Design of medical diagnostics products: A case-study of a saliva diagnostics kit

Linden Heflin, Sarah Walsh, Miguel Bagajewicz *

University of Oklahoma, Chemical, Biological and Materials Engineering Department, 100 E. Boyd St., T335 Norman, OK 73019, USA

ABSTRACT

This paper applies a recently proposed procedure for product design [Bagajewicz, M. (2007). On the role of microeconomics, multi-scale planning and finances in product design. *AIChE Journal*, *53* (12), 3155–3170] to the design of a medical diagnostics device. The case selected is a saliva diagnostic kit to detect kidney disease, with targeted consumers of doctors, hospitals and clinics. The procedure proposes to make a connection between consumer preferences in different markets to the characteristics of the product. The procedure includes a price–demand model and maximizes the profit by simultaneously changing product characteristics and product price. A consumer preference model based on the kit performance as a function of its design was developed to assess consumer choices. The best product from the consumer point of view turns out not to be the most profitable.

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1. Introduction

Medical diagnosis currently depends heavily on information gathered from blood tests, urine tests, biopsies, and physical examination. Saliva remains a largely untapped source of medical information that can enhance diagnosis accuracy while saving the patient from some of the discomfort associated with a blood test or other more invasive procedures. Many of blood's constituents make their way into saliva, thus making saliva an indicator of the current state of the blood and the rest of the body. Many biomarkers, or substances used as indicators of biological states, can be readily found in saliva. A road map for saliva diagnosis has been already under discussion for quite some time (Kaufman & Lamster, 2002; Li et al., 2005). In this paper, we focus on detecting symptoms and levels of kidney failure with a creatinine clearance test that utilizes saliva.

Kidney malfunction currently afflicts about one in twelve Americans. It is to blame for about 80,000 deaths per year making it the ninth killer in the country. Also about a half million Americans depend on dialysis or transplanted kidneys to survive (Caldwell et al., 1994). A diagnostic tool that could catch kidney problems in its early stages can save these lives and keep people from having to endure dialysis or operations. The creatinine blood test correlates levels of creatinine with kidney failure stages.

Urine forms mainly through passive diffusion, just like saliva, so many of blood's components exchanged at the kidney are also exchanged at the salivary glands. Thus, the concentration of creatinine in the blood ought to correlate with that in saliva. Because of this similarity, it makes sense to test these metabolites (creatinine and others that may interfere with the test) in saliva, instead of in blood (AACC, 2008), as the test would be less invasive, quicker and easier to make. The smaller the concentration of creatinine, the healthier the kidney because it is sufficiently removing creatinine from the blood.

The specific goal is then to identify the right design of the creatinine clearance test, assess its false positives and false negatives for diagnosis, build a consumer model that can help sort through all the decisions about the kit that need to be made and determine both the optimal kit and the most profitable kit, while maintaining the product within FDA requirements.

The major features of the methodology rely on the ideas proposed by Bagajewicz (2007) to use microeconomics models to make connections between consumer preferences, product price and structure, composition and or functionalities. A compromise between quality of the product as perceived by the customer and profit is found as needed. This contradicts directly the premise used by alternative product design procedures, like the one proposed by Cussler and Moggridge (2001) or Seider, Seader, and Lewin (2004), who advocate the identification of consumer needs first and use those as targets in the product design procedure without any other economical consideration. In other words: the best possible product, the one that would the most preferred by consumers, regardless of price is first designed. The response to price and the manufacturing cost is assessed later. In Bagajewicz's model, all are considered simultaneously and most important, products that do not fully satisfy the customer are allowed. It is important to also

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Nomenclature

d_i	demands of the product i
GFR	glomerular filtration rate
H_{ik}	preference for product i in market k
P_{cr}	plasma creatinine concentration
p_i	price of the product i
S_{cr}	salivary creatinine concentration
w_{ikj}	weight score of the product characteristics j for product i in market k
y_{ikj}	s score of the product characteristics j for product i in market k
Y	total market consumer budget

Greek letters

α	awareness function
β	product superiority function
ρ	parameter (related to the elasticity)

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point out how this methodology fits into frameworks currently in use by several companies for product development. In particular, one should mention the Stage-Gate^TM Product-Development Process (SGPDP) to manage the product design process, once the underlying technology has been developed (Cooper, 2005). In turn, for the technology development phase Stage-Gate^TM Technology-Development Process has been recently proposed (Cooper, 2001, 2002), which deals with all the innovation phases. Although the methodology proposed by Bagajewicz (2007) can be used to scope the technology development part, it requires considerations and modeling that has yet to be completed. In fact, the method is mainly applicable to the product development phase. This phase has various stages (concept, feasibility, development, manufacturing and product marketing). The first two help shape up the product based on consumer needs, consumer surveys and tests. At this stage the method also suggests building a business case for each product option. The main assumption is that once the concept and the feasibility have been tested one product to be refined will emerge. Bagajewicz (2007) claims that consumer preferences and behavior against price, as well as manufacturing costs, all treated simultaneously can help make the pre-cut choice better at these stages, preventing decisions that can later face manufacturing roadblocks (especially cost) or marketing problems (lack of profitability for example).

Thus, instead of making the process sequential, he argues that by incorporating elements of all steps, and especially the consumer behavior, one can sort out the different product choices better. Finally, although the current methodology has been that for the conceptual and feasibility stages one wants to search for superior products by targeting consumer needs, this is not necessarily true under the scheme proposed by Bagajewicz (2007). In fact, a recent study suggested a scenario in which innovation was discouraged because of market preferences and consumer behavior towards prices (Street, Woody, Ardila, & Bagajewicz, 2008). The simple example of this work shows the same.

This article is organized as follows. First a background on saliva, and the kidney disease targeted is made. Then, the proposed test with the existing design options is discussed. Then the consumer preference model is presented followed by the determination of the optimal product from the consumer point of view. An analysis of profitability follows indicating that an alternative design is more advisable.

