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Using the analytic hierarchy process as a clinical engineering tool to facilitate an iterative, multidisciplinary, microeconomic health technology assessment

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Abstract

Many articles have been written about applying decision support systems to clinical tasks, but little has been published about the complex problem of capital equipment decision making in healthcare. This problem has become the domain of health technology assessment experts, but there are few decision support systems reported in the literature. Technology assessment practitioners generally evaluate whether appropriate scientific studies exist to justify implementing a technology, or consider the macroeconomic implications that adopting a new technology may have on existing populations, economies, diseases, drugs, procedures, or devices. Following the confirmation of a technology's utility, however, the published materials available to assist the individual hospital or health system in their microeconomic health technology assessment (HTA) are very limited. In this study, the analytic hierarchy process is used to support and document the evolution of the multidisciplinary and interdisciplinary process of selecting neonatal ventilators for a new women's health hospital. Although the best ventilator had the highest purchase price, its safety, clinical and technical features, plus lower operating cost factors led to its high score. This study demonstrates the AHP's ability to facilitate an understanding of the underlying criteria and priorities, and to successfully support the hospital's purchasing negotiation. For these reasons, the AHP should be considered for use as a decision support tool for future HTA projects.

Scope and purpose

"Medicine is a science of uncertainty and an art of probability" Sir William Osler (c. 1904).

This article describes the use of the Analytic Hierarchy Process (AHP) to perform a microeconomic Health Technology Assessment (HTA) for the evaluation of expensive and complex critical care neonatal ventilators for a new women's health facility. This facility is to be built by a mid-size suburban teaching hospital that provides all levels of care up through the most severe trauma cases. Neonatal ventilators are specially designed

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devices used for critically ill newborn babies—called neonates. These ventilators must reliably sustain tiny, fragile lives until the neonates can safely breathe on their own. This study shows that AHP can be used to facilitate the interdepartmental interactions needed to evaluate an expensive technology in today's healthcare environment. Further, this study provides a detailed analysis of how a multiple stage AHP-based decision process accommodates the evolving knowledge and understanding of the hospital participants. Finally, the study helps to show the weights that a modern hospital may give to the competing criteria it considers when making capital equipment decisions. As will be seen, the weights of some criteria such as cost are different than found in many other purchasing situations because of the implicit life-and-death nature of the trade-offs. Although reducing the cost of healthcare delivery is desirable, the savings can be misleading if a wrong alternative increases the risk of patient injury or death.

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1. Introduction

In this paper, we describe the use of Analytic Hierarchy Process (AHP) (Saaty [1,2]) to help a hospital evaluate the best neonatal ventilator to purchase. The rapid evolution of new medical technologies and the complex interactions of outcome, efficacy, training, support, reimbursement, and cost have made evaluation of appropriate health technologies a difficult process. This process has become known as Health Technology Assessment, an important and growing worldwide discipline [3]. The high cost, complexity, and long-term consequences of evaluating and implementing medical technologies make Health Technology Assessment (HTA) a significant international research, regulatory, and budgetary issue for both industrialized and developing countries, as documented in recent publications by the Pan American Health Organization [4–6].

The process of evaluating the best model of approved, legally available health technologies is complex. The evaluation process requires thorough consideration of trade-offs between all health technologies' features, benefits, risks, and costs. Therefore, hospitals are required to have a formal technology evaluation team that includes medical, administrative, and clinical engineering members [7,8]. The clinical engineer often gathers and organizes the information and viewpoints to ensure that all relevant factors are examined and then manages and facilitates the discussion, evaluation, acquisition, installation, and support activities [9].

The underlying challenges to good decision making in the interdisciplinary and multidisciplinary field of medicine are several-fold. There are many important, and sometimes conflicting, issues to consider including the following.

- A variety of experts' opinions must be considered. For example, respiratory therapists, who have to set up, calibrate, clean, and adjust the ventilators throughout the day, usually have the best understanding of the relative ease of training and use, daily costs, and reliability of each ventilator. Physicians and respiratory therapists may require specific performance and features that they believe will give the best outcome for their patients. Clinical engineers can usually offer the clearest understanding of the complications that each ventilator may introduce to the installation, maintenance, repair, and support processes. In addition, clinical engineers can provide important understanding of the longer-term life cycle ownership costs and complications that are unique to ventilators. Administrators may be best equipped to anticipate the impact of new ventilators on

other variables such as income and costs if recovery time is improved, special staffing needs, potential labor-shifting between nursing, respiratory therapy and other departments, and the net costs of trade-in or sale of existing ventilators.

- Legal and regulatory agencies can have complex and conflicting requirements. For example, some cities require one or more special safety certifications for electrical devices that are purchased for use within their jurisdictions. Every ventilator may not meet those requirements, or certification may be an extra cost option.
- Many medical technologies have unexpected interactions with other technologies. For example, one ventilator may not interface properly with the Neonatal Intensive Care Unit's (NICU) central alarm system, or its alarms may not be easy to distinguish from other nearby critical alarms.
- Patient care settings like the NICU often have conflicting needs: Even though neonates need a ventilator that is so flexible it can treat many complex illnesses, it must be simple and safe for clinicians to operate. Also, though alarms must be distinctly heard, they cannot be so intrusive that they upset the neonate or the neonate's family.
- The cost of procuring, using, and maintaining a medical technology like a neonatal ventilator has diffuse budgetary impacts. Capital investment, depreciation, and general facility expenses like oxygen and electricity may come from a central funding pool, but other costs may be shared by other departments. Operational staffing may be provided by respiratory therapy, but training costs may be charged to nursing. Installation, maintenance, and repair expenses may come from the clinical engineering budget. Managing cost diffusion is critical in this era of managed care, as the hospital receives only a fixed payment per patient, regardless of the total cost.

