

Colour Science for Silicone Prosthetics

By Charlie Carroll & Mabel Carroll

What is happening when we assess colour?

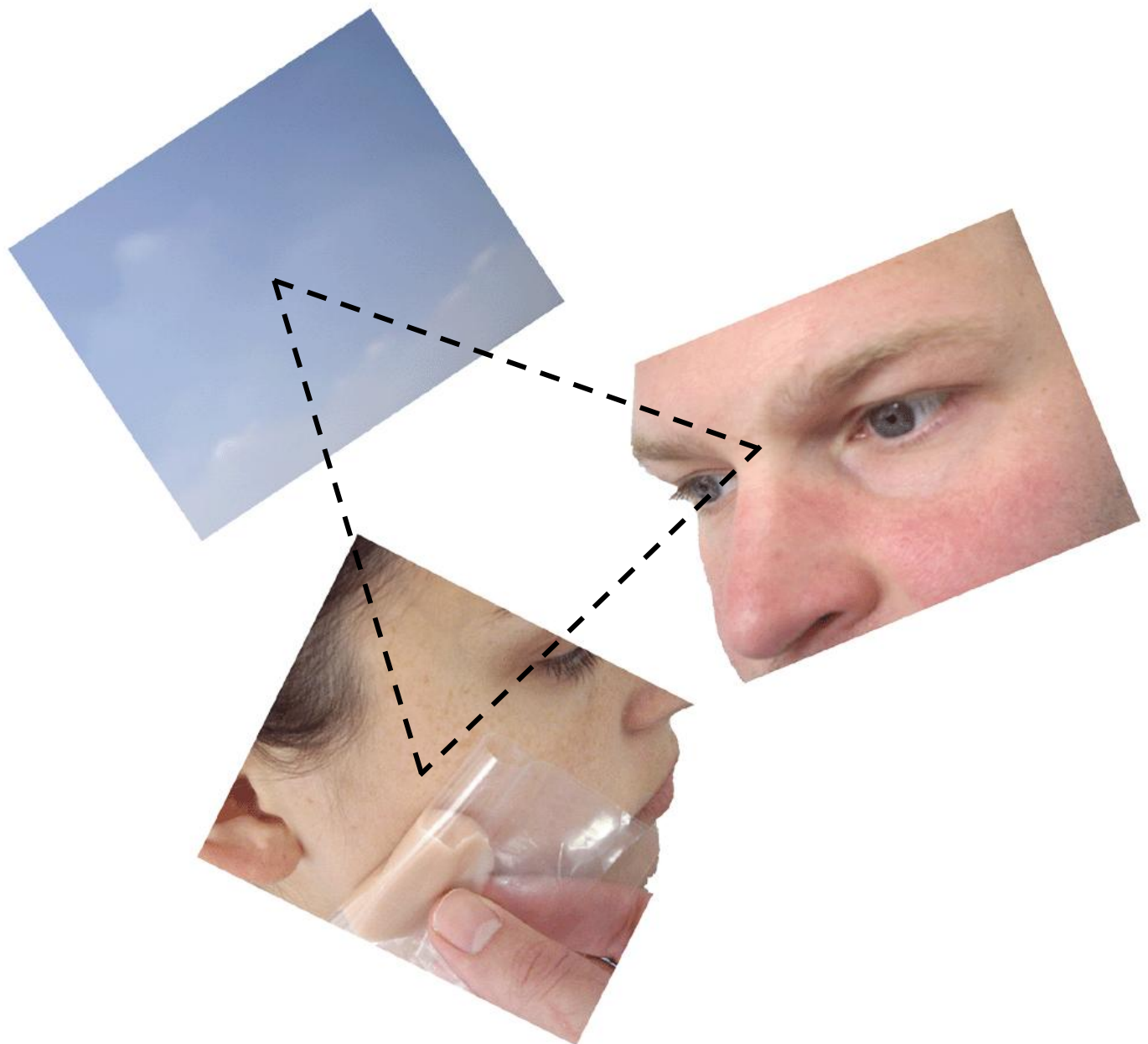


Fig 1: The three elements required for a colour sensation to be produced; light, object and observer

Introduction

Colouring silicone to match a patient's skin tone remains one of the most challenging aspects of silicone prosthetics. There are numerous optical factors that dictate the colour matching process and this makes the relationship between colouration and the resulting colour complex. This paper aims to explain these effects based on sound scientific principles to inform your clinical practice.