2. Saliva

Saliva is 98% water with some mucus and a wide variety of electrolytes (Table 1) (Aydin, 2007; Caldwell et al., 1994; Tenovuo, 1989).

3. Kidney failure test

The kidney's main responsibility is cleaning the blood of waste. A wide variety of symptoms may prompt a kidney test to be used (AACC, 2008). These symptoms are:

- High blood pressure.
- Fatigue, less energy.
- Poor concentration and appetite.
- Trouble sleeping and night time muscle cramps.
- Swollen feet and ankles.
- Puffiness around eyes, particularly in the morning.
- Dry, itchy skin.
- More frequent urination.

Saliva testing can replace the initial blood test in these situations. A positive saliva test may lead to more invasive tests, but a negative outcome could spare the patient and physician this inconvenience. When blood tests indicate elevated creatinine levels, patients are usually asked to submit urine tests. For a 24 h period, the patient collects and stores all urine they produce and returns it

Table 1
Components of saliva.

Electrolytes	Concentration	Mucus	Concentration
Sodium	32 mmol/L	Mucopolysaccharides	
Potassium	22 mmol/L	Glucose	175 μmol/L
Calcium	1.7 mmol/L	Metabolites	
Magnesium	0.18 mmol/L	Bilirubin	15 μmol/L
Copper	0.4 mmol/L	α-ketoglutaric acid	2.4 μmol/L
Lead	0.55 mmol/L	Pyruvic acid	75 μmol/L
Cobalt	1.2 mmol/L	Proteins	
Strontium	1 μmol/L	α-amylase	650–800 μg/ml
Hydrogen Carbonate	20 mmol/L	Peroxidase	5–6 μg/ml
Iodide	10 μmol/L	Secretory IgA	96–102 μg/ml
Bromide	14 mmol/L	Lactoferrin	1–2 μg/ml
Hypothiocyanate	1.2 μmol/L	Fibronectin	0.2–2 μg/ml
Nitrate	1.1 μmol/L	Cells	32 mmol/L
Nitrite	178 μmol/L		
Fluoride	68 μmol/L		
Sulfate	5.8 μmol/L		

Table 2
Kidney disease stages.

GFR	Stage	Description	Treatment
90+	1	Normal kidney function	Observe, control blood pressure
60–89	2	Mildly reduced kidney function, with urine abnormalities, indicates kidney disease	Find out why kidney function is reduced
30–59	3	Moderately reduced kidney function	Make a diagnosis with additional testing
15–29	4	Severely reduced kidney function	Plan for end stage renal failure
14 down	5	End stage kidney failure	Dialysis and/or transplant

for analytical testing. Through the use of a salivary test, the patient may altogether circumvent the use of a blood test in this sequence.

Salivary levels of creatinine share a close relationship with serum levels, with an average concentration 10 times less than serum (Lloyd, Broughton, & Selby, 1996):

$$P_{cr} = 10S_{cr} \tag{1}$$

where P_{cr} is the plasma creatinine concentration and S_{cr} is the salivary creatinine concentration.

An elevated creatinine level in the blood suggests kidney malfunction. The creatinine concentration in the blood is related to the glomerular filtration rate (GFR). The glomerulus is a web of capillaries that functions as the first interface between the blood and the kidney at the Bowman's capsule. Doctors use GFR most frequently to identify the stage of kidney disease progression. A healthy pair of kidneys will have a GFR above $100 \, mL/(min \, 1.73 \, m^2)$ (National Kidney Foundation, 2008). The reason the surface area is included is to adjust the value to body size. A GFR below 14 is a sign of end stage kidney failure. Simply put, the GFR is the rate at which toxins are removed from the body's blood. Correlations between serum creatinine concentration and GFR are available, and can be used to develop an equation relating GFR to salivary creatinine concentration. The Cockcroft–Gault equation relates the GFR to the mass and age of the patient as well as the salivary creatinine level S_{cr} (mmol/L) (Levey et al., 1996):

$$GFR = \frac{(140 - age)mass}{8150S_{cr}} \tag{2}$$

Table 2 shows the relationship between GFR and the stages of kidney disease (National Kidney Foundation, 2008). The description of the symptoms and the advised treatment is also given.

4. The test

The chemistry used in the creatinine clearance test is the Jaffe reaction which involves the combination of picric acid with creatinine to produce the so-called Janovsky complex, which has a red color (Sanders, Slotcavage, Scheerbaum, Kochansky, & Strein, 2005). A spectrophotometer tracks the extent of reaction by following the intensity of the red color. The assay also requires NaOH to provide an alkaline environment in which the picrate will form picric acid, the active compound.

There are however some expected interferences produced by other compounds. False negatives can occur due to the influence of bilirubin (Weber, Van, & Zanten, 1991). Bilirubin causes the apparent concentration of creatinine to decrease, so that a patient with a high concentration of creatinine (indicating problems) might be told that they are healthy (false negative). To decrease this influence sodium dodecyl sulfate (SDS) can be added (Lolekha & Sritong, 1994). Interference leading to false positive test results is known to occur due to the presence of acetophenone,

acetone, propiophenone, benzylacetone, cyclobutanone, cyclopentanone, cyclohexanone, and acetohexamide (Butler, 1988; Kroll, Roach, Poe, & Elm, 1987). Carbonyl compounds like pyruvic acid, α-ketoglutaric acid, oxaloacetic acid, acetone, glucose and in particular, acetoacetic acid are also known to falsely influence the Jaffe creatinine reaction (Weber et al., 1991). Glucose and pyruvic acid cause this to a much larger extent than those above and are the ones taken into account here. Pyruvic acid, however, may not be a false positive after all. It is associated with the same renal failure as creatinine is. It is also associated with hepatic failure (Diseases Database, 2008), for which very different symptoms than renal failure exist. It is also a symptom for other less common diseases (hereditary, vitamin B1 deficiency, etc.). Thus the doctor would be able to distinguish.

