Designing preterm neonatal cyanosis simulation

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Abstract. Premature newborns have a lower survival expectancy than full term neonates. Determining their possible health risks is crucial. Training for health risk assessment is one of the factors that might help in lowering the mortality of premature neonates. The paper describes the design approach to develop a premature neonate simulator showing colorization of the facial skin to simulate cyanosis to be used in training sessions for health risk assessment.

Keywords: simulation, mannequin, neonate, cyanosis, design

1 Introduction

Training neonatologists and nurses in recognizing and dealing with health risks, is one of the activities that help in lowering the mortality numbers of premature neonates [11, 12, 6, 14]. A popular way to train is in team training sessions, not only focusing on the actual skills but also on team cooperation and communication. This paper discusses the design of a prototype of a premature baby manikin[1] to be used in simulation training. Simulation training for medical education using manikins is already common practice [21]. The advances in technology permit creating manikins with increasing fidelity, improving realism and meaningfulness of the training [5]. The manikin described in the paper, is to be used for training and will be able to simulate properties needed for visually determining one of the vital signs of a premature newborn child, viz. oxygenation. Other vital signs that are usually also assessed when a premature child is born will be developed at later stages and will eventually be combined in one single manikin prototype.

The structure of the paper follows the structure used for the development of the prototype. After determining the actual phenomena that are scored, the way of assessing these by the medical staff and possible interventions and the physiological factors that determine the phenomena scored are investigated and used as inspiration to explore possible solutions for simulation. A short introduction into the physics of the phenomenon is given that, together with the physiological knowledge, leads to several possible solutions for simulation of the phenomena. Selection of a limited amount of solutions is done based on user requirements,

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[1] a life-sized anatomical human model, "mannequin" is also frequently used for this

product requirements and implementation feasibility. The chosen solutions are realized and built into prototypes, later to be used to perform experiments, testing the opinions of professional medical staff with respect to the simulation of the phenomena. The outcomes of the experiments -to be performed in the future- will lead to a final choice for an implementation. In this paper we focus on the design of one element only, the skin coloring of the manikin.

2   Skin color

The oxygenation state of the neonate is one of the vital signs that needs to be monitored closely. This state is directly reflected in the skin color of the newborn. The actions performed by the medical staff to monitor this oxygenation state are discussed in paragraph 2.1, the physics of light and a description of material properties is given in section 2.2, a description of the actual physiology involved influencing the skin colorization is given in section 2.3 and the factors determining the actual perception of the skin colorization are discussed in section 2.4. These descriptions are non exhaustive and focused towards the elements that influence the assessment of a blue/pale colorization of the skin. Sections 2.5 and 2.6 show the actual combination possibilities of the elements discussed before to come to cyanosis simulation.

(a) Peripheral cyanosis (©iStockPhoto)   (b) Central cyanosis (source:[9])

Fig. 1. Cyanosis

2.1   Medical aspects

According to medical specialists, the assessment of cyanosis[2] by visual inspection is highly subjective [2, 29]. A subdivision [31] is made in central cyanosis (see Figure 1(b)) and acrocyanosis or peripheral cyanosis (see Figure 1(a)). Central cyanosis usually indicates presence of potentially serious and life-threatening disease [31]. Peripheral cyanosis is usually caused by lung problems. Newborns

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[2] blue colorization of the skin, derived from κυανός, the Greek word for blue

may suffer from cyanosis and usually this can be treated by the administration of supplementary oxygen, the application of continuous positive airway pressure, restoring ventilation and/or assisted ventilation [2]. When cyanosis is established, appropriate treatments should be instituted immediately and the cause of impaired oxygenation should be identified. We focus on central cyanosis.