The three main challenges faced by the clinician are:

- We cannot use the actual colorants that make up the target skin colour.
- The colour match is expected to be maintained for all lighting conditions and observers.
- The wet material is not representative of the final cured material.

We will discuss what colour is and how each element in its perception – the light source, the clinician and the observed objects – can affect the success of the colour matching process.

We will examine the key areas where the optical properties of silicone materials will most affect the appearance of the final prosthesis.

The issues and problems that arise will be considered and where appropriate we will offer recommendations on how best to manage or mitigate the situation.

What is colour?

Colour is what we see as a physical experience in the mind of an observer. It is the result of the brain's interpretation of the stimuli received by the eye.

The experience of colour depends on three factors:

- *The light source*
- *The object*
- *The observer*

The sensation of colour in the human brain results from our eye detecting light that is reflected and transmitted from the coloured object. The light source

under which the object is viewed, the colourants in the object and the observer will all affect the colour.

A change in the light source, object or observer will result in a change in colour.

The visible spectrum

The electromagnetic spectrum covers a broad range of wavelengths including radio waves, X-rays, ultra violet and infra-red radiation. Our eyes are sensitive to only a small portion that we call light.

As most of us will have seen, when we pass light through a prism we create a coloured pattern that looks like a rainbow. This pattern is called the spectrum.

The visible light with the longest wavelengths is red and the shorter wavelengths are violet in hue. Light can be described by its relative power at individual wavelengths measured in nanometres (nm). The visible spectrum spans wavelengths between 380 and 780 nm.

In order to accurately describe or predict colour we must look at how each element is defined across the entire visible spectrum. The relative power of a light source, the spectral reflectance from an object and the relative sensitivity of the human eye can all be assessed across the visible spectrum.

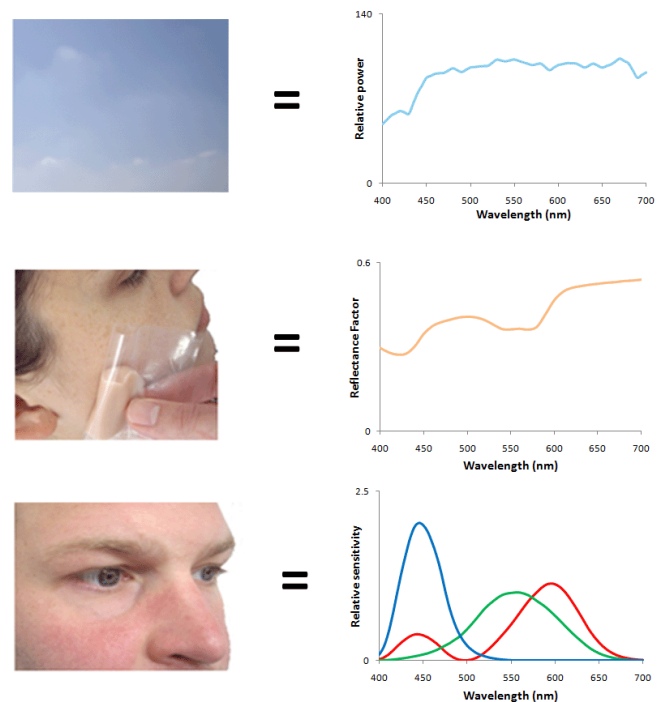


Fig 2: Shows how each element is numerically described. Each element is described across the entire visible spectrum. Light is shown as relative power, the object is shown as spectral reflectance and the observer as relative sensitivity.

Element 1: The Clinician

How our eyes respond to light

Light enters our eyes and is focused onto the retina at the back of the eyeball. There light receptors absorb some of the incoming light and create a signal that is interpreted by the brain.

There are two sets of receptors - rods and cones. For the purpose of colour perception, our discussion here will be limited to the cones. Our sensation of colour is a result of having three types of cone receptors responding to short, medium and long wavelengths of light.

