Modeling the Cost and Performance of Early Identification Protocols

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Abstract
This is the first in a series of three papers concerned with the early identification of hearing loss. In this paper, a simple model is presented that permits the calculation of the performance and cost of early identification protocols. In the second paper (Turner, in press), this model is used to compare four early identification protocols that differ in hearing screening strategies. The third paper (Turner, in press) examines the factors that influence the early identification protocol. The model described in this paper is sufficiently general to accommodate most early identification strategies including those that meet the goal of identification and habilitation by 6 months. The model measures protocol performance using hit rate, false alarm rate, and selected posterior probabilities. The model also calculates two measures of the financial cost. One measure reflects the cost of implementing the protocol; the other reflects the cost-effectiveness of the protocol. The parameters required by the model are also specified and are based on published clinical data. The model is provided to help audiologists design and select early identification protocols that are optimum for their particular clinical situation.

Key Words: Hearing loss, early identification, infant, model, cost-benefit analysis

It is generally accepted that hearing-impaired children benefit from the early detection and habilitation of hearing loss. The Joint Committee on Infant Hearing (1982) has recommended that hearing loss be identified and habilitation begun by 6 months of age. The need for such an effort is clear to most audiologists, but how does one determine the most appropriate early identification (EID) protocol?

One approach is to rely entirely on intuition and clinical experience. This, however, is only appropriate with extremely complex problems that defy any type of quantitative analysis. Unfortunately, this strategy is often used because it is the least demanding. While it has a certain appeal, such a subjective approach is often vulnerable to bias and undetected error. Decisions may be based on inappropriate assumptions that result from atypical or limited clinical experience. Also, it is difficult to evaluate and validate the decision making process because it is seldom explicitly known.

Another strategy is to quantify every variable and then perform a detailed cost-benefit analysis. Theoretically, this is the best approach, but often it is too difficult to be practical. With this strategy it is necessary to assign some quantitative measure of cost to errors and benefit to correct decisions. The problem is that some important variables may be difficult or near impossible to quantify. For example, what are the actual financial and societal costs of not identifying a hearing-impaired infant?

There is a third strategy that is a compromise between the two described above. A simplified model can be developed to serve as an objective, defensible starting point. With this model, certain issues can be evaluated quantitatively. Factors that can not be included in the model can then be considered to yield the ultimate decision. Thus, the cost-benefit analysis combines objective data derived from a quantitative model with a subjective evaluation of important factors. While there is a subjective component to this strategy, at least the decision process begins with a more rigorous, objective foundation.

What factors would we want to quantify in a model? There are many important factors to
consider when selecting an EID protocol, but the two most fundamental are performance and cost. By performance, we mean how many hearing-impaired (IH) infants will be detected. It would also be useful to know how many normal hearing (NH) infants will be incorrectly called hearing impaired. Since resources are limited, some measure of the cost of implementing an EID protocol is essential, as well as some measure of cost-effectiveness. Thus, reasonable measures of performance and cost are the minimum information we would want when evaluating and selecting EID protocols. It is difficult to see how an appropriate decision can be made without this basic information. Fortunately, performance and cost, the most basic factors, are also the easiest to quantify in a model.

Prager et al (1987) used a simple model to compare the cost-effectiveness of newborn hearing screening with the Crib-O-Gram and auditory brainstem response techniques. This paper extends their work and presents a more general and detailed model for EID protocols. The techniques for calculating the cost and performance of EID protocols are described in detail. Essential data for the implementation of these techniques is also provided.

This model is easy to implement and can be used by audiologists to develop their own EID protocols. The quantitative results of this model can be considered along with more subjective local factors to evaluate different EID strategies. Each program can design an EID protocol that is optimum to its particular need instead of relying on one universal recommendation.

**PROTOCOL DESIGN**

The first step in developing the model is to specify the basic design of the EID protocol (Fig. 1). This design is sufficiently general to accommodate many actual protocols. With certain implementations, it is consistent with the goal of identification and habilitation by 6 months. The model does not consider the identification of progressive loss.

**Nursery**

The first component is the hospital nursery. This can be either a well baby nursery (WBN) or an intensive care nursery (ICN). It is necessary to distinguish between the types of nurseries because prevalence of hearing loss can be very different. In addition, screening tests may perform very differently on infants from the two nurseries. In general, infants in either nursery are referred to a screening protocol; however, this is not essential.