A salivary test has many advantages over a serum test. Because there are no blood cells in saliva and a saliva sample does not require centrifugation before testing. The saliva's ease of collection gives it yet another advantage over serum testing in that the tools are cheaper and easier to use. Before a patient can give blood, he must have the area from which the blood is drawn sterilized. The physician or nurse must then go in with a sterile needle and draw the blood. Saliva diagnostics requires a less expensive and less invasive vial.

Finally, regarding the speed of the test, it has previously been shown that 5 min of rest after eating is sufficient time for a patient's mouth to be free of food particles (Levey et al., 1999). A patient with a dry mouth may be asked to chew inert paraffin gum for up to 2 min to stimulate flow. Collecting 5 mL of saliva is simple and gives a copious amount for a saliva test.

5. Product design options

Various product designs were proposed. Two sets of criteria were used as a basis to propose different designs. It is clear that the level of minimum detectable concentration will have a big impact on product preference. The second criteria for design deals with including/excluding certain components which help to counter the effects of interfering compounds in saliva.

5.1. Minimum detectable concentration options

Two options were considered: one option sets a low minimum detectable concentration of 16.8 μmol/L, while the other sets it at 40 μmol/L. The product able to detect low concentrations of creatinine is to be used with a spectrophotometer and therefore includes standardization material. It is designed to provide information precise enough to indicate Stage 2–5 kidney failure. The second case, in which only high concentrations of creatinine are able to be detected, may be observed visually and does not need standardization material for spectrophotometry. However, this test is not sensitive enough to determine the lower stages of kidney failure.

5.2. Inclusion of anti-interference components

To deal with the interference of certain components, four options were considered which addressed the issue in different ways. The first option was to add nothing to the test to counter the negative or positively interfering components. The second option includes SDS to counter the negatively interfering bilirubin, but does nothing to deal with the possibility of positively interfering compounds. A glucose meter was included in the third option so that consumers may test their glucose level in the event that they receive a positive test result and wish to check if it may be due to abnormally high levels of glucose. The third option does not include any additives to counter negatively interfering components. The

Table 3
Design options.

Minimum detectable concentration	Inclusion of anti-interference components
Low	Option 1: No additives
16.8 μmol/L	
Stages 2–5	Option 2: SDS included to counter negative interference
Spectrophotometer	
Includes standards	Option 3: Glucose meter to monitor positive interference
High	
40 μmol/L	Option 4: SDS and glucose meter counter interference
Stages 4 and 5	
Determined visually	
Standards unnecessary	

Table 4
Weights.

Characteristic	Weight (%)
Sensitivity	25
False negative rate	26
False positive rate	27
Patient discomfort	22

- *Sensitivity*: Describes the ability of the test to detect very low levels of the target compound. The lower the detectable levels, perceivably the better the diagnosis ability.
- *False negatives*: An important parameter to evaluate for consumer preference as well as consumer safety. False negatives are test results that indicate the patient is healthy when they are actually unhealthy. They occur because bilirubin causes the apparent concentration of creatinine to decrease.
- *False positives*: An important parameter, although less crucial than the false negatives. False positives prompt the realization of an additional test. As described above pyruvic acid, present in saliva can also react with creatinine causing its apparent concentration to increase. Because this is not a false positive, unless not accompanied by other symptoms of liver failure we only worry about glucose, whose level determination might or might not be included as part of the test, depending on the design.

fourth option includes SDS and a glucose meter to manage both positive and negative interference. The various costs and preference parameters associated with each option were included in the economic analysis.

All design options are shown in Table 3.

6. FDA approval

A salivary diagnostic device falls under the FDA's regulation. The creatinine assay would be considered a medical device, which is regulated by the FDA's Center for Devices and Radiological Health (U.S. Food and Drug Administration, 2007). The first step in the approval process is to classify the device. There are three different classifications, each with differing amounts of approval required. A salivary creatinine test falls into category II, meaning that pre-market notification is required, but the much more extensive pre-market approval is not.

The main purpose of pre-market notification is to establish substantial equivalence. In the case of this device, the test must compare to a blood test and meet the following requirements:

- Must have the same intended use as the predicate; and
- Must have different technological characteristics and the information submitted to FDA:
  ○ does not raise new questions of safety and effectiveness; and
  ○ demonstrates that the device is at least as safe and effective as the legally marketed device.

Other regulations imposed by the FDA are called Good Market Practices or Quality System Regulation. These criteria must be met, and pertain to issues such as design, process control, employee training, etc.

7. Consumer preference model

The first step of the methodology is to assess consumer preferences. We use a linear weighted average of consumer preferences of specific characteristics

$$H_{ik} = \sum_j w_{ikj} y_{ikj} \qquad (3)$$

where H_{ik} is the preference for product i in market k, y_{ikj} is the score of the product characteristics j for product i in market k and w_{ikj} the corresponding weight. In our case, we use only one market, so the preference refers to a product only.

We use the following product characteristics:

The first step is to establish the value of the weights, which is done using consumer surveys. These weights are used to create a relation between the different consumer properties so that they can all be integrated and considered in a product design model. The important characteristics, along with their respective weights appear in Table 3 and where obtained using informal polls (Table 4).