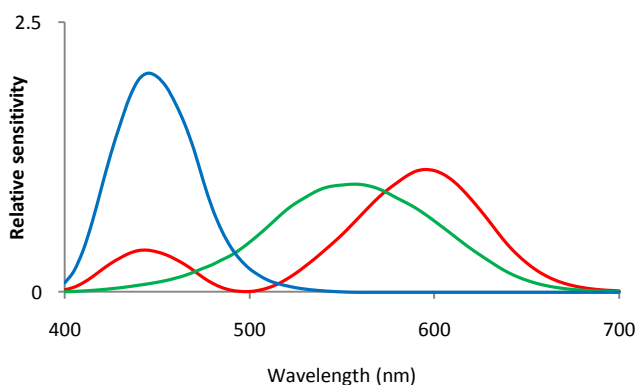


Fig 3: The relative sensitivity of the three cone receptors spanning the visible spectrum where our eyes are sensitive. It is worth noting that our sensitivity is not equal at each point and that our sensitivity trails off towards each end.

Trichromacy

The brain simplifies the response to light stimuli by aggregating the light at each wavelength across the entire visible spectrum. Thus each type of cone receptor will reduce a large amount of information to a single signal. We do this for each type of cone and the result is that our sensation of colour is reduced to just three signals. This is called trichromacy.

When two illuminated surfaces produce the same signal response in our visual system the two surfaces will be perceived as being the same colour. As the incoming light is condensed to three signals, it is possible for us to perceive the same colour from very different spectral inputs. This leads to the occurrence of the single most important aspect of skin colour matching – metamerism.

Metamerism

Metamerism is the phenomenon in which spectrally different stimuli match to a given observer. The fact

that stimuli do not have to have identical spectral properties in order to match in colour makes it possible to reproduce colours without using identical materials. It is important to understand that without metamerism a silicone prosthesis could never match a patient's skin colour!

Another example of metamerism usefulness is colour television, where three colour lights are used to represent the entire world on a screen.

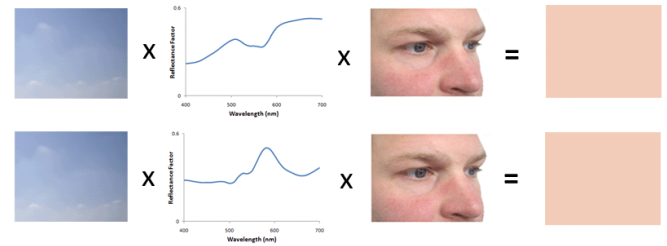


Fig 4: Metamerism means objects with very different spectral characteristics produce the same cone response and thus the same colour.

However, metamerism can also be a challenge when we observe the effect of two coloured samples matching in one situation but not in another. There are several forms of metamerism but here we will just consider the two that are most problematic for skin matching in silicone prosthetics.

Illuminant metamerism

We have all noticed how two coloured samples can appear a good colour match in the clinic room under fluorescent light but when viewed outside the colour samples do not appear to match. This effect is called illuminant metamerism.

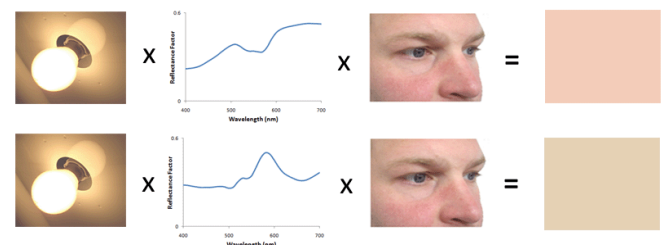


Fig 5: Shows the same coloured objects as figure 4 which would produce a match under daylight illumination. When viewed under a different light source such as a tungsten bulb the colours would appear to mismatch. This effect is called illuminant metamerism

Observer metamerism

There is a significant range of colour vision amongst different people who are all considered to have normal colour vision. Even an individual's colour vision can be affected by a number of factors including

emotional state, health and age. The consequence in colour matching of these variations is called observer metamerism.

Observer metamerism is exhibited when two colour samples match for one person but fail to match when seen by a second person. In this case the cone sensitivities of the two people are different. This can be very problematic when the two people are, for example, a clinician and a patient.

You may have also noticed the presence of observer metamerism when you record prosthesis through digital photography. This is because the colour response of camera sensors greatly differs from our eyes' colour sensitivity.

A prosthesis that matches only some of the time can cause considerable concern and distress for the patient.