As described above, the ventilator assessment process involves multiple stakeholders and multiple, sometimes conflicting evaluation criteria. For these reasons, the authors believed that the AHP would be an appropriate decision-making methodology for this task. This application of AHP closely parallels many hospitals' existing qualitative evaluation processes, in which multiple medical device criteria and individual product specifications are compared against one another. The AHP was expected to improve on existing processes by clearly soliciting and documenting each expert's perspective. In addition, the AHP makes the organization and rationale behind the individual and collective judgments transparent, and shows the resulting weight of each criterion and specification. This can reduce conflicts between hospital departments by ensuring that no important criterion is overlooked and clearly discloses the relative performance of each ventilator.

2. Literature review

There is no simple way to examine medical treatments in isolation because of the complicated performance, cost, and safety trade-offs between alternatives like devices, drugs, food supplements, homeopathic therapies, or surgical procedures. Instead, treatments are best viewed as a group of potential "health technologies" for consideration. Since the 1980s, HTA is a field with its own international journals, societies, and vocabularies [3,10–14].

HTA is performed at two levels, which Goodman describes as microeconomic assessment and macroeconomic assessment [15]. Macroeconomic HTA is sometimes referred to as evidence-based HTA. By their nature, macroeconomic studies are long and complex, requiring rigorous clinical,

methodological, and statistical comparisons. Macroeconomic HTA examines broad systemic issues at national or regional levels, and patient demographics, economics, laws, health infrastructure, and even moral values must be evaluated. Macroeconomic HTA research has evolved into an international dialog in which available scientific studies are scrutinized for validity and then used to compare alternatives [3,13,15]. The World Health Organization has recently developed the Essential Health Technology Program [16] software to help government agencies perform macroeconomic HTAs for health policy and health system decisions.

By contrast, microeconomic HTA is used in local situations, such as a hospital or physician practice evaluating a specific drug, device, or procedure for adoption. By necessity, a microeconomic HTA is tightly constrained by the target patient population, clinical care practices, legal, ethical, and social standards of care, economic circumstances, availability of other necessary resources, and other similar details [17,18]. Because of local circumstances, no two situations or assessment outcomes are exactly alike. A microeconomic HTA can be helpful in deciding whether or not a particular neonatal ventilator model can successfully save the lives of neonates delivered in a specific hospital. If the hospital delivers a large number of premature, drug-addicted neonates with complex illnesses, simple ventilators designed for less fragile neonates may not be appropriate for this need. A microeconomic HTA study should be used to help select the best neonatal ventilator that fits the specific situation.

At present, existing microeconomic HTA techniques help identify promising products for purchase but, as discussed below, the available techniques do not include all of the critical decision factors that must be considered and evaluated so that the best product is purchased for a specific situation. Microeconomic HTA studies commonly use one or more of the following methods: net present value (NPV) and life cycle cost (LCC) financial analyses [19], cost-benefit analysis [20,21], or product feature and performance comparisons [22,23]. For example, many hospitals discover that for certain brands and models, a ventilator's initial purchase costs are modest compared to the expensive disposable sterile humidification tubing and water packages consumed for each patient, which a good NPV and LCC analysis will disclose. LCC analysis clarifies expensive ownership costs of many health technologies, but this is often only one of many critical issues like safety or ease of use to be considered. A financial assessment used by itself, however, can lead to a poor decision because other critical decision factors like nurse training or patient safety limitations are not easily included. Unlike the AHP, existing microeconomic HTA techniques that focus on financial issues do not provide a consistent way to reliably assess and interpret numerous competing quantitative and qualitative factors.

Cost-benefit studies focus on patient care costs or patient recovery rate and mortality factors. For example, a cost-benefit analysis might be done to decide if home ventilator support would be advantageous for a certain category of ventilator dependent quadriplegic patients. This type of study would typically require that the portable ventilator meets the clinical needs and reduces an insurer's costs, but it may fail to account for factors like the need for a light, portable design for wheelchair use; the costs for home delivery of oxygen and humidification supplies; the long and dangerous delay for emergency transport back to a hospital from a rural setting when problems arise; or the need for expensive backup electricity generators and emergency fuel delivery where frequent winter power outages occur. Unlike the AHP, the existing tools for cost-benefit analysis do not accurately or reliably compare and evaluate each factor, especially for criteria such as safety or ease of use, which are difficult to accurately identify or quantify as a precise cost.

Finally, feature and performance HTAs have limitations, too. Vendor-supplied features are often incomplete, making direct comparison inaccurate. For example, some ventilator vendors may not disclose how long the batteries will operate at high breathing rates, or how long the batteries will take to completely recharge. On the other hand, independent published performance tests are usually generalized, simulating typical or expected worst-case situations. Local temperature or humidity conditions found in ambulances or homes might not be tested, though, limiting the value of the assessment for those applications. Again, unlike the AHP, existing feature and performance HTAs are not able to reliably weigh the numerous qualitative and quantitative criteria that must be assessed for a specific application.