We now make a scale of preferences for each of these attributes using consumer surveys. In our case, we interviewed informally doctors and patients. This approximation to the real preference profiles is useful (and inexpensive) at first to determine if a more rigorous marketing approach is warranted later. Each of these consumer identified attributes are then connected to a physical property of the test in order to influence the product design. At the end, a connection to a design option needs to be made. The conceptual undertaking of the procedure is described in detail elsewhere (Bagajewicz, 2007; Street et al., 2008). We now discuss each of the product characteristic preferences in detail.
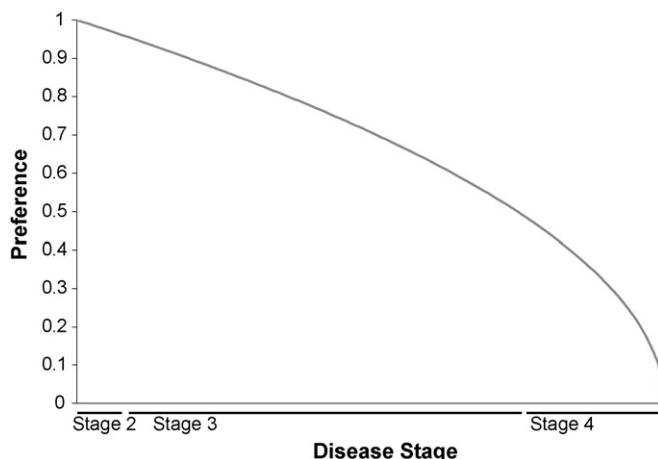

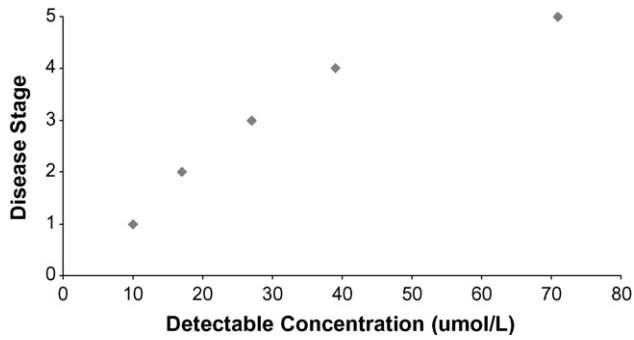**Fig. 1.** Consumer preference versus disease stage at diagnosis.

Fig. 2. Relationship between disease stage and minimum detectable concentration (Lloyd, Broughton, & Selby, 1996).

Fig. 4. Consumer preference versus percent false negative.

7.1. Sensitivity

Fig. 1 indicates how consumer preference changes with the sensitivity of the test. The sensitivity of the device is described by the patient's disease progression at diagnosis.

The sensitivity of the diagnostic device can be related to the detectable concentration limit of the test. By relating sensitivity to concentration, a qualitative measure of consumer preference can be quantified and related to a physical property of the product. Fig. 2 shows the way in which kidney disease state varies with minimum detectable concentration.

Using this relationship, consumer preference can be related to the minimum detectable concentration of the diagnostic test. This produces a curve as shown in Fig. 3.

7.2. False negatives

Fig. 4 shows the consumer response to the percentage of tests that give a false negative. The consumer preference decreases rapidly with increasing percent false negative.

As stated above, false negatives can occur due to the presence of bilirubin (Weber et al., 1991). Bilirubin causes the apparent concentration of creatinine to decrease, so that a patient with a high concentration of creatinine (indicating problems) might be told that they are healthy.

In order to quantify the percent false negatives that would occur through the use of a saliva creatinine test, it is important to determine the percentage of patients at each stage of kidney failure and the amount of bilirubin present in saliva. Fig. 5 shows the distribu-
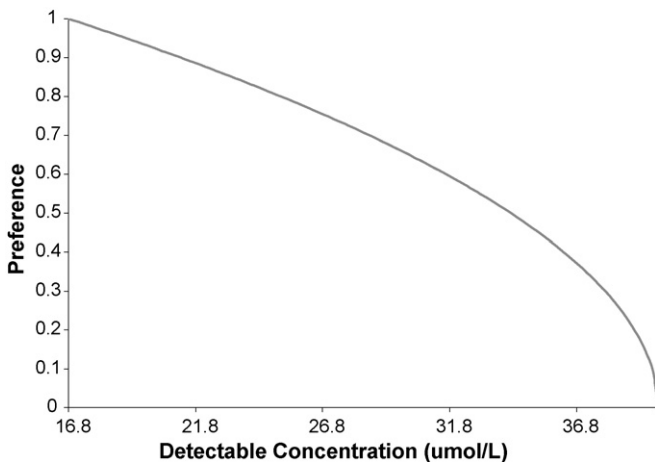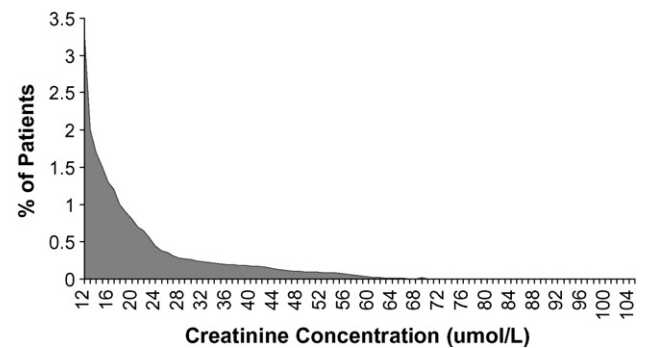

Fig. 5. Distribution of patients with specific salivary creatinine concentrations (USA Center for Disease Control and Prevention, 2005).

tion of patients having specific salivary creatinine concentrations. These concentrations correspond to glomerular filtrations rates, which correspond to the stages of kidney disease.