Chromatic adaptation

It is an extraordinary quality of our colour vision that under everyday conditions the colour appearance of certain objects appears more or less the same when illuminated by different light sources. White paper, for example, always looks white, irrespective of the light source. Our visual system is making a compensation to account for differing illumination and this process is called chromatic adaptation.

Colour constancy

Colour constancy is closely linked to metamerism. In fact the two are often confused. Metamerism concerns a pair of colour samples while colour constancy is a property of a single colour sample.

Chromatic adaptation, allows normal colour samples to look similar when viewed under different illumination. However some colour samples appear different in differing lighting conditions and these are said to be of low colour constancy.

An example that we all may have experienced is when an item of clothing purchased in the shop as green looks brown when we go outside.

Each colour sample in a metameric pair can be considered to have a different measure of colour constancy.

Working with our visual system

We are all familiar with identifying colours with names such as red, yellow, green and blue. However, within

the name of "red" there can be a considerable range of colours which any one person might accept as being "red". These variations in perception can lead to problems when discussing colour differences.

It is a well-known fact that our visual system is very good at detecting whether colour samples match or not but it is relatively poor at estimating the degree and direction of mismatch.

This can result in the clinician tending to describe the difference between skin and the coloured silicone in terms of the effects their particular colourants might have when added to the silicone mix.

It is interesting to note that when faced with samples that are defined by a spectrophotometer as more red, yellow, blue or green these colour differences are often not recognised as such by the clinician.

Due to this limitation of our visual system, it is not uncommon for the clinician to be faced with a situation where he or she is unable to discern in what way the target skin colour is different from the coloured silicone. In this case a practical tip is to take part of the coloured silicone and divide that into three or four and to each add a single colourant from those being used. This changes the situation to one of estimating which of these new samples of coloured silicone is closest to the target - a much easier task.

The coloured silicone should be placed on or next to the target skin colour. Any gap between the silicone and skin will decrease our precision in assessing colour difference.

The background colour should ideally be similar to the colours being assessed. If this is not practical then a light mid tone grey is preferable. This should help minimize any distracting contrasts that could affect the job of assessing colour differences.

Element 2: The Lighting

General principles

When considering which light sources to use for patient colour matching two general principles apply:

- The type of illumination should exactly mimic that under which the prosthesis will be viewed.
- The level of illumination should exactly mimic that under which the prosthesis will be viewed.

In our case either principle is not straight forward. The patient prosthesis will be viewed under a large variety of lighting intensity and lighting sources. In reality the patient will never always be under just one illuminant. Figure 6 shows just how much variation there is between commonly found lighting, outside, at home, shopping or at work.

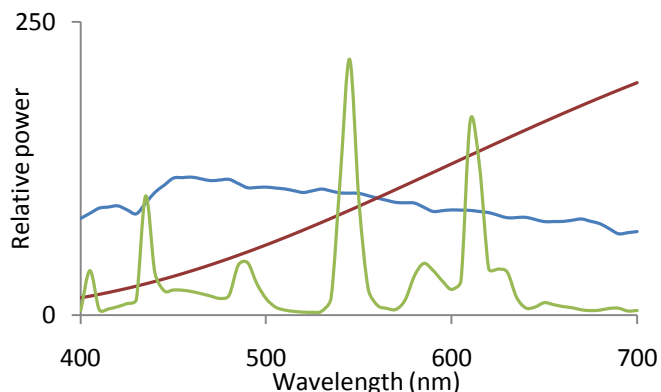


Fig 6: Shows the measured relative power of common light sources as a function of wavelength in the visible spectrum. — Daylight, — Tungsten, — Fluorescent

How the light source affects metamerism

Our discussion in the previous section on trichromacy and metamerism makes clear the importance of careful selection of light sources when colour matching. Each light source can be described by measuring the relative power at each wavelength of the visible spectrum. The amount of relative power at a specific wavelength will have the effect of either enhancing or reducing the mismatch between the spectral reflectance of the target skin colour and coloured silicone.

When the relative power of one light source is different from another it makes our visual system more or less sensitive to different areas of the visible spectrum and in turn able to pick up differences in the spectral mismatch.