2.2   Physics of light

The visible light spectrum is a very small range of wavelengths from the electromagnetic waves spectrum. Each individual wavelength represents a particular color. Purely looking at physics, the light leaving an object's surface is determined by the spectrum and angle of the incident illumination, specific light properties of the object and possibly light transmitted by the object itself [1]. The light properties of an object (like reflectivity, absorption, transmission, refraction, translucency, transparency, electro-luminescence) determine the way the incident light continues its way [1]. A light beam striking an object's material can be reflected, transmitted and/or absorbed. How much and in what directions the light leaves the surface depends on the material properties [1, 35]. Environment light is usually not monochromatic [17] and since a material can have different properties for different wavelengths of light some wavelengths will be more influenced than others resulting in reflected light with a different composition of wavelengths than the original incident light [1].
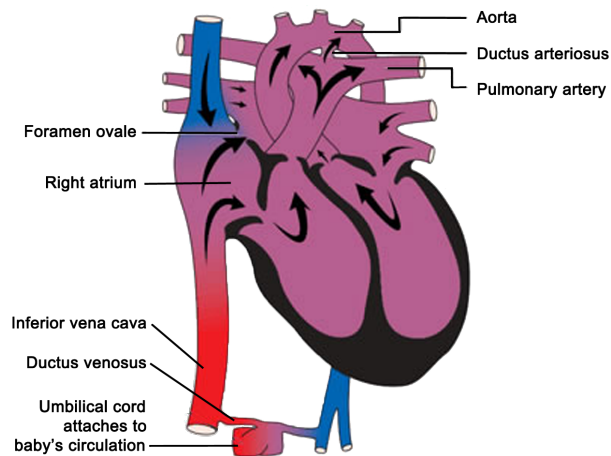

Fig. 2. Fetal circulation (source [27])

2.3   Physiology - Blood circulation

The main function of the blood circulation is to transport oxygen -bound to hemoglobin- to all the tissues of the human body [15]. Oxygenated hemoglobin

is carried from the left ventricle of the heart via the aorta through a network of ever smaller arteries and capillaries to its destinations [3]. Waste products and deoxygenated hemoglobin return to the right atrium of the heart via the network of veins. The fetal circulation, as can be seen in Figure 2, is different [18]. At birth the neonate's umbilical chord is cut and the oxygenated and deoxygenated blood circuation change, caused by aeration of the lungs taking over the oxygenation process [10] and the closure of ductus arteriosus and foramen ovale (see Figure 2). These changes all occur shortly after birth; for a term neonates usually within 24 hours [16]. In some cases the closure of the ductus arteriosus is incomplete or takes more time, upto 96 hours [24], and then deoxygenated blood is still able to bypass the lungs, causing a less optimal oxygenation, possibly causing cyanosis (see Figure 1). The slower closure (more than 24 hours) of the ductus arteriosus is typical for premature born babies [24].

2.4   Color perception

The physics of light is explained by the theory of electromagnetic waves, characterized by wavelength and intensity [35]. This theory by itself however does not fully explain what color a human perceives. Color is what is perceived when light waves collide with an object and the resulting light leaving the object is detected by the eye and processed by the brain [4]. The topics investigated in the next paragraphs serve as an inspiration for decision making and design of the cyanosis simulation of the baby manikin.

Human perception of colors starts at the color receptors (or cone cells) [4] in the eye where three different types of color receptors are present -short, medium and long cone types, also (incorrectly) named blue- green- and red-cones-, each sensitive for a specific range of colors. Signals from the red and green cones, that only capture information about the specific color range's intensity, are compared by specialized 'opponent' cells that compute the balance between red and green light coming from a particular part of the visual field. Other opponent cells compare signals from blue cones with the combined signals from red and green cones. The cones are responsible for trichromatic color vision as argued by [19], the opponent processes as described by [20] arise in the retinal ganglion cells. The information of these cells is further processed in the brain. The final 'decision' on the color observed is determined by this information, but depends on other factors (e.g. psychological factors, context) as well.

2.5   Combining physiology, physics and psychology

Deoxygenated venous blood has a greater absorption coefficient in the red spectrum than oxygenated venous blood [23]. Also the spectral characteristics of light propagation in tissue cause blue light not to penetrate as deeply into tissue as red light. The presence of deoxygenated hemoglobin in the blood vessels and capillaries near the skin surface and the light characteristics of the skin layers above these blood vessels causes the blue colorization of the human skin. Refraction and absorption properties of the skin and of deoxygenated blood make

the skin remit more blueish light in skin areas where veins with deoxygenated blood are close to the skin surface [23]. The retinex theory [25, 26] furthermore states that the remission of this area is influenced by the remission of the area around it. Yet another influencing factor is the spectral sensitivity response of the human eye, which is not uniformly distributed and thus influences the color perception. More factors can be mentioned (ambient lighting color and intensity, color of objects in the environment [28], and even psychological causes [7]). Many of these factors make the human color perception highly subjective, so although most humans have no problem in perceiving color, objective evaluation is difficult [32].