The average concentration of bilirubin in saliva is $15 \pm 5\,\mu$mol/L. Using a normal distribution, the percentage of patients with 10, 15, and 20 μmol/L was determined. Using data from the literature, the interference of bilirubin was found as a function of the bilirubin to creatinine concentration ratio (Weber et al., 1991). Fig. 6 shows the ratio of apparent creatinine concentration to actual creatinine concentration versus the bilirubin/creatinine ratio. From this figure, it can be seen that a bilirubin/creatinine concentration ratio of 4, for example, would
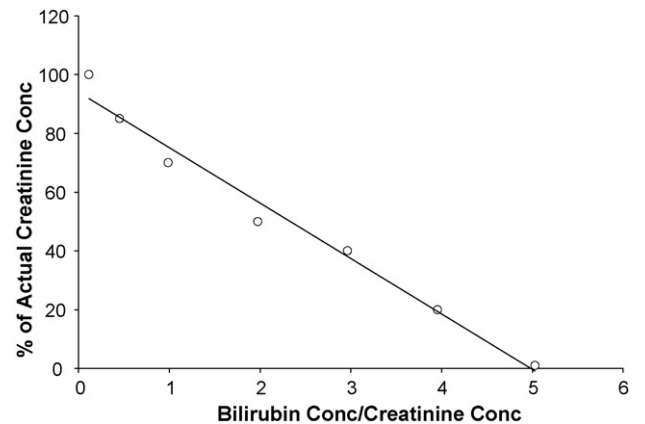

Fig. 3. Consumer preference versus minimum detectable concentration.

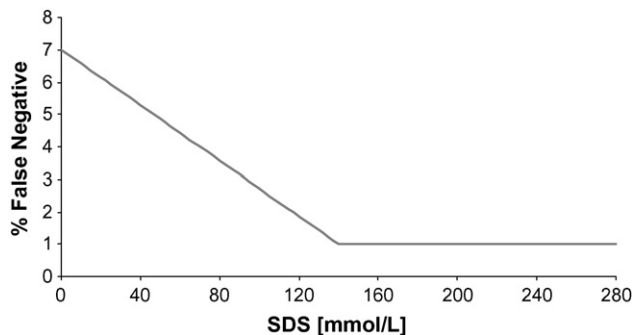**Fig. 6.** Bilirubin interference for a given [bilirubin]/[creatinine] ratio.

Fig. 7. Reduction of false negative rate due to presence of SDS.
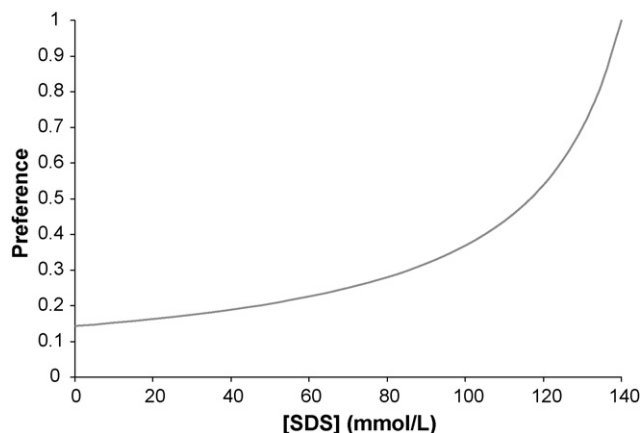

Fig. 8. Consumer preference versus Concentration of SDS.

yield a test result that is only 20% of the actual creatinine concentration present.

Using this data, the creatinine concentrations that would yield false negatives for the average and the average ± the standard deviation salivary bilirubin concentrations can be determined. Once it is known what creatinine concentrations would give a false negative result, the percentage of patients that would generate a false negative can be found using the distribution of patients previously mentioned. This gives the total percent false negative expected for this test.

It has been found that the addition of sodium dodecyl sulfate (SDS) to the reaction solution decreases the interference of bilirubin (Lolekha & Sritong, 1994). Fig. 7 shows the percent false negative versus SDS concentration. The percent false negative decreases linearly with increasing SDS concentration until a con-
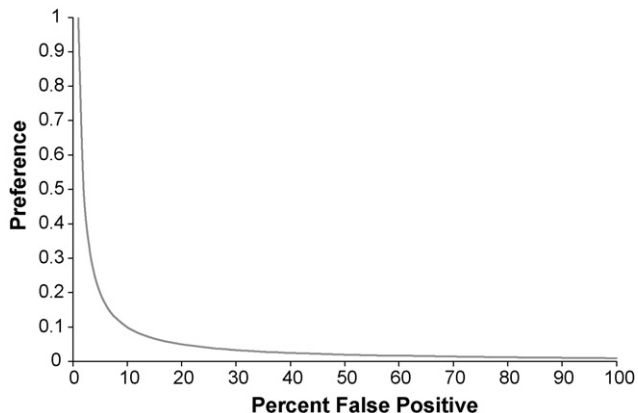
centration of 140 mmol/L where the usefulness of SDS levels off (Lolekha & Sritong, 1994). Using this relationship, the consumer preference was related to the concentration of SDS added to the reaction solution. Fig. 8 shows how consumer preference varies with SDS concentration, obtained as a composite of the previous data (Figs. 4–7). Indeed, as SDS concentration increases, the number of false negatives decreases, which increases the satisfaction.

7.3. False positives

Fig. 9 shows the consumer response to false positives. The response is similar to that for false negatives.

As described above, positive interference leading to a false positive test results is known to occur due to the presence of ketoacids and aromatic compounds (Butler, 1988; Kroll et al., 1987). From this literature, the apparent increase in creatinine concentration due to the presence of these compounds can be determined. Using the average salivary concentrations and the same data on the distribution of patients with specific salivary creatinine concentrations, the percentage of patients with the concentration of interferents required to produce a false positive result was determined. The percent false positive associated with the test turned out to be much smaller than the false negatives associated with the test. Fig. 10 shows the percent false positive versus total concentration of interfering compounds, which is linear. Fig. 11 shows the combined relationship between consumer preference and concentration of interfering compounds.