**Screening Protocol**

The primary purpose of any screening protocol is to reduce the cost of identification. The screening protocol identifies infants at risk, that is, infants with a higher probability of disease than the general population. This reduces the infants who must be followed and tested with the diagnostic procedures, reducing the cost of identification. Usually, the result of screening is either pass or fail; the screening is not diagnostic. Infants that fail are referred for diagnostic testing. Infants that pass are not followed. Experience has shown that with some screening protocols, all infants cannot be tested before discharge. A provision for this is incorporated in the model.

**Follow-Up**

Technical limitations prevent the diagnostic testing of newborns; therefore, infants must
be followed until they are sufficiently old for diagnostic procedures. Both infants who fail the screening and infants who were not screened before discharge must be followed. The reason that this component must be explicitly shown in the model is that there is some expense in following infants until diagnostic testing. In addition, experience has demonstrated that some infants will be lost from follow-up. Both factors will have a significant impact on the cost and performance of EID protocols.

**Diagnostic Protocol**

The final component in the EID process is the diagnostic protocol. It is this component that actually identifies hearing loss. Infants with hearing loss are referred for additional evaluation, habilitation, and management.

**MEASURES OF PERFORMANCE AND COST**

Simple, but adequate, measures of test performance are hit rate (HT) and false alarm rate (FA). These same measures can be applied to test protocols (Turner et al., 1984). Hit rate for the EID protocol (HTp) is the percentage of hearing-impaired infants in the nursery who are identified by the protocol. False alarm rate for the protocol (FAp) is the percentage of normal hearing infants in the nursery who are incorrectly called hearing impaired by the protocol.

Also of interest are the posterior probabilities. One posterior probability (PPf) is the probability of hearing loss in an infant who fails screening. PPf indicates how much confidence we can have that an infant who fails is actually hearing impaired. A second posterior probability is PPp. This is the probability of hearing loss in an infant who passes screening.

There are many different measures of financial and societal costs that could be used. For our purposes, we will restrict our calculations to two basic measures of financial cost. These are the dollar cost of the EID protocol per infant in the nursery (CPIN) and the dollar cost of the EID protocol per hearing-impaired infant identified (CPHL). These two measures reflect different aspects of protocol costs. CPIN is a measure of what it costs to implement the program, whereas CPHL is a measure of cost-effectiveness. A program could be inexpensive to implement, but could identify few IH infants. In this case, CPIN would be low but CPHL would be large. On the other hand, an expensive program could identify many IH infants. CPIN would be large, but CPHL small.

**MODEL PARAMETERS**

To calculate performance and cost for an EID protocol, it is necessary to specify the parameters that are used in the model. For calculating performance, the parameters are disease prevalence, HT/FA of the individual tests in the protocol, and test correlation (Turner et al., 1984).

To determine CPIN and CPHL we must know the cost of each component of the EID protocol plus protocol performance. Hit rate and false alarm rate of the total protocol are not sufficient; we must also know the number of infants processed by each component. This means tracking the infants, in detail, all the way through the EID protocol.

For EID protocols, two additional factors must be considered. First, the percentage of infants who cannot be screened in the nursery are combined with the screening failures to constitute the infants to be followed. Second, it is necessary to specify a follow-up percentage. This is the percentage of infants who remain in the program until diagnostic testing.

In general, the model parameters will be derived from published clinical data. This is not without some problems. For many parameters the reported values can vary significantly. A parameter will be selected that is the average of the reported values or is within the approximate middle of the reported range. An additional problem is that some of the parameters have received little attention in the literature. In this case a best guess will be made based on available information. A summary of the selected model parameters is shown in Table 1.

**Prevalence**

Prevalence (Pr) is the percentage of infants in a nursery with hearing loss at the time of testing. Determining prevalence is more complex than it may seem. The first problem is defining hearing loss in terms of degree of loss, type of loss, and unilateral versus bilateral hearing loss. Historically, most prevalence data, particularly for the general population, have been for moderate to profound sensorineural loss. Newer techniques in the ICN have made possible the detection of milder losses, conductive losses, and unilateral losses. For our pur-
poses, we will focus on the identification of moderate to profound sensorineural loss, unilateral or bilateral.

