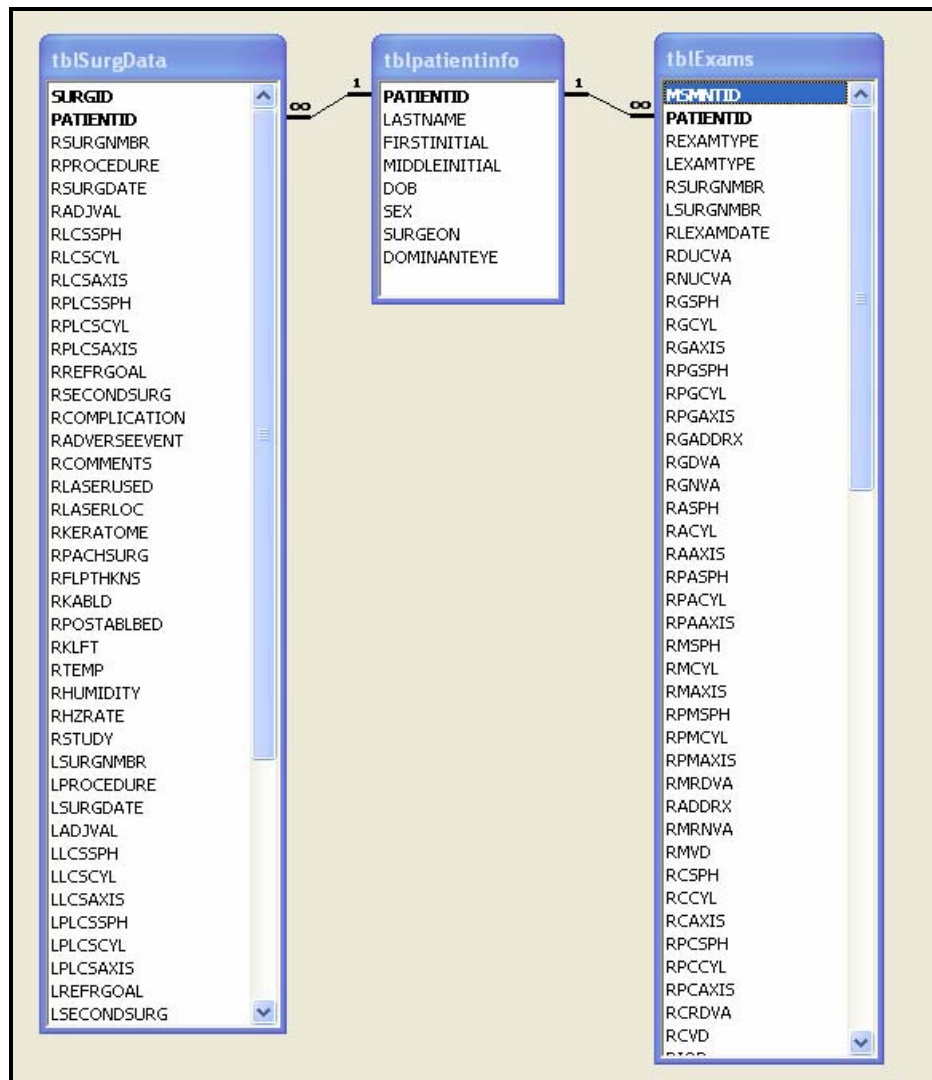


Figure 4: VisionTracker Data Model

is stored in the tblExams and the surgery data is stored in the tblSurgData. The relationships are also shown in the figure. A patient is examined and both the left eye and the right eye data are part of one record in the tblExams table. Typically there is a pre-op exam and multiple post-op

exams at regular intervals of 1 day, 1 week, 1 month, 3 month and 1 year after the surgery. Typically there is one surgery record for each patient. If an enhancement is needed, then it is possible that a patient may require multiple surgery records. Temporary tables are used for the analysis of the data.

THE INITIAL DECISION PROCESS

Planning for the surgery involves using the nomogram calculations form. This form is shown in Figure 5. Initially, less experienced surgeons will want to use a pooled nomogram approach that uses data from other physicians to help create their own nomogram. Surgeons can develop their own nomogram once they collect enough data for statistical analysis by the program. Based on the age group of the patient and severity of the correction needed, there are pooled nomograms available in the literature that give the amount of adjustment that should be performed. The nomogram calculations form provides a what-if analysis capability and displays the laser setting to use based on several different values of percentages of adjustment factors. N1, N2, and N3 represent three theoretical nomograms that a surgeon generates. These may also be based on discussions with other surgeons who use similar techniques and operate in similar environment in addition to the ones from the literature. The idea is to allow the surgeon to see a range of spherical treatment adjustments calculated from the percentage adjustments to the spherical equivalents. The cylinder is not adjusted. The default cylinder and axis is taken from the cycloplegic refraction boxes.