As discussed above, we only expect glucose interference. It was proposed that the addition of a glucose meter to the test kit would decrease the positive interference by allowing the user to differentiate between the concentration of glucose and creatinine. The
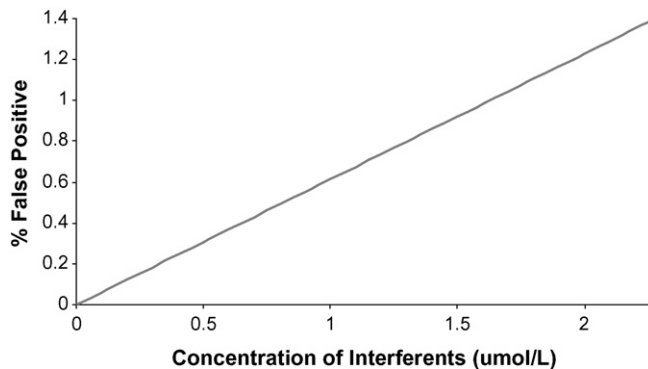

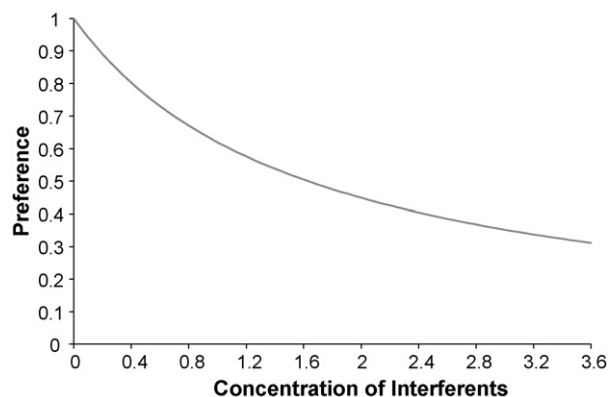**Fig. 10.** Percent false positive versus concentration of interferents.

Fig. 9. Consumer preference versus percent false positive.

Fig. 11. Consumer preference versus concentration of interfering compounds.
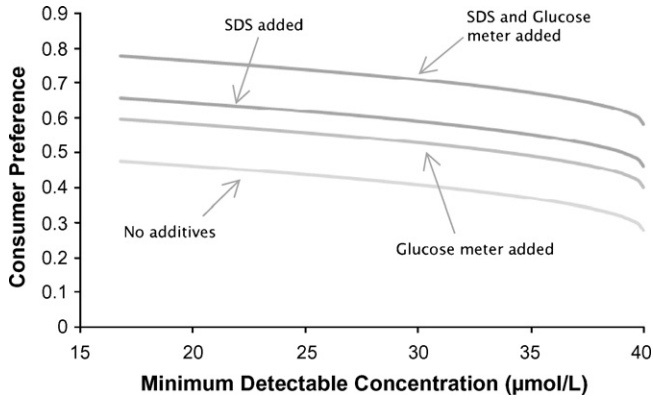
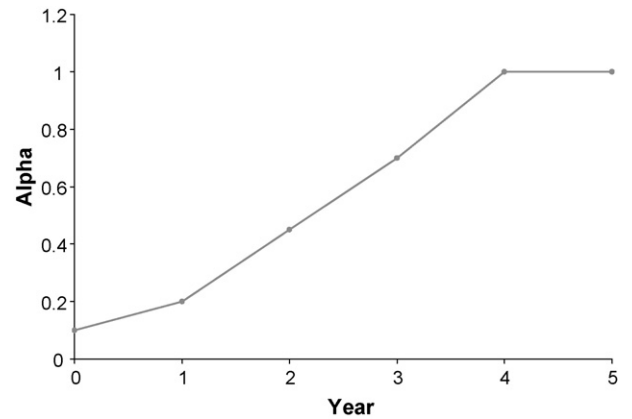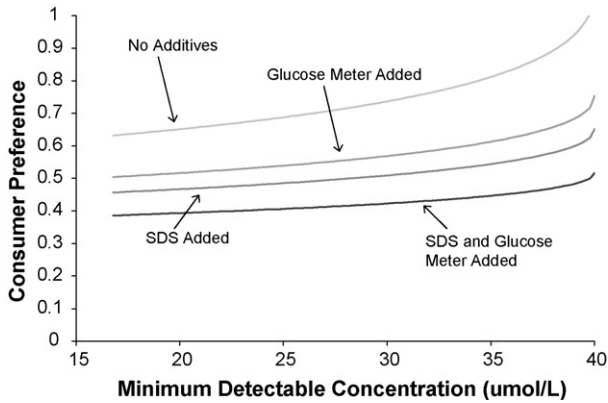**Fig. 12.** Consumer preference for various test scenarios.

Fig. 13. Consumer preference for various product scenarios.

sensitivity of the glucose test determines the final curve: if the glucose meter is added, then the false positives are reduced.

7.4. Discomfort

Consumer preference for discomfort is related to the comparison of a saliva test to a test in which blood is drawn. Here the consumer preference is 100% for the saliva test, and 50% for the blood test, indicating that half of the patients are indifferent to either test.

8. Maximum consumer preference

We now determine the product that consumers would prefer most. To do this, consumer preference (H_1) for different levels of

Fig. 15. Consumer awareness versus time.

interference was calculated using Eq. (3) and plotted for various detectable concentrations (Fig. 12). These plots were created for four interference scenarios. The first was with nothing added to decrease interference, the second with only SDS added to reduce negative interference, the third with a glucose meter used to quantify the positive interference, and the fourth with both SDS and a glucose meter.

Not surprisingly, consumer preference is maximized for the test with the minimum detectable concentration and both SDS and a glucose meter. Also, the test with SDS added has a higher consumer preference than with just the glucose meter because the negative interference has a larger effect than the positive interference. Clearly, the test with no additives yields the lowest consumer preference, because it has the most interference.