A number of studies provide estimates of prevalence for the ICN. Some good reviews of relevant studies are provided in Murry et al. (1985), Jacobson and Hyde (1986), and Stein (1986). Estimates of prevalence vary from about 1 to 8% with the generally accepted range being 2 to 4 percent (Committee on Infant Hearing, 1989). If conductive loss was included, then the prevalence would be higher. Three percent will be used as the model parameter for prevalence in the ICN.

We are also interested in the prevalence in the WBN. In general, this figure has not been determined directly; we must estimate this from data for the general population. Reported prevalence has varied from less than 0.1 to more than 0.3 percent, but the most frequent reports are 0.1 to 0.2 percent (see Peckham, 1986; Riko et al, 1985 for reviews). We would expect the prevalence in the WBN to be smaller than the general population for two reasons. In many studies prevalence is based on hearing loss in children from 5 to 8 years of age. Some of the measured hearing loss would be progressive and not present in the WBN. Also, the general population consists of infants from the WBN and the ICN where the prevalence of hearing loss is greater. We will use 0.1 percent (1 per 1000) as the model parameter for prevalence in the WBN.

**Screening Test Performance**

A variety of different tests have been used to screen infants for hearing loss. Today, the only tests in extensive use are the high-risk register (HRR) and auditory brain stem response (ABR) screening; therefore, we will concentrate on these two tests for the model. As new screening tests are developed, these can be incorporated into the model as long as the hit rate and the false alarm rate can be specified.

The performance of some screening tests can be quite different in the two nurseries; therefore, the nurseries must be considered separately. Remarkably, there is little information in the literature on the performance of the HRR in the ICN even though the HRR has been employed in many studies. Frequently, the HRR has been used to determine which infants receive ABR screening without any attempt to evaluate the performance of the HRR. One study (Simmons et al, 1979) found HT/FA = 96/64 percent for the HRR in the ICN.

Several studies do report failure rate (FR) for the HRR. These rates have varied significantly from 20 to more than 90 percent (Alberti, 1986; Hosford-Dunn et al, 1987; Swigonski et al, 1987; Kramer et al, 1989). FR can provide an estimate of false alarm rate. When prevalence is low, the FA will be only a few percent smaller than FR. With a FR of 20 percent, a 3 percent prevalence would yield a FA of almost 18 percent. Thus, the FA for the HRR in the ICN will vary as the FR varies. In general for a diagnostic test, as false alarm rate decreases so does hit rate. Thus, a low FR means a low FA, which may indicate a low HT. Unfortunately, there is no information on the HT of the HRR when FR is low. We will use as a model parameter, HT/FA = 95/65 percent, consistent with the results of Simmons et al (1979).

There is information on the performance of the HRR in the WBN and the general population (Mencher, 1974; Feinmesser and Tell 1976;
been summarized by Murry et al (1985), Jacobson et al (1982; Mencher and Mencher, 1982; Stein et al, 1983; Alberti, 1986; Coplan, 1987; Elssmann et al, 1987; Kramer et al, 1989). The results of the two populations are similar, although we would theoretically expect a slightly higher HT and FA for the general population because that would include ICN infants. HT varies from approximately 50 to 75 percent; FA from approximately 7 to 12 percent. We would expect some variation because different high-risk items have been employed. In general, the more restricted the HRR, the lower the HT and FA. Feinmesser and Tell (1976) found the performance of the HRR reduced from HT/FA = 72/20 percent to 60/7 percent when fewer items were used. We will use HT/FA = 60/10 percent for the model parameter for the HRR in the WBN.