Refractive Surgery Data Entry Form

Patient ID: 116013 Last Name: SAMPLEPT103 FI: C MI: M DOB: 7/14/1949 Sex: F MD: NFW Best Eye: OD

(-) Exam Data Entry (-) Nomogram Calculations (-) Surgery Data Entry (+) Exam Data Entry (+) Nomogram Calculations (+) Surgery Data Entry Reports

RIGHT EYE

Date: 6/23/2000 REExamAge: 51 No Correction: Dist: <20/400 Near: 20/200

PRE-OP EXAM? ☒ RSxSequence#: 1

	Sphere	Cylinder	Axis	AddRx	Dist. VA	Near VA
GLS	-3.750	-.750	20		20/60	20/50
AR						
MR	-5.000	-.750	20	+2.000	20/25	20/25
CR	-4.750	-1.000	45		20/25	

IOP	K's	Flat	F/Axis	Steep	S/Axis	C	TF/Axis	TS/Axis
14		46.50	5	47.75	95	K	4	94

MRSE	CRSE	MVD	PACH	ABL	FLAP	PUBED	KLFT
-5.375	-5.250	14	498	63	160	275	435

Adjust Factor %	A/F	A/V	Sphere	Cylinder	Axis
N1 Reduce by 5	0.05	+263	-4.488	-1.000	45
N2 Reduce by 8	0.08	+420	-4.330	-1.000	45
N3 Reduce by 11	0.11	+578	-4.173	-1.000	45

Estimated Laser Setting

-1.000 45

LEFT EYE

Date: 6/23/2000 LEExamAge: 51 No Correction: Dist: 20/400 Near: 20/70

PRE-OP EXAM? ☒ LSxSequence#: 1

	Sphere	Cylinder	Axis	AddRx	Dist. VA	Near VA
GLS	-4.000	-.750	145		20/30	20/30
AR						
MR	-4.250	-.750	130	+2.000	20/20	20/20
CR	-4.250	-.750	130		20/20	

IOP	K's	Flat	F/Axis	Steep	S/Axis	C	TF/Axis	TS/Axis
13		46.50	8	47.87	98	K	3	93

MRSE	CRSE	MVD	PACH	ABL	FLAP	PUBED	KLFT
-4.625	-4.625	14	498	63	160	275	435

Adjust Factor %	A/F	A/V	Sphere	Cylinder	Axis
N1 Reduce by 5	0.05	+231	-4.019	-.750	130
N2 Reduce by 7	0.07	+324	-3.926	-.750	130
N3 Reduce by 9	0.09	+416	-3.834	-.750	130

Estimated Laser Setting

-.750 130

Record: 1 of 1

Figure 5. Nomogram Calculations Form

Surgeons would decide on the settings to use based on an analysis of the suggestions made by the system and their own judgment. Using Sprague and Carlson's framework [1982] it can be argued that the system helps with semi-structured decisions. Once a surgeon performs several procedures, there may be enough data in the system for a statistical analysis. This system includes statistical analysis functionality, as described in the next sub-section.

THE MODELBASE MANAGEMENT SYSTEM

Capability for data analysis with statistical methods is built into this system through the use of the Total Access Statistics software from FMS Inc. Total Access Statistics runs as a Microsoft Access add-in program and offers a wide range of statistical functions for data analysis. Typically the data is analyzed from Access tables or queries. Microsoft Access itself provides reporting features with charts for visual presentation of data as well as some simple linear regression analysis. Figure 6 shows a graphical presentation of the relationship between attempted correction and achieved correction at 1-month post-op. A linear trend line and its equation are also displayed. The simple idea here is that a surgeon can use this chart to back-calculate the correction setting needed to achieve a particular desired correction.