9. Pricing model

We use a constant elasticity model proposed by Bagajewicz (2007).

$$p_1 d_1 = \left(\frac{\alpha}{\beta}\right)^\rho p_2 \left[\frac{Y - p_1 d_1}{p_2}\right]^{1-\rho} d_1^\rho \tag{4}$$

$$d_2 = \frac{Y - p_1 d_1}{p_2} \tag{5}$$

In these expressions, d_1 and d_2 are the demands of the new product and the existing products, respectively and p_1 and p_2 are the corresponding prices. In turn, α is the awareness function (zero when consumers are not aware of the new product and one when they are fully aware), α is the awareness function (explained in detail below), and β is the product superiority function, which is
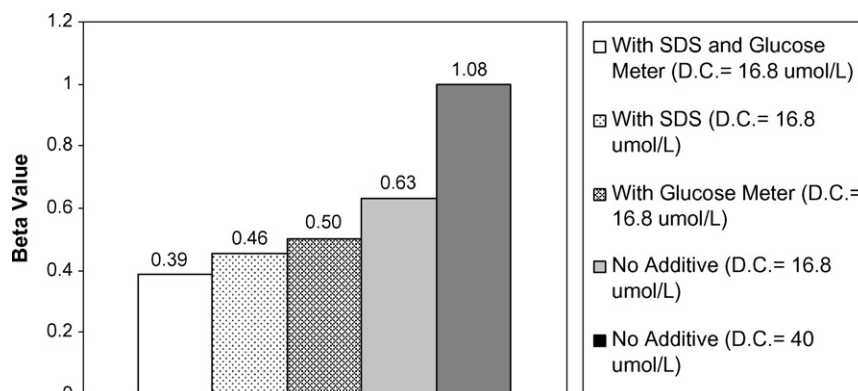

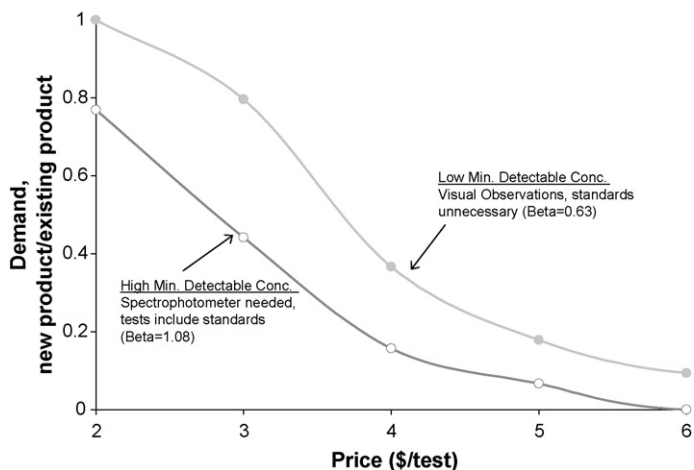**Fig. 14.** Values of β for various product scenarios.

Fig. 16. Price and demand for different minimum detectable concentrations (Product option 1: without SDS or glucose monitor).

the ratio of the consumer preferences ($\beta = H_2/H_1$). Finally ρ is a parameter (related to the elasticity; here we used 0.75) and Y is the total market consumer budget (3.6 million in our case). Bagajewicz (2007) discussed in detail the advantages and shortcomings of the above model in view of other alternatives.

10. Superiority function

We now compare the consumer preference for the saliva test to the serum test by calculating the consumer preference with the serum test and dividing that value by the various preference values for the saliva test. The consumer preference value is plotted in Fig. 13 versus minimum detectable concentration for various product options (Fig. 14).

The values of β used for the economic analysis were first chosen at the highest and lowest minimum detectable concentration, and then for the four interference scenarios.

11. Awareness function

The awareness function (α) is a function of time, advertising, and professional education. Fig. 15 gives an example of how α varies with time, ultimately reaching a value of one which indicates perfect knowledge of the new product.
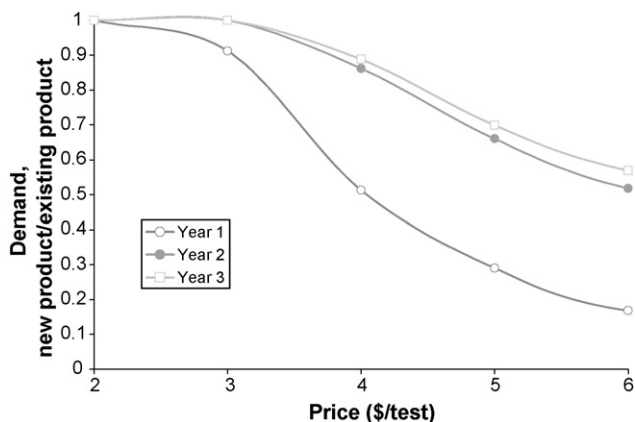

Fig. 17. Price and demand for first 3 years for one product option (low minimum detectable concentration with SDS to counter bilirubin effects leading to false negatives).
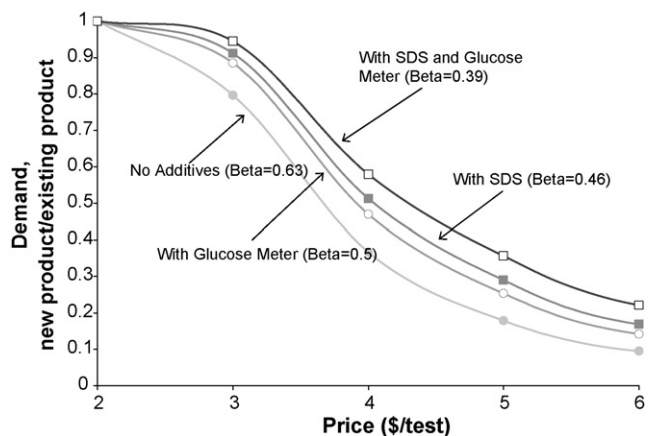

Fig. 18. Price and demand for various product options (low minimum detectable concentration).

Awareness (α) can be shifted to the left mainly through advertising thus increasing the demand for the new product. Additionally, actively spreading knowledge of the test to medical professionals will shift α even further to the left. This is not considered in this paper.