In addition to its advantages over existing methods, the AHP was expected to have excellent potential as a microeconomic HTA tool because it has been successfully used elsewhere in similar environments where alternatives have widely differing characteristics [24–26]. To our knowledge, AHP software like Expert Choice has not been used for the critical decision support needs of microeconomic HTAs. Healthcare-related studies using AHP have addressed medical product design facilitation [27,28], clinical procedure decisions [29,30], and medical staff evaluation [31], but not technology assessment.

3. Case study: A new women's health addition for a mid-size suburban teaching hospital

This case study describes an application of AHP in an actual hospital-focused microeconomic HTA to select the best neonatal ventilator.

The Expert Choice 2000 implementation of AHP (called Expert Choice in the remainder of this paper) was chosen for this study because it provides a mixture of graphical tools that supplement the numerical computations. In the authors' prior research activities, the graphical features proved to be a very valuable way of demonstrating to decision makers how the AHP works. This helps ensure buy-in and confidence in the AHP. Further, the authors found that the ability to use Expert Choice's bar charts and pie charts enhanced the decision maker's ability to understand the impact of the numerical data that the model uses. The other advantage that this particular version of Expert Choice offers is a graphical user interface for model development. This allows easy revision of the model's structure during discussions, so that the participants can actually see the impact of their comments. Easy model revisions also inspire "what if" brainstorming efforts, because the model can be restored to a prior version if the new model proves undesirable.

Expert Choice also includes integrated sensitivity analysis tools to help interpret the significance of complicated option, price, and feature concessions that happen during final vendor negotiations. The completed AHP model can thus improve the hospital's ability to negotiate effectively and help it make a final purchasing decision that follows Hogarth's [32] recommended problem structuring for decision making.

The authors decided to use Expert Choice for this study because of the above features and their successful application of the software for other decision support studies [33,34].

3.1. Applying AHP to a hospital health technology assessment project

In order to apply AHP to perform an HTA, a number of factors need prior consideration because of the effort that will be required. First, the hospital should be actively planning to make a significant

purchase to help justify the investment of hospital staff time. Second, the technology selected for evaluation should be clinically interesting, valuable, and medically important. Third, the hospital should be committed to implementing the decision when the project is complete. However, if the HTA reveals that the alternatives do not score well based on the hospital's criteria and weights, it may be better for the hospital to defer the purchase until either its needs change or a better alternative is found. Fourth, the technology should have large variation among the alternatives. For example, evaluation of a generic item, such as a standard needle or syringe, might not yield any measurable differences other than pricing. Fifth, the appropriate stakeholders at the hospital need to be identified (they must be available to participate in the development of the model). Sixth, active participation of these stakeholders in the entire decision process from development to implementation is needed.

The following sections describe the hospital, technology, and hospital staff participants in the case study.

3.2. The hospital and the technology that was evaluated

The hospital has more than 500 beds and is a major trauma center and teaching institution in the suburbs of one of the top 10 US cities (by population). It was founded in the early 1900s and has remained one of the few independent hospitals in the region. The hospital has many thriving specialized services, including a large in-vitro fertilization (IVF) program. In 2000, it had one of the largest obstetrics programs in the area, with approximately 4400 deliveries. There were over 400 admissions to the 25-bed NICU, including neonates who were transferred from other area hospitals. The IVF program also contributes to the number of NICU admissions; some of these women are older, higher risk, and have a greater tendency towards complicated deliveries.

The NICU has a state-of-the-art design that minimizes noise, activity, and other stresses to critical and fragile neonates and their families. A wide range of technologies are integrated into the NICU environment, including incubators, bassinets, infusion pumps, central-station and portable physiological monitors, resuscitators, and specialized neonatal ventilators for patients who cannot breathe on their own. The technologies require knowledgeable use, routine inspection and maintenance, and appropriate supplies and drugs to be effective. Most technologies have built-in alarms and choosing alarms that work well together is important. Minor alarms should not mask serious ones, and the overall noise level should not be disruptive.

Due to the growing number of IVF, obstetrics, and general women's health patients, the hospital purchased a nearby piece of land to build a women's health hospital. Building this facility is creating the need to identify the proper technologies for many expanded departments, including the NICU. While some of the existing equipment is likely to be used, some devices are no longer being manufactured. Older, used products might be purchased and refurbished for the new NICU. However, the hospital would like to consider whether new technologies should be purchased to allow it to incorporate new care practices.

The neonatal ventilator became the focus of our HTA because it is a critical and expensive device that the hospital needs to purchase for the NICU. Neonatal ventilators are unique devices because many of the neonates arise from premature deliveries. The neonate's lungs are often incompletely developed and may be quite stiff and fragile. The small size of neonates (as small as 0.5 kg, or about 1 pound) presents demanding electromechanical requirements. The ventilator must deliver rapid, tiny puffs of precisely blended air and oxygen. A neonate's lungs may only be the size of an adult's

small finger; over-inflation could rupture the lungs or block the blood that the heart is trying to pump through the lungs. The ventilator's precise volume controls must be sustained during rapid cycles of 100 breaths per minute. The neonatal ventilator also has to synchronize with the weak inspiratory and expiratory efforts of the neonate. The ventilator's sensitivity to the neonate's effort can be a life-or-death balance; the baby may fail to thrive or survive if the ventilator requires too much muscular or metabolic capacity. Neonatal physiology also limits access to an artery or vein, which often makes it useful to deliver precisely metered inhaled drugs with the breaths. This requires accurate and dependable drug mixing and control because any interruption can cause a serious risk in some drug regimens. Together, these demands create very high performance and reliability criteria for neonatal ventilators to meet.