There is limited information on the HT of ABR screening in the ICN. To determine hit rate, it is necessary to know how many hearing-impaired infants were missed by the screening. This means that infants who pass the screening must be followed; unfortunately, this is seldom done. Three studies attempted to follow all infants that had been screened with ABR (Shannon et al, 1984; Bradford et al, 1985; Swigonski et al, 1987). In all studies, HT = 100 percent for the ABR screening, but in each case the number of infants tested was relatively small. In the largest relevant study, over 700 infants were followed (Hyde et al, 1990). HT for ABR screening varied from 98 to 100 percent depending on criterion for passing the screen. It is important to note that in this study, infants were tested under ideal conditions at 3 months of age or later, not in the ICN. In addition, this study did not consider low frequency loss that can be missed by ABR testing with a click stimulus. These studies indicate a high HT for ABR screening; however, we would not expect HT = 100 percent. A small number of hearing-impaired infants could be missed because they have low frequency loss or because a high click level (e.g., 40 dB nHL) was used for the criterion (Riko et al, 1985; Durieux-Smith et al, 1987; Kramer et al, 1989). For the model parameter, we will use HT = 95 percent for the ABR in the ICN.

There are extensive data on the failure rate of the ABR in the ICN. A number of studies have been summarized by Murry et al (1985), Jacobson and Hyde (1986), and Stein (1986). In general, FR varies from 10 to 25 percent in these reviews with an average FR (as calculated from Murry et al and Jacobson and Hyde) of about 17 percent. As discussed previously, the FA will be several percent below the FR. A FA of 15 percent will be used as the model parameter so as to reflect general experience, not optimum performance. Recent improvements in technique may consistently improve the FR for ABR. Gorga et al (1988) tested ICN infants under ideal conditions, including insert earphones, and found that only 5 percent of the ears failed the screening. This corresponds to a failure rate of 5 to 10 percent depending on the distribution of impaired ears among the infants.

There is little information on the performance of ABR screening in the WBN. This strategy has seldom been used because of the large number of infants to be tested and the low prevalence of hearing loss. There is no obvious reason to expect the HT in the WBN to be much different than in the ICN. As for the ICN, we will use HT = 95 percent as the model parameter. We would expect the FA in the WBN to be lower than the ICN. There would be fewer infants in the WBN with developmental delays or transient conductive loss. A lower limit on false alarm rate is indicated by the work of Hyde et al (1987). They tested more than 200 normal infants who were not at-risk for a hearing loss. The infants were screened at approximately 4 months with ABR under ideal conditions, except that insert phones were not used. They found a FR of 7 percent for a 30 dB nHL click stimulus. Assuming no hearing-impaired infants in this population, the FA would be identical to the FR. We would expect the FR to be slightly higher in newborns, as opposed to 4 months; therefore, FA = 10 percent will be used as the model parameter.

Cannot Test

Certain screening tests such as ABR require physical access to the newborn in the nursery. In the ICN, testing is most reliable when the infant is less ill, that is, right before discharge. This significantly reduces the time available for testing. In the WBN, infants may be hospitalized for only 2 or 3 days, again reducing the opportunity for testing. A certain percentage of infants (CNT) will be discharged before testing can be accomplished. This issue is seldom discussed in published studies, but conceivably could impact on the cost and performance of EID protocols. Durieux-Smith et al (1987) reported that 21 percent of the infants could not be screened with ABR before discharge. On the other hand, Kramer et al (1989) were able to test 95 percent of infants with ABR.
before discharge. For screening protocols that use ABR, we will use \( \text{CNT} = 10 \) percent as the model parameter; otherwise, \( \text{CNT} = 0 \) percent.

**Follow-Up Percentage**

Another important parameter that has received little attention in the literature is follow-up percentage (FU). This is the percentage of infants that are successfully followed until diagnostic testing. There has been no specific study of follow-up rates or the factors that influence follow-up success. Several studies do give some indication of follow-up, but usually without much detail as to the procedure for following infants (Mencher, 1974; Simmons et al, 1979; Stein et al, 1983; Durieux-Smith et al, 1987; Elssmann et al, 1987; Swigonski et al, 1987; van Zanten et al, 1988; Kramer et al, 1989). In these studies, follow-up percentages varied from 40 to 90 percent. Jacobson and Hyde (1986) summarize about a dozen studies (Table 5-2, pg. 93) and indicate the number of infants tested at follow-up. Follow-up percentages ranged from 32 to 100 percent with an average of 50 percent.

The author was involved with an EID program that included initial diagnostic testing at several months. Long-term follow-up success to that appointment was about 50 percent with a modest effort to recall infants for testing (Jacobson et al, 1990). Based on this very limited information, \( \text{FU} = 50 \) percent will be used for the model parameter.