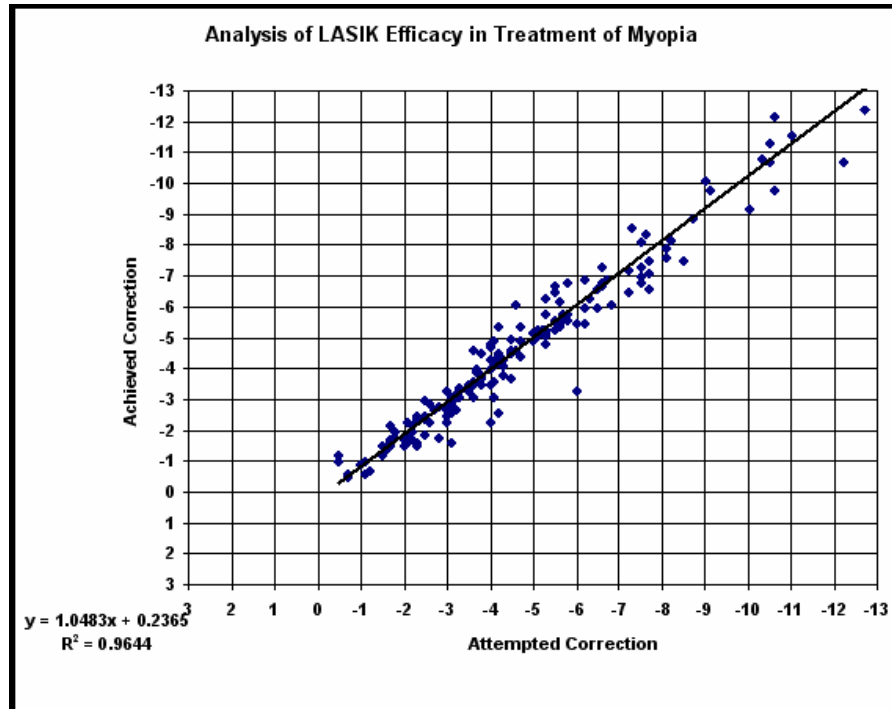


Figure 6. Microsoft Access Report Showing the Relationship between Achieved Correction and Attempted Correction

THE DECISION PROCESS FOR EXPERIENCED SURGEONS

Experienced surgeons can click the estimate button in the nomogram calculations form (bottom center in Figure 5). When this button is clicked, the add-in is invoked to run the multiple regression scenarios. If significant results are not found, the user is prompted to wait till there are more patient data in the system. If significant variables exist, the system prompts the surgeon to enter the values for all the significant variables one at a time and then computes and displays the

estimated laser correction settings to use. An explanatory capability is built into the system that can be displayed by clicking the explain estimate button. When the surgeon clicks this button a form is displayed as shown in Figure 7. The popup form shows the variables, the coefficients and the values. Clicking the estimate button computes and displays the laser correction settings to use. In the sample in Figure 7 the desired correction, the average depth, the temperature and the hertz rate of the laser were found to be significant. Because data-entry mistakes are inevitable, the system incorporates a feature to check the multiple linear regression analysis. The surgeon can run a simple linear regression analysis and cross check that result with the multiple linear regression analysis. The chart-based reports provide another cross check for parameters to use in the surgery.

frmRegCalcMinus : Form

Multiple Linear Regression Analysis of Variables to Approximate the Best Adjustment of Refractive Error to Yield the Best Outcome

RIGHT EYE Estimate **LEFT EYE**

	β_n	X_n
AchSE	0.8194	-5.250
Age	0	51
Kavg	-0.049	47.125
Pachym	0	498
IOP	0	14
Temp	0.0294	72
Humidity	0	50
HzRate	-0.045	10
Y	LCSSE	= -4.956

Est. Laser Correction Setting

SPH	CYL	AXIS
-4.456	-1.000	45

	β_n	X_n
AchSE	0.8194	-4.625
Age	0	51
Kavg	-0.049	47.185
Pachym	0	498
IOP	0	13
Temp	0.0294	72
Humidity	0	50
HzRate	-0.045	10
Y	LCSSE	= -4.447

Est. Laser Correction Setting

SPH	CYL	AXIS
-4.072	-.750	130

$Y = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8$

Simple Linear Regression Analysis of the Most Significant Variable to Approximate the Best Adjustment of Refractive Error to Yield the Best Outcome

RIGHT EYE Explain Simple Regression **LEFT EYE**

SPH	CYL	AXIS
-4.166	-1.000	45

SPH	CYL	AXIS
-3.735	-.750	130

$Y = \beta_1 X_1$

Figure 7. Multiple Regression Analysis for Estimation of Laser Settings

REPORTING AND OTHER CAPABILITIES

This system can also be used for tracking a patient's progress over time. A patient is examined a day after the surgery and the data is entered into the system. Other measurements are taken at

intervals of 1 week, 1 month, 3 months and 1 year and entered. Once the data is entered, the reports tab can be used to generate several reports (Figure 8). As shown in Figure 8, the system can generate Achieved vs. Attempted corrections at each of the measurement times. Further, data may be exported for analysis in Microsoft Excel or other software. An extensive summary report is also available. Utilities for exporting the data to and from external storage (e.g., a floppy) provides flexibility for working on multiple computers in the office, in the operating theater, and in examination rooms. This system can be used to provide decision-support for treating both hyperopia and myopia.