The project's aim is to create a prototype manikin usable for training the correct diagnosis of cyanosis. Some of the aspects discussed before (like ambient lighting conditions, colors of objects in the environment, observer perception variations) are out of control of the manikin to be constructed, some are controllable by defining/standardizing the environment (e.g. ambient lighting), others are not controllable at all (e.g. observer perception variations), posing some real implementation problems because the resulting perception of blue colorization has to be caused by aspects that *are* controllable in the manikin. An overview of these controllable/uncontrollable/definable aspects is given in Section 2.8.
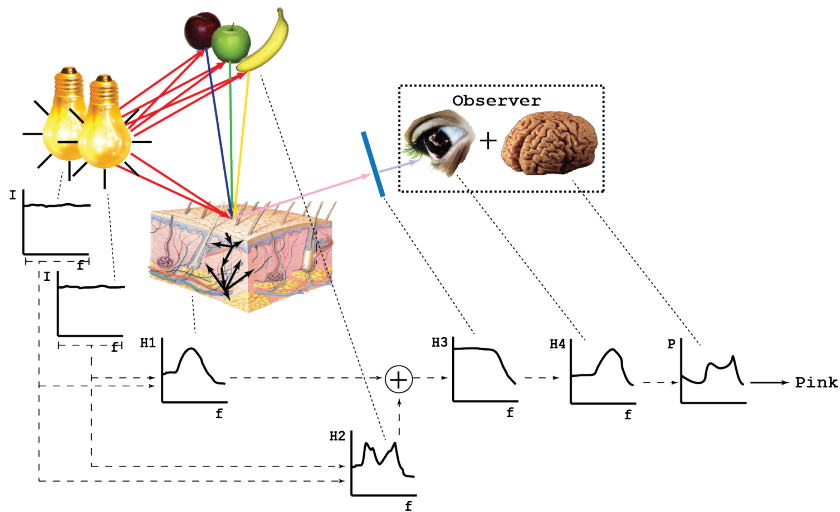

Fig. 3. One observer model

2.6   Design Explorations

The information presented so far gave a coarse overview of elementary phenomena and theories related to the actual perception of skin color. A model that

combines and depicts this is shown in Figure 3. In this figure I is used for the incoming light function, f refers to the light frequency and H refers to a transfer function altering the light spectrum. The light distribution function $I(f)$ is determined by the light source. The transfer functions $H_1(f)$, $H_2(f)$, $H_3(f)$, $H_4(f)$, and P represent the influence of skin light properties, reflecting objects in the environment, filtering, the human eye and the mind. The transfer functions and the input light distribution function are the parameters that determine the observer's perception of color and therefore are candidates for intervention. This results in 5 possibilities for intervention to influence the color perception of the manikin's skin. These possibilities are shown in Table 1.

Table 1. Five possibilities for intervention in color perception

Parameter	Intervention
Incident light	Control the incident light color spectrum
Manikin skin	Control skin light related properties
Ambient color	Control environment objects color
Filter	Control reflected light before reaching the eye
Mind	Control interpretation

Possibilities for controlling the incident color are e.g. using multiple colored light sources or beamers. An environment object's color influence is twofold. For one it acts as an object reflecting light onto the skin. This reflected light can be influenced with the same lighting techniques mentioned before, colored light sources or beamers. The second way colored objects interact with perceived color is described in Section 2.4 and offer no easy possibility for intervention. Filtering can be done e.g. by using spectacles that change color and controlling the manikin skin light properties can be done by e.g. controllable pigments or light sources underneath the skin.

Controlling interpretation means altering the processes going on in the observer's mind, and could e.g. be realized by training. Training the observers to interpret specific colorization as cyanosis *will* influence the actual color chosen to diagnose cyanosis but is not applicable for real-time control of the manikin's skin color perception. The remaining interventions from Table 1 *do* allow for interactive control. The possibilities to influence the incident lighting conditions or to influence the environment objects are less preferable because they would change the training environment, which is preferred to be as close to the real situation as possible. Also, controlling incident lighting will not provide the necessary accuracy to e.g. only change the manikin's lips color. If, for the sake of color perception only, the training participants are also seen as environment objects that reflect light onto the manikin, their mobility makes it impossible to control the environment objects. The similarity to a real environment also make the choices that need extra tools or instrumentation of the observers less preferred. The preferred approach remaining is therefore controlling the manikin's

skin light related properties. The actual step of translating this possibility to implementation is described in the next sections.