Ventilators for neonates range in price from around \$18,000 to nearly \$40,000, and each manufacturer and model has different features. Also, the ventilators have a very significant life-cycle cost of ownership due to supplies and maintenance requirements, which can dwarf the initial purchase price. The hospital needs to purchase two dozen or more units for the new NICU. When combined with 5–10 year life cycle costs of supplies, maintenance, and repairs, the purchasing decision for 24 neonatal ventilators becomes a million dollar commitment. In addition, competent clinical and technical training and support are needed for a decade or more for safe and effective patient care, so the staffing costs are significant. Because of the large overall investment that neonatal ventilators require, the clinical engineering and respiratory therapy departments agreed to use AHP to help the hospital make the best selection.

The hospital staff viewed this study as an opportunity to evaluate the AHP process. Millions of dollars of additional medical technology will be needed for the new hospital, along with large investments in physical plant, information systems, and other infrastructure. If AHP was successful for neonatal ventilator evaluation, then it might be used for other HTA decisions.

3.3. Identification of the HTA and project team members

The directors who participated in the technology assessment team were selected from two departments:

- **Respiratory Therapy.** This department provides the routine clinical staffing to support the patients. It evaluates technology to meet the physicians' requirements (e.g., requirements of neonatologists and cardiologists) and manages capital and operating budgetary decisions.
- **Clinical Engineering.** This department evaluates, installs, inspects, repairs, and maintains the devices. It manages device accident investigations, recalls, and updates, and is responsible for meeting the safety criteria of local, state, and federal agencies.

The director of the respiratory therapy (RT) department, with 26 years of clinical experience and 15 years at the hospital, agreed to be the primary clinical liaison. The clinical engineer (CE), who is the assistant director of the biomedical engineering department, has 36 years of experience and 11 years at the hospital. The CE has an in-depth technical understanding of a broad range of medical devices. He oversees the daily support of the hospital's complex medical technology inventory. The CE has access to numerous information sources about devices, and he agreed to coordinate the project and to gather necessary information such as critical safety requirements.

Table 1
Evolution of the AHP model for selecting the neonatal ventilator

Iteration	Information source ^a	Primary criteria categories	Secondary criteria categories	Additional criteria categories		Number of rating criteria “bottom-level”	Comments
		First level	Second level	Third level	Fourth level		
1	Authors & CE	4	19	0	0	19	Prototype model
2	CE	4	21	26	0	39	Refined per CE expertise
3	CE & RT	4	22	29	0	42	CE & RT discussion; agreed on overall model
4	CE	4	23	33	0	46	CE began pairwise comparing of criteria
5	CE	4	20	35	2	46	Cost demoted to least important
6	RT	4	20	35	2	46	Several technical judgments were revised by RT

^aInformation sources: CE-Clinical Engineering Director, RT-Respiratory Therapy Director.

One of the authors (Sloane), who is also a clinical engineer with 25 years of health technology assessment and ventilator experience, assisted the HTA team by providing subject matter expertise, especially during the development of the initial prototype of the model. All of the authors participated in the project team that developed and implemented the AHP model for neonatal ventilator assessment discussed in this paper.

3.4. Development stages (iterations) of the AHP model

Table 1 shows the overall stages of evolution of the AHP model including the individuals whose input was used, and the total number of primary, secondary, and additional criteria categories that were created. This table also lists the total number of bottom-level criteria (these are the criteria on which each alternative is evaluated). After consideration of the large number of bottom-level criteria in the final model (46) and the potential number of alternative neonatal ventilators that could be considered, the authors decided to use a ratings approach instead of pairwise comparing the alternatives. The ratings approach differs from pairwise comparison of alternatives in that individual ratings are defined for each criterion. It offered another advantage in that the hospital staff was familiar with the use of similar techniques for clinical assessments. For example, the Apgar score is a commonly accepted rating system that is used to evaluate a newborn’s condition during the first critical minutes after delivery [35].