Figure 8. The Reports Form

LIMITATIONS

A technical weakness of this program is that it does not treat the cylinder in a way that is as involved as some algorithms in the literature suggest. The intention was to keep the system as simple as possible for the users and not give them so many choices and so many forms to fill out that they don't do any accountability checks by themselves. Even though the intention was to keep the system simple through user-centered design principles, the system was perceived to be complex in informal interviews with the users. Using the system to track patients and for decision-support added complexity to the system. A system for decision support should probably only track the independent variables and the outcomes, especially for the clinical audience and the environment in which the system is used.

Another limitation was the architecture. The installation of the system with the standalone runtime version of Microsoft Access was too complicated for this audience. Even though utilities in the system export the data to a removable storage media and then append the data to a master database, it was perceived to be too cumbersome to manage and keep the data in that one central location. A Web-based or an Intranet-based architecture might have been more appropriate for designing this system. In the next section we describe such architecture.

IV. TOWARDS A MEDICAL NOMOGRAM SERVER

The VisionTracker system is an example of how decision support systems can be used for a specific medical nomogram situation. We argue that other medical nomogram situations can benefit similarly from decision support systems. We envision a medical nomogram server for this purpose. Such a server will contain:

- a nomogram repository (both built-in and user contributed),
- a database for user data, statistical and other models,
- sub-systems for extracting relationships between variables using user data,
- a capability for generation and display of interactive nomograms for supporting decision-making.

Based on experiences with the previous system, several requirements were identified for the new system:

- the system should be capable of being installed through a Web browser,
- the system should provide decision support by displaying interactive nomograms,
- the system should be able to store general nomogram templates and generate specific nomograms for a particular situation,
- the system should allow for easy data entry,
- the system should be able to extract relationships between variables using past data, and represent these relationships as nomograms for subsequent use,
- the user should be able to access the system from multiple computers,
- the user should be able to access the system from mobile devices like PDAs or smart phones,
- the system should provide offline or paper-based decision support in addition to online decision support, and
- the system should represent and serve most medical nomograms.

We are developing a system to address these requirements. In this section, we first review existing systems that address similar needs. Then we briefly describe the mathematics of nomography with an illustrative example, followed by a description of system components and the implementation technology for this nomogram server.

EXISTING SYSTEMS FOR NOMOGRAM SOFTWARE

Memorial Sloan-Kettering Cancer Center [2004] provides online nomograms for cancer risk assessments. Their nomograms can be used online in a Macromedia Flash format or downloaded to PDAs. For example, their nomogram for prediction of breast cancer's spread from the sentinel lymph nodes to auxiliary lymph nodes helps physicians obtain accurate estimates of a patient's risk for additional disease. This nomogram takes several pathological factors into account, including tumor size, tumor type, estrogen-receptor status of the primary tumor, the method of detection of sentinel lymph node metastases, and the number of positive and negative sentinel lymph nodes. Users enter values, check checkboxes and select options from drop-down list boxes and the decision aid computes the probability for additional disease.

A Java-based applet for constructing nomograms designed by Berelson and Jones is available on the Web at the University of Rochester. Based on parameters entered by the user, this applet

constructs a nomogram. Users can pick a functional form for the relationship from several functional forms available. They can specify the ranges of values for the variables as well as descriptive labels for them. Users can drag and drop a straight line by using their mouse and the system displays the values of the independent variables and the dependent variable. Further they can save and retrieve the nomogram parameters and the straight lines that they draw in files.

NOMOGRAPHY

Nomography is the mathematics of creating nomograms. Johnson [1978] provides a simple and direct approach to nomography without the use of complex matrix algebra. Consider the nomogram given in Figure 9. This nomogram depicts the relationship between a person's weight, height and the Body Mass Index (BMI). Physicians routinely counsel patients regarding their health risks based on their BMI. Constructing this nomogram manually or by programmatic generation requires several parameters. First, one needs the range of values for the weight variable (e.g. 100lbs – 300 lbs), the range of values for the height variable (e.g. 45 in – 85 in) and the range of possible values for the BMI variable (e.g. 10 – 70). Then one needs to know the mathematical relationship between the independent variables (weight, height) and the dependent variable (BMI).