2.7   Selection

Looking at the theories and preferences described before, the possibilities all boil down to controlling the wavelength spectrum of the light received from the manikin's skin at the observer's eye. Still this allows for many possibilities. Several of these are shown in the mind map of Figure 4. As can be seen, possibil-
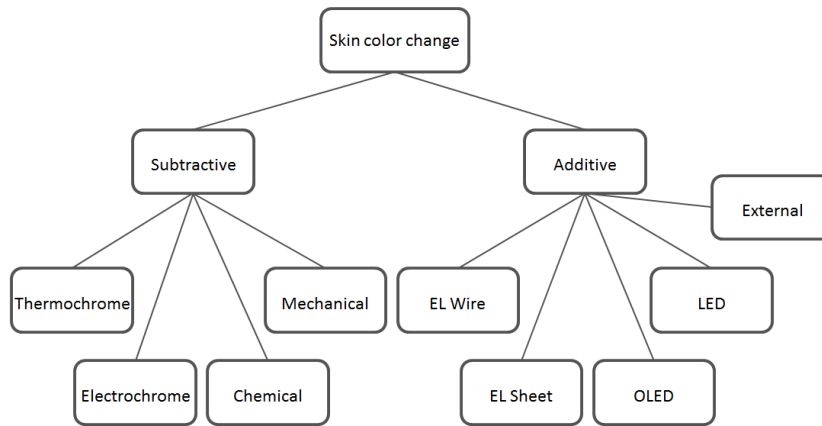
Fig. 4. Prototyping possibilities

ities exist for subtractive and additive approaches, and for each of these several possibilities are considered. A final selection is made based on initial impressions, technical and material requirements and availability. Partial prototypes are created that allow to evaluate the construction issues as well as the first impressions. The possible implementations that pass the requirements (technical, construction and impression wise) are implemented as prototypes. They could be used for experimental user validation but such formal experiments are considered outside of the scope of this paper. The additive approaches all use an 'addition' of light originating at the inside of the manikin to create the required effect. In contrast with the subtractive approach which is based on reflection, addition of light will have to be dealt with when ambient lighting changes using sensors detecting the ambient lighting conditions and adjusting the intensity of the added light accordingly.

2.8   Prototyping

To enable the choice for actually creating the partial prototypes, several semi-experimental setups for skin coloring are considered and evaluated. An overview

of the possibilities is shown in Table 2. The OLED, electro-chrome and mechanical setups were not actually constructed. OLEDs and electro-chrome displays were still in a research stadium at the time and not available for experimenting; the construction of mechanical pixels was considered to be not feasible because of the extreme miniaturization needed. Experiments done using thermochrome pigments were promising. However, in practice premature neonates are often placed under a heat-lamp for initial warmth and to prevent cooling down. This would interfere with the operation of the thermo-chrome pigments. Experiments using the chemical approach, based on litmus colorization and acidic and alkaline fluids, showed several disadvantages. Without proper sealing, fluids are easily spilled, which is disadvantageous in an environment where electronics are used. Furthermore the results were not realistic enough: the mixing of the acidic/alkaline fluids in the experiment led us to believe that this would not result in a usable solution The arguments for and against for these and the other selected methods are shown in Table 3. Besides the arguments mentioned

Table 2. Skin colorization experiments

Method	Implementation detail
Thermo-chrome	Thermo-chromatic paint and heating element in skin
Electro-chrome	Electro-chrome display below translucent skin
Chemical	Container with litmus and acid/base supply below translucent skin (see Figure **??**)
Mechanical	Mechanic pixels below translucent skin
EL-wire	EL wire below translucent skin (see Figure 6)
EL-sheet	EL sheet below translucent skin (see Figure 6)
OLED	OLED below translucent skin
LED	RGB LEDs reflecting on scattering surface below translucent skin (see Figure 6)
Beamer	Projecting on skin

there for specific implementations, the implementations based on the additive approach all are quite sensitive to environmental lighting intensity conditions, so precautions should be built in to dynamically alter the (dis)colorization in changing lighting conditions. Furthermore, independent of the implementation chosen, the manikin will be part of a bigger computer controlled system and also the manikin will have to be portable, so there is a preference for solutions that can be controlled via software and electronics, and have low power consumption. As a result of these preliminary investigations three partial prototypes are built using the EL-sheet, EL-wire and LED techniques. The initial explorations done using EL sheet are shown in Figure 5 and were quite promising and resulted in

a patent for artificial skin colorization [13]. The figure shows the EL-sheet and transformer needed to operate the sheet. The El-sheet is cut into a shape that fits around the manikin's mouth. In this way mimicking circumoral cyanosis, a frequently occurring phenomenon in cyanotic neonates [22].
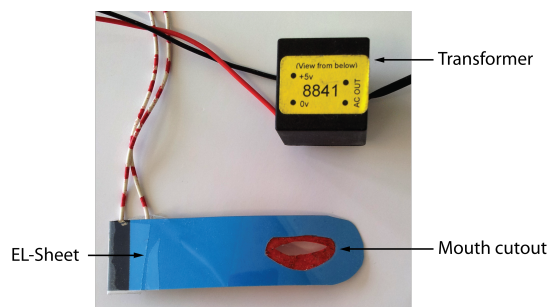
Fig. 5. EL sheet and driver transformer