The first model (Iteration 1) is based on a prototype that was generated by one of the authors to initiate the discussion with the CE (see Fig. 1). This model was initially formulated by using published reports in ECRIs Health Devices Journal [36] and Product Comparison Reports [37], manufacturer’s specifications, and online information found in Amethyst Research’s Web site

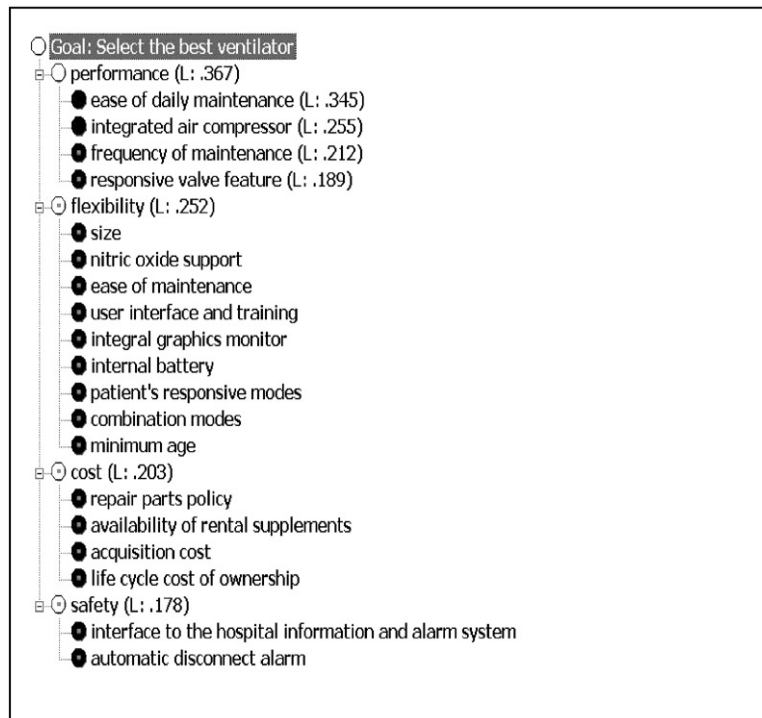


Fig. 1. Expert Choice hierarchy showing the first iteration: initial prototype model.

(<http://www.ventworld.com>). After reviewing the model, the CE was asked to suggest appropriate improvements to the criteria and hierarchy. He was also asked to provide pairwise comparisons for the criteria and one group of subcriteria to gain an understanding of how AHP and Expert Choice worked. As shown in Fig. 1, performance receives the largest weight followed by flexibility, cost, and safety.

The second iteration of the model occurred during a later meeting between the authors and the CE to obtain his judgment on the structure of the hierarchy. This second iteration led to a change of the names and descriptions of the first level criteria. In addition, the number of subcriteria more than doubled, and most of these were placed in a third level of the hierarchy. During this meeting no pairwise comparisons were collected.

The third iteration (Fig. 2) resulted from a joint meeting with the RT and CE. In this discussion, certain overlapping criteria and concerns were discussed and revised. Thus, Fig. 2 represents the first model that is based on the combined expertise of the directors. After this meeting, the hierarchy had the same first-level criteria as determined in the second iteration. However, there were some minor changes made to the lower-level criteria. At this point, the directors felt that the hierarchy had been appropriately structured. During this meeting the rating attribute ranges and descriptions began to evolve, but no pairwise comparisons were collected.

In the fourth meeting, the authors and CE began the pairwise comparison of the subcriteria in the safety and biomedical engineering groups, and of selected subcriteria within the clinical factors

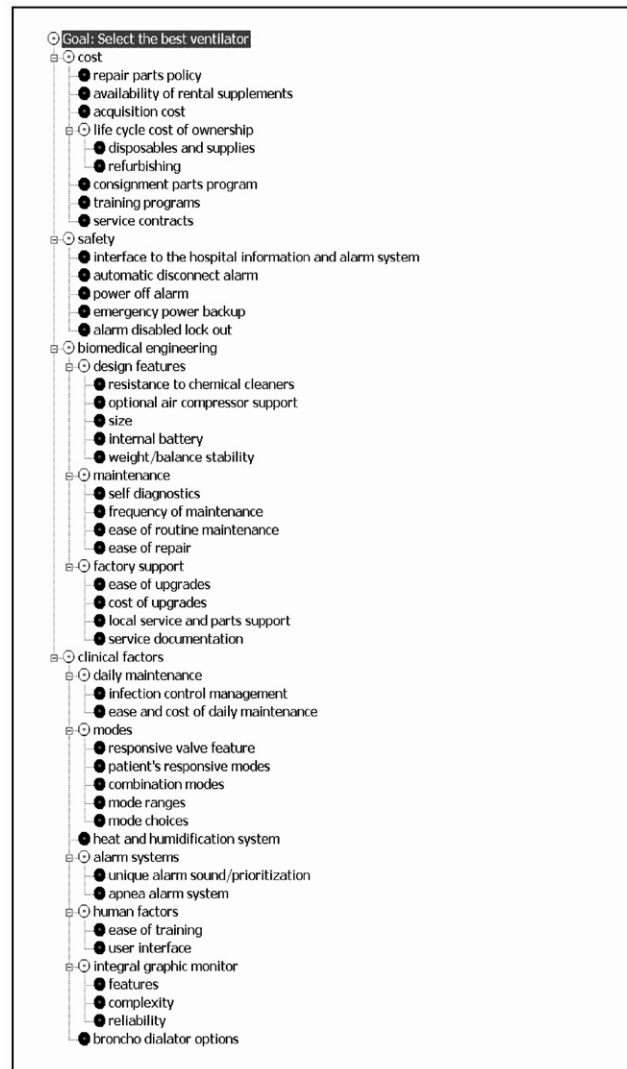


Fig. 2. Expert Choice hierarchy showing the results of the third iteration: joint CE and RT views.

group. To facilitate the collection of the necessary judgments at each level of the hierarchy, the CE was asked to provide a preliminary ranking for the criteria at the next lowest level. The criteria at all levels of the hierarchy were then rearranged (highest ranked at top) to make it easier for the CE to see his order of preference. During this fourth discussion, most of the CE's rating attribute descriptions and their associated weights were defined.