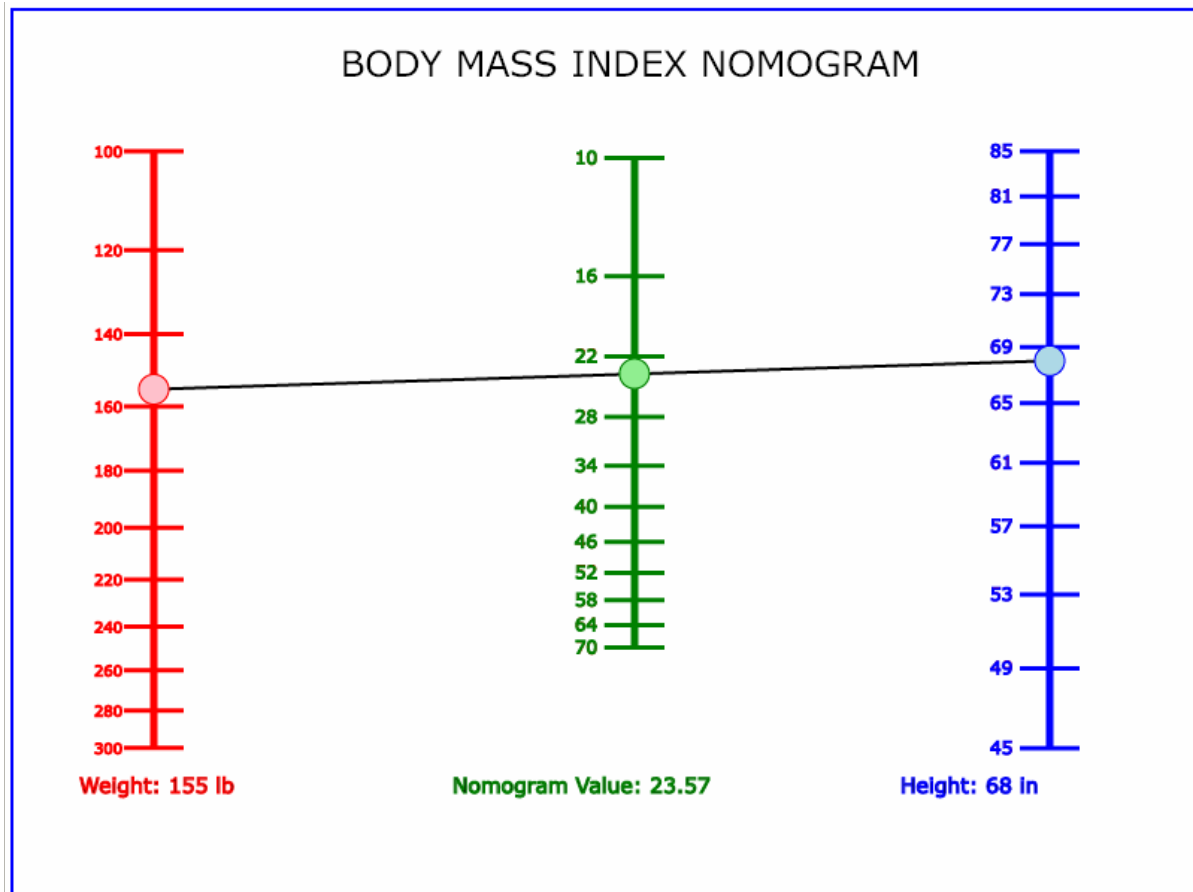


Figure 9. Interactive Body Mass Index Nomogram

BMI is calculated by multiplying 703 by the ratio of weight in pounds to the height in inches squared (i.e. $BMI = 703W/H^2$). Equations with three variables of the form $f_1(u) + f_2(v) = f_3(w)$ and $f_1(u) * f_2(v) = f_3(w)$ can be represented by parallel scale nomograms [Johnson, 1978]. For the BMI

example, $f_1(\text{weight})$ would be $703 \cdot \text{weight}$, $f_2(\text{height})$ would be $1/\text{height}^2$ and $f_3(\text{BMI})$ would be BMI and functional form would be $f_1(\text{weight}) * f_2(\text{height}) = f_3(\text{BMI})$.