12. Demand

The demand as it varies with price is shown in Fig. 16 for both high and low minimum detectable concentrations. We consider a consumer budget (Y) of 3.6 million and a competitor price of $10 per test. The test that is able to detect lower concentrations of creatinine has a lower beta value due to the more appealing aspects of a test that can indicate earlier stages of kidney failure, causing the demand to be higher than that for the high minimum detectable concentration product.

While the demand was higher for the low minimum detectable concentration product, it was also more expensive to manufacture because of the need to include standards. Because of the cost difference, it was important to determine the net present worth by including both demand and product cost.

Demand was calculated for the first 3 years of the project for scenarios with low minimum detectable concentrations and various options for dealing with interference. Fig. 17 shows the case in which SDS was added to the product. The demand is higher in years two and three due to the increase in consumer awareness.
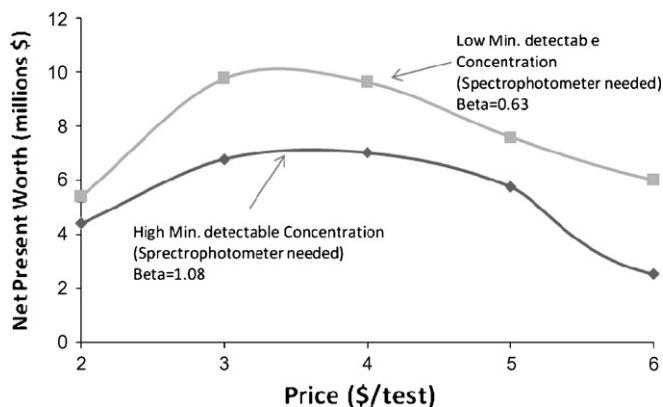

Fig. 19. NPW over 3 years for different minimum detectable concentrations (Product option 1: without SDS or glucose monitor).
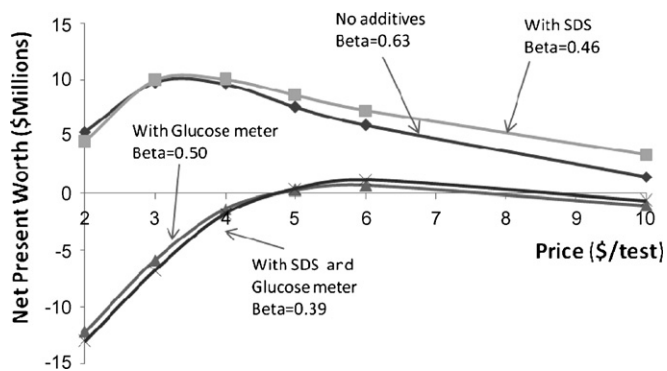
Fig. 20. NPW over 3 years for various product scenarios (low minimum detectable concentration).

In these two graphs, the decreasing trends show that consumers are less willing to choose the new product over the existing product as the price of the new product increases, even though it might have more appealing properties.

Fig. 18 shows how demand varies with price in the first year for each of the four anti-interference options. Each option was analyzed for a low minimum detectable concentration design.

The lowest demand is for the product that has no additives to manage the interfering compounds. The glucose meter is seen to be less important than the addition of SDS as indicated by the lower demand. The option with the highest demand is the one including SDS to counter the negative interference from bilirubin and also includes the glucose meter to monitor glucose levels. Lower beta values result in higher demands. However, it is again important to realize that the option with the highest demand does not necessarily correspond to one that is the most profitable due to the costs associated with adding components to the design.

13. Maximizing profit

As previously mentioned the most profitable scenario must be determined by net present worth (NPW) and not demand alone. While the demand for the product able to detect low concentrations of creatinine was higher than that of the product only able to detect creatinine concentrations above 40 μmol/L as seen in Fig. 16, the manufacturing costs were also higher. NPW accounts for both cost and demand and is plotted at different selling prices for both the high and low minimum detectable concentration scenarios in Fig. 19 (advertising effects have been ignored at this stage). To simplify our analysis, some fixed costs associated to manufacturing have been ignored. They can only shift curves up and down, so the conclusions do not change.

In this case, the higher demand for the product detecting lower concentrations was a larger contributing factor to the NPW than the higher manufacturing costs that accompanied the product. This NPW calculation determined that a product detecting lower concentrations of creatinine was more profitable.

The four anti-interference options were then applied to the low minimum detectable concentration scenario and their NPWs were determined. Fig. 20 shows how NPW for each option changes with the selected selling price. The maximum in each trendline indicates the best price for each option. Prices set too low will not bring in enough revenue to create a profit, but prices that are too high will lower the number of consumers willing to purchase the product.

As seen before, lower beta values, which indicate an increased consumer preference, correspond to greater demands. However,

lower beta values do not necessarily mean more profitable products. When factoring in the expense associated with the various options, it was determined that the most profitable option was that of the product with SDS to counter negative interferences, but without glucose monitoring. While including a glucose meter increases demand by reducing the likelihood of false positive readings, it is not the best option because the increased demand is not substantial enough to justify the large added expense. The optimum selling price is $4 per test and results in a NPW of $10 million for an ROI of 10%. Only slightly less profitable is the product with no additives sold at either $3 or $4 per test and also the product with SDS sold at $3 per test, all of which have NPWs above $9.6 million.

We now conclude that the nest step is to perform some analysis of the influence of uncertainty, especially if market information like market size (Y), consumer preferences (β), as well as consumer awareness (α) is considered in a fuzzy manner at very early stages of product development. Other extensions that need to be made are the response of the competition, multiple market pricing, etc., which is left for future work.

14. Conclusions

The use of saliva as a diagnostic fluid as opposed to blood is an obvious alternative, and has previously been shown to be applicable towards diagnosis of various diseases. The use of creatinine to diagnose kidney health is an established practice that translates well into the development of a salivary assay. In this study, it has been shown that the development and marketing of a salivary creatinine test would be a profitable venture. Through the analysis the test kit the consumers would prefer the most was shown to be less profitable than a design that would take care of the false negatives but not false positives, with high test sensitivity.

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