Each of the meetings took 1–2 h and included two or three of the authors and one or both of the hospital directors. Because the directors were becoming rather proficient with Expert Choice by this time, a manual data-capture form was designed to facilitate off-line data collection for the remaining criteria. The directors used bar and pie charts generated from Expert Choice to assist them in

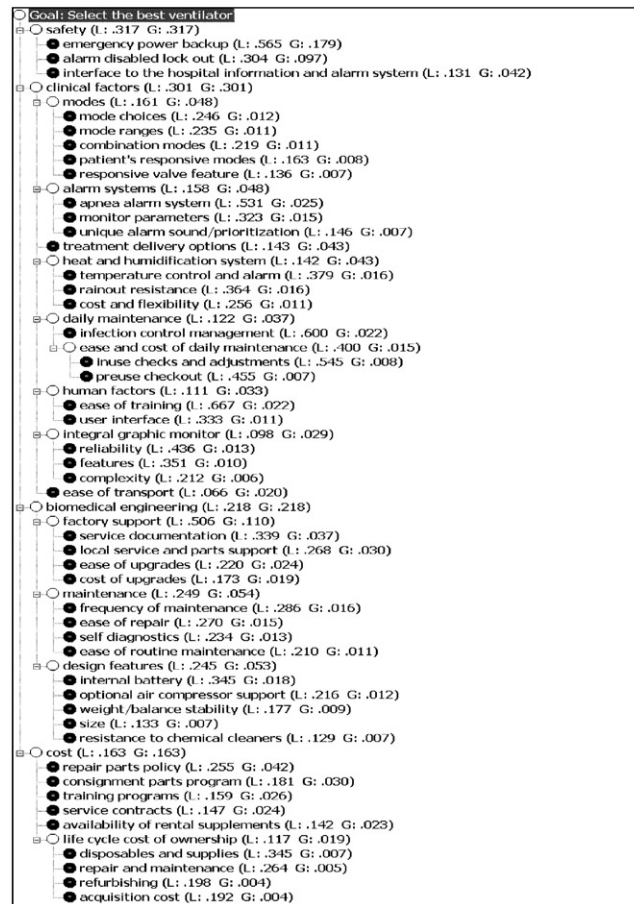


Fig. 3. Expert Choice hierarchy showing the final, sixth iteration model with local and global weights.

assessing the impact of different numerical pairwise comparisons. When combined, the data-capture form and the calibration charts allowed the directors to make pairwise comparisons without the help of the authors.

Once the CEs data-capture forms were collected and the data entered into the model, a fifth meeting was held with both directors. During this meeting, the CE completed his rating attribute descriptions and pairwise comparisons; the CE and RT achieved consensus on the criteria weights at all levels discussed thus far; and the RT was trained to use the input forms and calibration charts for the remaining clinical criteria. The drop-and-drag interface available in Expert Choice allowed the directors to easily modify the model when necessary, and facilitated refinement of the model. The participants also found the Expert Choice bar charts were very helpful in displaying the proportional weight for each criterion. In the fifth iteration, Safety received the largest weight (0.317), followed by Clinical Factors (0.301), Biomedical Engineering (0.218), and Cost (0.163).

Fig. 3 shows the results of the sixth iteration. The RT agreed with the overall weights that had emerged in the prior iterations, and made no further changes. The discussion and completion of the

Table 2
Sample rating names, descriptions, and weights

Category	Rating name and description	Weight
Daily maintenance requirements: Pre-use check	Simple: easy to reliably learn and perform quickly	1.0
	Somewhat intensive: takes time to learn and perform well	0.76
	Very intensive: likely to be complex and time consuming	0.29
Alarm system unique sounds and prioritization	Large number: many alternatives can be configured	1.0
	Select number: several usable choices are available	0.76
	Minimal/none: too limited or not available	0.35
Responsive valve feature	Excellent: unusually sensitive response	1.0
	Adequate: should meet most of our neonates' needs	0.49
	Limited: not likely to meet some of the neonate's needs	0.10
Factory support: Service documentation	Excellent: current materials readily available for purchase	1.0
	Limited availability: restrictions are placed on who can buy current and/or complete documentation	0.40
	None: significant material is limited to manufacturer's employee use only	0.09
Training program	2 staff training: training for at least two hospital staff members is free	1.0
	1 staff training: training for only one hospital staff member is free	0.53
	No staff training: all training must be paid separately	0.19

sixth iteration was held with the RT after his data-capture forms were processed. A few of his pairwise comparison matrices had unacceptably high inconsistency levels (i.e., inconsistency ratio > 0.10). After discussion, the RT revised selected pairwise comparisons, which led to acceptable inconsistency ratios. Because the CE had given the RT final approval, the RT performed a final review of all of the weights and changed three of the comparisons to finalize the model.