To create a nomogram of the multiplicative form as needed for the BMI computation, the weight, height and the BMI are represented on a logarithmic scale. A weight scale is constructed by using an appropriate plotting scale, where the distance is proportional to the log of the weight variable, from an initial value of 100 lbs to a final value of 300 lbs such that it fits in the given amount of space. Similarly a height scale is constructed by using an appropriate plotting scale for a range of values from 45 in to 85 in. Using these plotting scales the placement of the BMI scale as well as its plotting scale are computed. Using the values 10 and 70 as the upper limit and the lower limit the BMI scale is drawn. Once constructed, the nomogram is used in the following fashion. If a line is drawn from the point representing a weight of 155 pounds to the point representing the height of 68 in, the point of intersection with the BMI scale gives the BMI value corresponding to these two independent variables. The BMI is 23.57 in this case. If an interactive nomogram is generated programmatically then it would be possible for the user to drag and drop the little circles representing the weight and height variables to compute the value of the BMI. Or the nomogram could be printed and used for computation of BMI just by using a straight edge.

A program for generating such a nomogram is what we call a nomogram skin. Parameters for a specific nomogram (the limits for the variables and the functional form of the relationship) would be stored in the database. As seen in Figure 9, the parameters needed for generating a nomogram include the start value for the first independent variable (u_b), the end value for the first independent variable (u_e), the start value for the second independent variable (v_b), the end value for the second independent variable (v_e), the start value for the dependent variable (w_b), and the end value for the dependent variable (w_e). The functional forms are specified in MathML³.

When a request for a nomogram is received, these parameters would be applied to the nomogram skin and the specific nomogram would be displayed. Alternatively, historical data stored in the database would be analyzed by statistical methods and relationships between the independent variables and the dependent variable extracted in the form of a linear regression. Coefficients of the linear regression together with the ranges for the variables would form the input to the nomogram skin program and a specific decision aid would be generated. We next describe the architecture for such a system and its implementation.

NOMOGRAM SERVER ARCHITECTURE

The current system under development, the Nomogram Server, addresses the system requirements identified at the beginning of Section IV by using a Web-based architecture. Power and Kaparathi [2002] provide an overview of Web-based decision support systems. They define a Web-based DSS as a computerized system that provides decision support information or decision support tools to users using a "thin-client" Web browser like Netscape Navigator or Internet Explorer. The computer server that hosts the DSS application is linked to the user's computer by a network using the TCP/IP protocol. Figure 10 shows the architecture for the nomogram server. This system uses familiar and existing off the shelf software including a Web browser with a Scalable Vector Graphics (SVG) plug-in from Adobe on the client computer, the Microsoft IIS Web server, and the Macromedia ColdFusion MX Application Server [Kaparathi and Kaparathi, 2001] with access to a Microsoft SQL Database Server on the server-side.

³ W3C's current recommendations on MathML are presented at www.w3.org/Math/.