**Diagnostic Protocol**

We would expect the performance of any reasonable diagnostic protocol to be quite good, although not necessarily perfect. Hyde et al., (1990) found ABR screening at several months to have excellent performance (HT/FA = 98/4 percent). More comprehensive ABR testing combined with other procedures should yield a performance as good as, or better than, ABR screening. Behavioral testing at an appropriate age should also have excellent performance. For this model, it is reasonable to assume that the diagnostic testing is definitive, that is, HT/FA = 100/0 percent. This simplifies calculations and should not introduce much error. In reality, we would expect an occasional miss or false alarm. The number, however, would be so small as to have little effect on the cost and performance of the EID protocol. In addition, the diagnostic protocol would usually be the same when comparing different screening protocols. Any errors would impact on all protocols and have little impact on their relative cost or performance.

**Costs**

To determine protocol costs, it is necessary to specify the cost of the individual components in the protocol. This would include the screening and diagnostic tests and follow-up. Specifying these costs is difficult; actual expense could vary significantly with institution. Also, there is little information in the literature as to the expense of testing and follow-up.

Costs were determined based on the time required to provide the service. It was assumed that there was a general expense of $80 per hour for any activity. What we assume for this rate is not particularly critical if our primary interest is in comparing the relative costs of different protocols. The time required per infant for each activity is given in Table 1. This was multiplied by $80/hour to determine the cost per infant tested or followed.

There is a tendency to ignore the cost of a HRR. Some minimum time is required to review charts and identify those infants to be followed or screened. Ten minutes per infant was assumed for a cost of $13. A time of 45 minutes per infant was assumed for ABR screening. This would include testing time, set-up time, travel time to the nursery, reports, and record keeping. The cost for ABR screening is $60 per infant.

A follow-up of 50 percent was specified for the model. This was based, in part, on the author's own experience with an EID program. In that program, all record keeping was performed by computer. Infants were automatically identified for follow-up with minimum labor expense. The effort to retrieve infants for testing was modest. On this basis, 10 minutes per infant was assumed for follow-up to the first visit for a cost of $13.

The final component is diagnostic testing. The actual composition of this protocol could vary significantly, thus producing a significant variation in cost. To illustrate the techniques, we will assume a particular diagnostic strategy that consists of ABR threshold testing plus some limited behavioral and immittance audiometry. Infants that demonstrate hearing loss would return for additional audiologic testing and evaluation by other professionals. This is a streamlined strategy; 2 hours are specified for
TEST CORRELATION

Test correlation is the tendency of two tests to identify the same patients the same way. Test correlation can have a significant impact on protocol performance. Limited clinical data suggest that audiologic tests that distinguish cochlear from retrocochlear site of lesion have a mid-positive correlation (Turner et al., 1984). There is essentially no information on correlation for the tests commonly used in an EID protocol.

For this model, we will assume a test correlation of zero. This means that the tests are independent; the results on one test do not influence the other. To illustrate, consider two tests, A and B. Test A evaluates a group of infants. Test B evaluates the infants that fail Test A. If the tests have zero correlation, then the hit rate and false alarm rate of Test B would be the same on the original population of infants as on the subpopulation that failed Test A. If correlation was not zero, this would not be true.

An assumption of zero correlation simplifies the calculation for the model. This assumption is reasonable for several reasons. Test correlation is only an issue when two or more tests are combined. If one of the tests has perfect performance (HT/FA=100/0 percent), then test correlation does not matter. We have assumed perfect performance for the diagnostic protocol; thus, correlation between the screening protocol and the diagnostic protocol is not an issue. The only time we must worry about test correlation is when the screening protocol consists of two or more tests. We have limited our interest to just two screening tests, HRR and ABR. The mechanics of these two tests are so different that there may, in fact, be little correlation between these tests. When these two tests are combined into a screening protocol, we will assume zero correlation.

EXAMPLE

There are two ways to determine protocol performance and cost. It is possible to derive explicit equations for the EID protocol in Figure 1 that would permit the direct calculation of HTp, FAp, CPIN, and CPHL using model parameters. These equations, however, would be fairly complex. In addition, there would be no information as to the characteristics of a protocol other than the calculated measures of cost and performance.