3.5. *Defining ratings and weights*

After the model development effort was completed, the RT and CE created meaningful ratings for each criterion using pairwise comparisons. This approach allowed the directors to assess the relative importance of each rating by using the Expert Choice format. Each rating was given a brief description to facilitate interpretation when evaluating ventilator alternatives. A sample of the ratings, descriptions, and weights is given in Table 2. The diverse criteria and ratings in this table illustrate why the rating system makes the results easier to interpret by clinical, technical, and administrative staff members. For example, the hospital staff can readily grasp the meaning of simple daily maintenance requirements, and can also reasonably interpret the comparable weight (0.29) that would be given to a very time-intensive alternative.

The ratings for each criterion were arranged so that they were ordered from the highest weight to the lowest weight. Human factors research [38] has shown that consistent task organization (e.g., best to worst) helps to prevent mistakes and improve efficiency. The authors have also observed that when using Expert Choice, users can detect ordering mistakes when they expect every list to be in the same order. The RT and CE were reminded throughout the model construction process that they were not bound by prior rankings, and were encouraged to immediately make any desired changes.

3.6. Evaluating the ventilator alternatives

The hospital decided to consider three neonatal ventilators. Alternative 1 is the current (newest) production version of the most common neonatal ventilator already in use at the hospital. This newer design has digital displays and more flexible adjustments and alarms. Alternative 2, from a different manufacturer, is one of the latest ventilator models available. It has a very flexible selection of many advanced operating modes and alarms. The hospital has successfully deployed a few of the Alternative 2 ventilators in the NICU and is very pleased with the results. Alternative 3 is the ventilator already in use. This is a reliable but old (20 + years) design that is no longer in production. However, this model has proved generally adequate and reliable for the hospital and can be purchased in used condition from other hospitals.

The CE and one of the authors worked together for several hours to rate each ventilator using the manufacturer's specifications, manuals, and feedback from the RT and the ventilator repair technician. Table 3 shows a sample of ratings for each of the three neonatal ventilator alternatives. The first category evaluates the daily pre-use checkout requirement for each unit. The existing ventilator (Alternative 3) and its current updated version (Alternative 1) were both rated as simple. The more complex, state-of-the-art unit (Alternative 2) received the lowest rating of very intensive. The second category evaluated the unique sounds and prioritization of each ventilator's alarm system (i.e., ability to discriminate life-threatening from less serious alarms). In this case Alternative 2 had the best rating. The other two ventilators' alarms were given the minimal/none rating. In the remaining three categories Alternatives 1 and 3 have the same ratings, while Alternative 2, is rated higher in two of these categories. When the three alternatives were evaluated on all of the 46 bottom-level ratings, Alternative 2 had the highest overall score (0.825), followed by Alternative 1 (0.531) and

Table 3
Ratings for three neonatal ventilator alternatives

Category	Alternative		
	1	2	3
Daily maintenance requirements: Pre-use checkout	Simple	Very intensive	Simple
Alarm system unique sounds and prioritization	Minimal/none	Large number	Minimal/none
Responsive valve feature	Limited	Excellent	Limited
Factory support: Service documentation	Excellent	Limited availability	Excellent
Training program	No staff training	2 staff training	No staff training

Table 4
Final weights for the four top-level criteria and scores for the alternatives

Top-level criteria	Weight	Alternative scores		
		1	2	3
Safety	0.317	0.168	0.262	0.122
Clinical factors	0.301	0.160	0.248	0.116
Biomedical engineering	0.218	0.116	0.180	0.084
Cost ^a	0.163	0.087	0.134	0.063
Overall		0.531	0.824	0.385

^aNotes: The cost criterion includes multiple subcriteria, as shown in Fig. 3. Higher scores mean better (i.e., lower) costs for an alternative.

Alternative 3 (0.384). In general, Alternative 3's obsolete design did not score well, and its score was further reduced by the limited repair and service alternatives that remain. Although Alternative 1 is a newer design, it still lacks many of safety and clinical features that the RT and CE preferred. Table 4 shows how each neonatal ventilator scored for the four primary criteria categories (Safety, Clinical Factors, Biomedical Engineering, and Cost), as well as the overall score. Alternative 2 had the highest score in all four primary categories so that no combination of changes to those factor's weights would alter the overall analysis. Alternative 2 is the best choice for the hospital unless a major revision of the AHP model is made that changes the weights of the bottom-level criteria.

3.7. Outcome of the evaluation

As this study finished, the hospital's board was reconsidering whether the new facility should have an even broader mission than women's health. The new facility mission will dictate the final design, budget, construction timeline, and necessary resources. This study has provided clear support for the CE and RT to choose Alternative 2 when neonatal ventilators are purchased for the new NICU. If the final facility design creates new constraints on any of the criteria, such as drastic capital budget limitations or unique size constraints, the pairwise comparison matrices can be updated to determine if Alternative 2 is still the best choice. Further, if the facility is substantially delayed, this AHP model will also allow rapid assessment of any new neonatal ventilator that might become available. The CE and RT found AHP easy to use and apply, and await the final facility design to see where AHP can be used to improve other critical decisions.

4. Analysis and observations

Our iterative process allowed us to use AHP to perform a microeconomic HTA for the hospital's neonatal ventilator purchase. Building the model was efficient, as each meeting took only 1.5–2 h, and usually only one expert's time was required. Furthermore, some of the time invested in building this initial model will be reclaimed in future decisions by this hospital, because much of the general organization and analysis will apply to future medical technology purchases. In addition, the CE

and RT also take part in many of the hospital's technology acquisition decisions, and they will not need to relearn the AHP methodology. The confidence and understanding acquired in this decision process has equipped the directors to apply AHP to other purchasing problems for the new women's health facility.