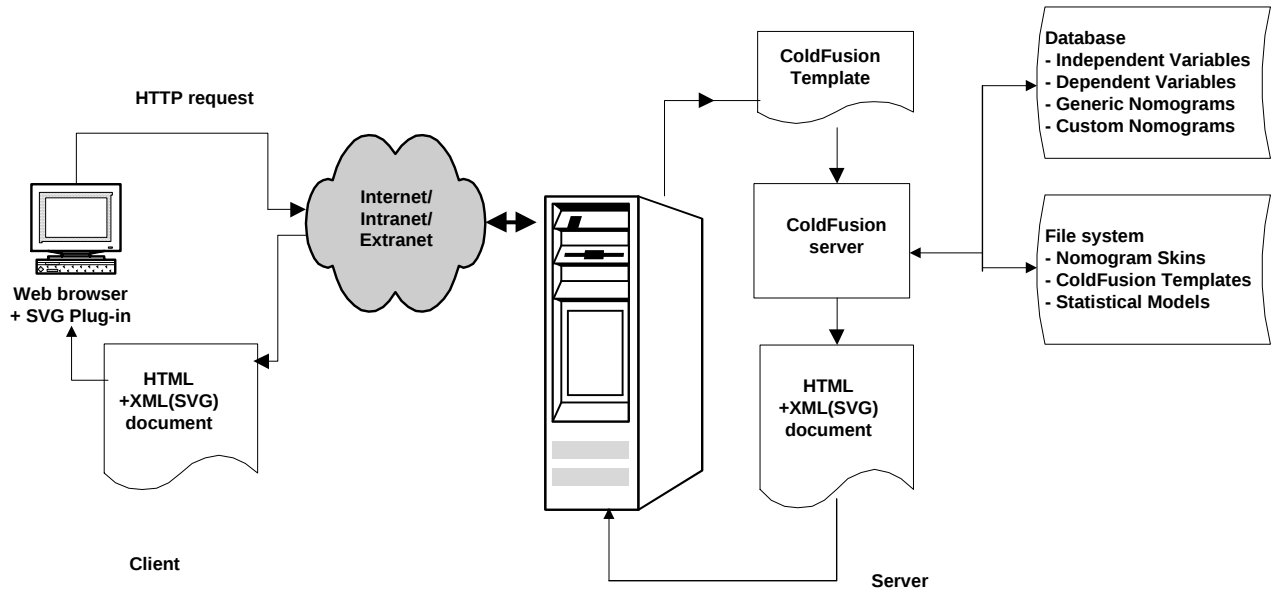


Figure 10. Nomogram Server Architecture

A physician or a technician accesses the decision support system by using a Web browser and typing the URL or clicking a hyper-link to the system on the Web or an Intranet or an Extranet. The server receives the HTTP request and serves an HTML page with a main menu. If used for refractive surgery situations, for the initial decision process a surgeon would use the pooled nomogram approach. When the server receives a request for a pooled nomogram, the ColdFusion Application Server processes the request. The parameters for the pooled nomogram are extracted from the database, which are then applied to a nomogram skin and a SVG document is generated and sent to the Web browser. The Web browser receives the SVG document and the SVG plug-in displays the nomogram as shown in Figure 11.

Figure 11 shows the pooled nomogram generated by the SVG document. SVG is a language for describing two-dimensional graphics in XML [Introduction – SVG, 2004]. SVG allows for three types of graphic objects: vector graphic shapes (e.g., paths consisting of straight lines and curves), images and text. SVG drawings can be interactive and dynamic. Animations can be defined and triggered via scripting. SVG 1.1 was approved in January 2003 by the WWW consortium. Several tools available for creating SVG documents⁴.

A physician would use the pooled nomogram shown in Figure 11 by first clicking and dragging the left side of the straightedge to the value of the desired correction. Then, the right side of the straightedge should be dragged and dropped on the value of the reduction factor obtained from the literature based on the person's age and the severity of the correction. While the straight edge is moved, the script computes and displays the value of the nomogram achieved by applying the particular reduction factor to the desired correction. Just by dragging and dropping the straightedge in the true spirit of the nomogram a surgeon is able to obtain an idea of the laser settings to use to achieve the desired outcome.

⁴ Similar to the Adobe Acrobat reader for PDF documents, Adobe SVG player is available for free download and install at the Adobe Website.