A second technique is to track infants through the EID protocol by calculating performance and cost at each component. Ultimately, HTp, FAp, CPIN, and CPHL are calculated, but there is much additional information provided as to the contribution of each component to the overall cost and performance of the protocol. This strategy will be illustrated by an EID protocol that uses ABR as the screening component. The model parameters from Table 1 are used.

Protocol Performance

Protocol performance is calculated first (Fig. 2). We assume that there are 100 infants in the...
nursery. The actual number of infants is not important because hit rate and false alarm rate are relative measures independent of the number of infants tested. The infants in the nursery are divided into 3 IH infants and 97 NH, consistent with a prevalence of 3 percent.

Ten percent of the infants are discharged before screening (CNT). This 10 percent is applied to both subpopulations of infants. Thus 0.3 IH infants and 9.7 NH infants are not screened. For convenience, there is some rounding of the number of infants. Thus, the 9.7 NH infants are rounded to 10.

A total of 89.7 infants (2.7IH/87NH) will be screened. The HT/FA of the screening protocol is 95/15 percent. The next step is to calculate the number of hits, misses, false alarms, and correct rejections that result from the screening protocol. The number of hits (2.6) is the number of IH infants who are screened (2.7) times the hit rate of the screening protocol (95% = 0.95). The remaining 0.1 IH infants (2.7–2.6 = 0.1) constitute the misses. Likewise, the false alarms (13) equal the number of NH infants screened (87) times the false alarm rate (15%). The remaining 74 NH infants (87–13 = 74) are the correct rejections.

The posterior probabilities can also be calculated. PPf, the probability of hearing loss in an infant who fails the screening, is simply the prevalence of hearing loss in the population of infants who fail. This is the number of IH infants (2.6) divided by the total number of infants who fail (2.6 + 13). For this protocol, PPf is 17 percent. PpP, the probability of hearing loss in an infant who passes the screen, is the prevalence of hearing loss in the infants who pass. This is less than 1 percent.

The misses and correct rejections (0.1/74) are the infants who pass the screening protocol and are no longer followed. The hits and false alarms (2.6/13) are the infants who have failed the screening protocol and are referred for follow-up. These are combined with the infants who were not screened before discharge to generate a total of 2.9 IH infants and 23 NH infants who are to be followed.

The follow-up percentage (FU) is assumed to be 50 percent for both IH and NH infants. The number that return for diagnostic testing is the number followed times FU. In this example, half the infants are followed and half are lost from follow-up. The actual number followed are rounded to 1.4 IH and 11 NH infants.

The diagnostic protocol is assumed to have perfect performance (i.e., HT = 100% and FA = 0%). Again, the number of hits (1.4) is the number of IH infants tested (1.4) times the diagnostic protocol hit rate (100% = 1.0). This means that all IH infants will be correctly identified as hearing impaired; there are no misses. The number of false alarms (0) will be the number of NH infants tested (11) times the false alarm rate (0%). All NH infants will be correctly identified as normal hearing; thus, there are 11 correct rejections and no false alarms.

The EID protocol hit rate (HTp) is the number of diagnostic protocol hits (1.4) divided by the number of IH infants in the nursery (3). Thus, we have

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HTp = \frac{1.4}{3} = 46\%.
\]

The protocol false alarm rate (FAp) is the number of diagnostic protocol false alarms (0) divided by the number of NH infants in the nursery (97). Thus,

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FAp = \frac{0}{80} = 0\%.
\]

As we would expect, the protocol false alarm rate will always be zero if the diagnostic protocol has FA = 0%.

Protocol Costs

Protocol costs for the example protocol (Fig. 3) are calculated next. To determine CPIN and CPHL, it is first necessary to calculate the total cost of the EID protocol (see Fig. 3). The parameters are the same in this example as in Figure 2. The costs of the individual components are from Table 1. Again it is assumed that 100 infants will be tested. While total cost is a function of the number of infants tested, CPIN and CPHL are relative measures independent of the number of infants. When calculating cost, it does not matter if an infant is hearing impaired or has normal hearing. Unlike when calculating performance, it is not necessary to separate the infants into an IH subpopulation and a NH subpopulation. What is important is the total number of infants processed by each component of the protocol.