For each of the partial prototypes an actual-size face of a premature baby is created using an Objet Eden 350 3D-printer [33] available at the department of Industrial Design. The remaining construction differs for each of the prototypes. For example, the EL-sheet and EL-wire are placed directly inside the head at the position of the mouth, as close to the surface as possible, because of the low light intensity of both solutions. The LEDs however are positioned further away from the surface using a diffuser between the LEDs and the surface to prevent the LEDs from being perceived as point-light sources. An impression of the preliminary head prototypes is shown in Figure 6. As can be seen, the base color of the printed material is close to white.

Looking at these pictures, one should take into account that they are taken using a digital camera and printed using a color printer. Both the camera used to take the pictures as well as the the printer will have a distorting effect on the color perceived. A camera has a different color sensitivity than the human eye and printed colors depend on printer settings and paper used. Although professional cameras and printers can be calibrated, it is likely that the impression from the picture in this thesis will be different from the actual perception of the (dis)colorization when looking at the *real* prototyped heads. Since the colors used in each different prototype are closely resembling, the distortion effect of the camera and printer are assumed to be similar so we can still compare the different prototypes to each other. Conclusions drawn later about which solution is best are best based on comparing the real prototyped heads, not on *pictures* taken from the heads. Figure 6 shows an empty head and the EL-wire, EL-sheet and LED prototypes when lit.

Tests have been done to paint the material used for prototyping the heads (see Figure 7) to come to a skin colored paint that is transparent enough to enable the skin colorization effect required. Results using Talens [34] Amsterdam

Fig. 6. All prototype heads

acrylic paint in the colors semi transparent burnt sienna, and semi-transparent zinc white delivered good results. The patches shown are painted using a brush, using an air-brush technique will lead to a smoother finishing. A comparison of
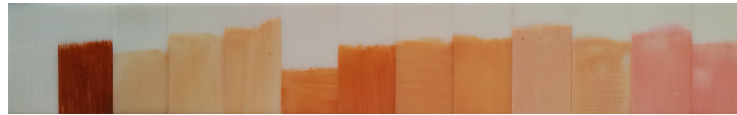
Fig. 7. Paint patches using Talens [34] Amsterdam burnt sienna, zinc white and naphtol red medium acrylic paint

the major pro's and con's of the explorations and implementations is shown in Table 3.

3   Conclusions

The best solution for simulation of cyanosis found so far is using LEDs. Their intensity and color is easily controllable using electronics, enabling a realistic cyanosis color generation. Furthermore they operate on a low voltage (2-5V). To prevent LEDs being perceived as point-sources of light, the light they emit has to be scattered using a diffuser. We found it easy to implement such a diffuser using a sheet of translucent material between the LEDs and the surface material. The additive nature of the LED-solution makes it necessary to adjust the intensity of the LEDs according to the ambient lighting conditions. This can be done by using a light sensor, causing the circuit controlling the LEDs to increase intensity if the ambient lighting intensity increases, and to decrease intensity if the ambient lighting intensity decreases.

4   Discussion

As can be concluded from this paper, decision parameters that exist for diagnosing cyanosis is based on highly subjective perception. No objective externalized

Table 3. Skin color experiment results

Method	Pros	Cons
Thermo-chrome	low voltage (3V)	inverse colorization, high power heat lamp sensitive
Chemical		contains fluids, fluid mixing
EL wire	intensity control, free form	low light emission, high voltage needed ($\approx 300V$)
EL sheet	intensity control, free form	low light emission, high voltage needed ($\approx 300V$)
LED	color control, intensity control low voltage (2-5V)	needs a diffuser
Beamer	usable for complete prototype	light easily obstructed, precision, fixed position

parameters exist. To be able to actually simulate situations that involve such parameters, objective measures need to be generated. In the case of cyanosis determination, a normalized surrounding (lighting, clothes worn, environment object colors...) and, if possible, actual wavelength determination of non-cyanotic and cyanotic skin colors might be needed to get an objective norm for cyanosis determination. Further research is necessary to investigate whether the assessment of other phenomena in determining vital signs (e.g. sound) is subjective as well.

5   Acknowledgments

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