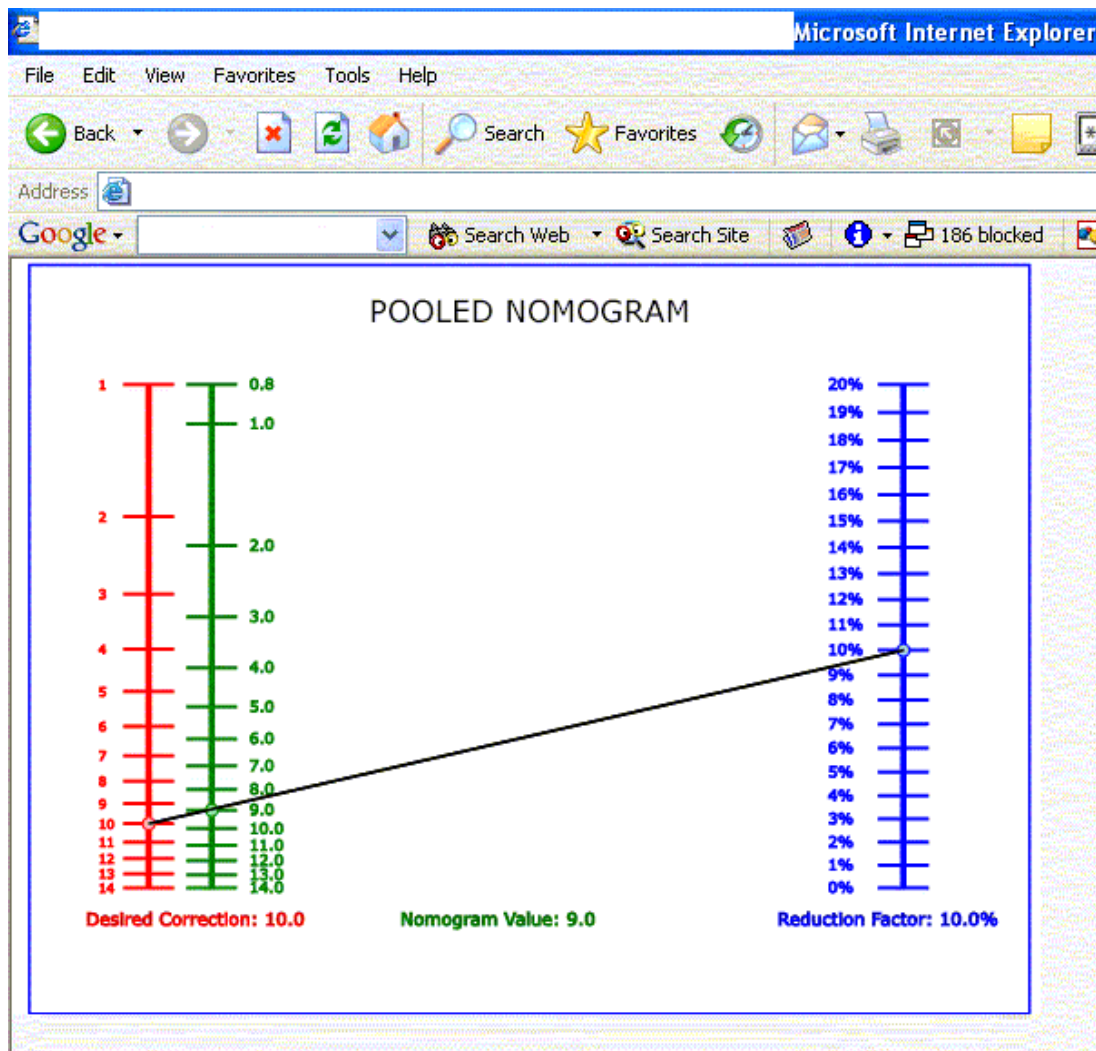


Figure 11. A Pooled Nomogram Displayed by the SVG Plug-in

Similar to the VisionTracker system after a surgery is performed, this system would allow for outcome analysis by providing input forms and data storage features for the independent variables and the dependent variable. Once enough data points are available, regression analyses can be performed and the number of significant variables determined. Based on the number of significant variables and the values of their coefficients a suitable nomogram skin would be picked from the file system. Surgeons would drag and drop straightedges on the nomogram for insight into the decision they are about to make.

V. CONCLUSIONS

People have been constructing and using nomograms for over a century. Given such a long history it is understandable that nomograms are used in several different formats. Some people refer to nomograms in the strictest sense as alignment charts, whereas some people interpret nomograms loosely as relationships between independent variables and dependent variables. Nomograms are used in most areas of sciences and technology. Even though calculators and computers decreased our reliance on them, they are still useful as quick decision aids in many situations and are popular in engineering and medicine. In this paper we reviewed medical nomogram applications.

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A nomogram is built by identifying the relationship between independent variables and a dependent variable. Typically data is processed by statistical methods to identify this relationship.

We suggested the use of a decision support system for this process. We reviewed medical applications of decision support systems and proposed a framework for organizing these applications. A specific medical decision support system for decision-making using the LASIK refractive surgery was described. Based on experiences in building and using that system, an enhanced architecture for a general nomogram server was proposed and demonstrated. This architecture is applicable for a wide range of medical and other applications.

If made available on the Web, users can use the built-in nomograms in the system; users can enter data and create their nomograms. Users can contribute nomograms to the nomogram repository and others can access and use them. Currently the WWW consortium is evaluating proposals for lighter versions of SVG that could be used in cell phones and other devices [Mobile SVG Profiles, 2005]. As these nomograms are in SVG they can be used in all devices that contain SVG players. Alternatively they may be printed out and used with a straightedge without the use of a computer for offline decision-making in accordance with the needs defined earlier for this architecture.

A wealth of knowledge and research exists about the design, use, and specific nomograms for many medical applications. Similarly a huge wealth of knowledge exists about the design and use of decision support systems. We believe there is much that both disciplines can learn from one another. The discipline of nomogram applications can benefit from the research in knowledge acquisition techniques like machine learning, data mining, neural networks, and rule inductions. Decision support researchers area can benefit from the wealth of knowledge in the nomogram area in terms of the simplicity, intuitiveness, and visual explanation capability of the decision aids as well as all the areas of their applications.

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EDITOR'S NOTE: The following reference list contains the address of World Wide Web pages. Readers who have the ability to access the Web directly from their computer or are reading the paper on the Web, can gain direct access to these references. Readers are warned, however, that

1. these links existed as of the date of publication but are not guaranteed to be working thereafter.
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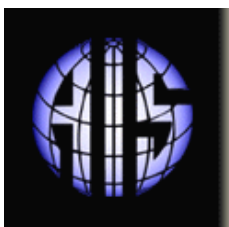
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Decision Support Systems, Internet Technologies, Bibliometric Analyses, Neural network models and applications in management.

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