As we saw, the model's structure was not finalized until the fifth iteration. In the early stages, the two directors focused on identifying all of the important factors under consideration. Later, as they considered the relative importance of each criterion, the software's bar chart and pie chart displays made it easier for them to visualize the impact of changing each criterion and pairwise comparison. In the final review of the model, both directors were satisfied that the model effectively represented their respective clinical and technical perspectives. The consensus-building value of creating this AHP model using collaborative, iterative model refinement and graphical feedback is similar to findings that are documented in prior organizational decision studies in healthcare and other fields [39,40].

It is interesting to note that the cost factor had the least weight in the final model. Four factors contributed to this.

1. Excellent support of high-risk pregnancies is of strategic importance to this hospital. Not only does it protect the hospital's perceived leadership role in the community, but it is also a critically important part of the success of other valuable programs like IVF.
2. In the hospital's experience, it has generally been able to secure cost-competitive bids from most manufacturers because of the economic pressures in healthcare today.
3. Good risk management strategy reinforced the value of considering safety and performance of the devices ahead of economics.
4. This particular hospital has strong community funding and endowments that enable it to maintain its focus on quality and service despite the economic pressures (e.g., it is one of the few hospitals building new facilities in the area, even while others are being closed).

The low weight of cost in the final model (0.16) is different from results found in the literature. For example, Stout et al. [41] showed cost as the highest weighted factor in an AHP-based manufacturing equipment evaluation study. Stout et al. also showed that a more costly alternative could be selected even when all other important criteria are taken into account.

Additionally, the results show that several criteria that remained in the model had very low weights and consequently had negligible influence on the evaluation. For example, the repair and maintenance and acquisition cost criteria (at the bottom of the model, under life cycle cost of ownership), only have a 0.7% and 0.4% contribution to the model, respectively. On the one hand, practitioners may readily dismiss such criteria as not only irrelevant, but as also adding unnecessary and distracting complexity to the model. Although technically correct, the participants felt that their model could not be presented or defended to their organization if criteria with low weights were omitted. Furthermore, there was concern about possible legal problems or ethical exposure that could be created if marginally important safety and clinical factors were not part of the final model. This may be a somewhat unique constraint of using an AHP for healthcare decision making. In a courtroom, the elimination of a decision factor could be construed as criminal negligence if it is later asserted that it was willfully dropped because of convenience or cost.

In this case study, AHP worked well in a hospital setting with the participation of key knowledgeable stakeholders. The AHP could be applied to a range of well-understood and accepted medical

technology decision problems, such as the selection of medical imaging, laboratory, and surgical devices. Realistically, other situations may require more than six iterations. As examples, the following situations can be expected to increase the number of iterations.

1. New, emerging technologies may have complex and poorly understood characteristics.
2. Less experienced staff participants may not have enough expertise to confidently identify all of the important criteria, necessitating more revisions to the model's structure and to the criteria weighting.
3. Hospitals may have more complicated planning and decision practices, requiring more participants and meetings.
4. Larger groups of participants may naturally lead to longer and more complicated debates about the model's structure and the priorities.
5. Participants from different disciplines may have more difficulty generating the pairwise comparison matrices.

The AHP does not replace health technology selection aids, such as ECRIs Health Devices evaluations or life cycle cost analysis. Rather, it should be used as an integrative tool to help determine and compare all appropriate criteria. The participants found that AHP can be used to accurately model their decision process. They also found that AHP is understandable and easy to learn and use effectively.

5. Conclusions

In this paper, we have shown that AHP can be used to rapidly and efficiently build a neonatal ventilator evaluation model. Unlike other microeconomic HTA tools, the Expert Choice implementation of AHP allowed a diverse set of decision factors to be assessed before making a product evaluation. Because the choice of a health technology has such expensive and extensive implications, and such technologies often are used by a hospital for well over a decade, careful consideration of all of the factors helps lead to a better overall outcome.

In addition, the drop-and-drag editing and interactive bar chart and pie chart displays aided design and refinement. These features provided the hospital staff with effective ways to visualize, understand, modify, and discuss the model.

The clinical engineering and respiratory therapy directors now have a working model to use for negotiating the purchase of neonatal ventilators. The model that they constructed reflects their own personal, professional, and institutional judgments. The flexibility of this model will allow them to evaluate the alternative that best meets the final needs when the new women's health facility is complete. The model can also be easily revised to include new features and requirements that may emerge in the months that are ahead. These directors also have the training and understanding needed for future applications of AHP.

The clinical engineering field spans many important multidisciplinary and interdisciplinary tasks in hospitals and health care systems. Based on the results of our study, we believe that AHP should be given serious consideration as a decision support tool when making technology assessments. The AHP can be used by a clinical engineer or other qualified facilitator to assist hospitals in making

the best possible choice for every technology acquired. If the appropriate experts participate in the assessment, and the AHP model is created properly, then AHP can help ensure that the technology acquisition will not only improve patient care, but will also contribute to controlling costs, risks, and labor requirements.

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