There are 89.7 infants to be screened by ABR at a cost of $60 per infant. The total cost of the screening protocol ($5382) would be the number of infants screened (89.7) times the cost per infant ($60). The next component is follow-up. From the performance calculations (see Fig. 2), we see that a total of 25.9 infants are to be
followed. The total cost of follow-up ($337) is the number of infants followed (25.9) times the cost per infant ($13). A total of 12.4 infants receive diagnostic testing. The total cost of diagnostic protocol ($1984) is the number of infants tested (12.4) times the cost of diagnostic testing ($160).

The total cost of the EID protocol is the sum of the cost of the individual components ($5382 + $337 + $1984 = $7703). The cost per infant (CPIN) equals the total cost of the EID protocol divided by the number of infants in the nursery ($7703/100 = $77). The cost per impaired infant identified (CPHL) equals the total protocol cost divided by the number of total protocol hits. From Figure 2, there are 1.4 protocol hits; thus,

$$CPHL = \frac{7703}{1.4} = \$5500.$$ 

**DISCUSSION**

Modeling EID protocols serves several important purposes. It forces us to consider all components of the EID process and the factors that influence performance and cost. It is easy to focus on one aspect, such as screening, and lose sight of the ultimate objective, which is the identification of hearing-impaired infants. There is a tendency to choose an EID protocol on the basis of the screening component, not the total protocol. The model forces us to consider total protocol cost and performance, the most basic factors, when developing an EID strategy.

With this model, we have identified issues, such as follow-up, that have been largely overlooked, but that can have a significant impact on the EID process. In addition, this work has revealed deficits in the published literature as to information essential for the evaluation of EID protocols. For example, the HRR is used extensively in the ICN, but there is little information as to its performance.

With this model, it is possible to explore the relationship between model parameters and the ultimate cost and performance of the EID process. This can be accomplished by using the model to calculate cost and performance while a model parameter is varied within a range that reflects actual clinical experience. For example, how does prevalence of hearing loss influence the design of a protocol? Would we want a different protocol if follow-up percentage was low instead of high? Consideration of such issues helps provide a better theoretical foundation for the development and selection of EID protocols.

An important feature of this model is the ability to compare different potential EID protocols on the basis of cost and performance. This would be particularly useful for hospitals that are going to establish an EID program and have no previous clinical experience. While actual experience may ultimately be somewhat different than indicated by the model, the model would still provide essential information as to the advantages and disadvantages of different protocols. This type of model is the only way to generate reasonable estimates of cost and performance when clinical data are not available.

Many hospitals have implemented EID programs. This model could be used to better estimate the expense and cost-effectiveness of an existing program. The accuracy of these estimates would be a function of the parameters that were specified for the model. Care was taken when reviewing the clinical literature to
derive reasonable estimates of these parameters; however, some model parameters could vary significantly with institution. The accuracy of the model could be improved by using parameter values that better reflect local experience.

Tests other than the HRR and ABR may be used for screening. Otoacoustic emissions is one technique that is currently being evaluated for this purpose (Stevens et al, 1990). Any procedure can be incorporated into the model provided there are reasonable estimates available for hit rate, false alarm rate, and cost of testing.

This model provides a more objective basis for the selection of an EID protocol. It generates a quality and quantity of information that is not available elsewhere. This information can be combined with other important factors, not considered in the model, to produce a reasonable, defensible cost-benefit analysis.

**SUMMARY**

Ideally, the selection of an early identification (EID) protocol should be based on a detailed, quantitative cost-benefit analysis. Practical considerations make this impossible. A good alternative to a totally subjective decision process is one based on a combination of quantitative data and qualitative factors. The quantitative data can be supplied by a simple model for the EID protocol. With this model, useful measures of protocol performance and cost can be easily calculated. The model is sufficiently general to accommodate most early identification strategies including those that meet the goal of identification and habilitation by 6 months. The parameters required by the model are also specified and are based on published clinical data.

This model is provided to help audiologists select an EID protocol that is optimal for their particular situation. If local experience indicates parameter values different than those specified in this paper, then the more appropriate values should be used. Hopefully, the concepts described in this paper will result in a more rigorous, defensible strategy for the selection of EID protocols.

**REFERENCES**