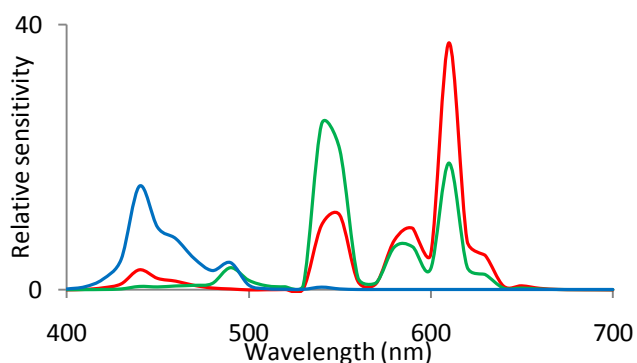


Fig 7: Shows how the relative sensitivity of our cone receptors (Figure 3) is affected by the relative power of a light source in this case a fluorescent tube.

It is a common misconception that a colour match performed under a carefully selected single light source (usually daylight or daylight simulation) will match under all other light sources. In effect matching in a single light source will only ever produce a match that is conditional to that light source and will not reduce metamerism.

How do we assess the quality of a light source?

There are a huge variety of light sources currently available. Viewing our colour match under all would clearly not be practical or possible so what information do we have available that can guide us to how each light source will influence our process?

- The colour temperature of a light source is usually expressed in Kelvins (K) that relate to the colour reference objects glow when heated. This is useful for indicating the colour of a light source - so 2500K being orange whilst 7500K being blue.
- Colour Rendering Index (CRI) is a measure of the effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant. Generally a high CRI is desirable. However, it is important to note that only lamps with a colour temperature of more than 5000K will be compared to daylight. Hence we see tungsten bulbs with very high CRI but would not necessarily mean that it would be a good light source for colour matching. The colour-rendering indices of fluorescent lighting vary greatly.
- Spectral Power Distribution (SPD) is a more accurate measure of a light source and one very rarely provided by manufacturers. This describes the light source in terms of the relative power distribution at each wavelength. Both a lamp's colour temperature and CRI are determined from measurement of the lamp's SPD. This is the only measurement that can actually show us, for example, how close a 'daylight' lamp is to real daylight as defined across the entire visible spectrum.

Working with light sources

In order to achieve as low metameric match as possible, it is essential to have a set of standardised light sources in which to assess the colour match. It is recommended that a daylight simulator, a tungsten bulb to simulate the home environment and at least one fluorescent tube to simulate the office or supermarket environment be used.

Matching the colour under two or more light sources is the only way for the clinician to establish the degree of metamerism between the prosthesis and patient without instrumental measurement.

We would advise that the patient is asked which light source is most important to them and where they are most conscious of being noticed.

Daylight simulators

If the patient specifies natural daylight as being an important light source this can be challenging. It is not practical to assume there will always be a good source of natural daylight. Moreover what do we mean by daylight? Daylight is not a fixed term and describes a huge range of colour temperatures and different SPD's affected by the time of day, orientation and cloud cover.

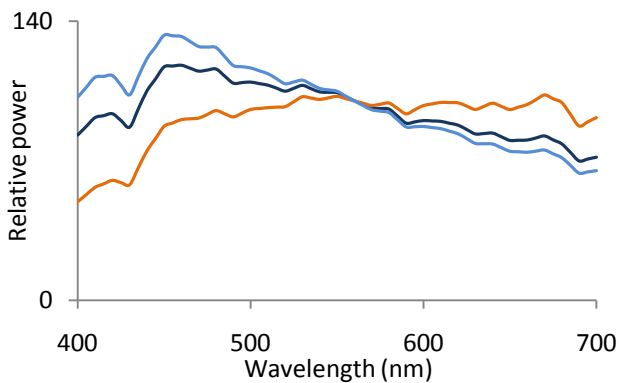


Fig 8: Spectral Power Distribution of Daylight standards — overcast sky (6500K) — sunny clear sky (5000K) — clear north sky (7500K)

Most 'daylight' bulbs designed to simulate daylight may be quite different in spectral power distribution (SPD) from any real daylight. In fact none accurately replicate the spectral power distribution of actual daylight.

Figure 9 shows two common Daylight simulators. Both have excellent CRI and the correct colour temperature but clearly have substantial spectral mismatches.

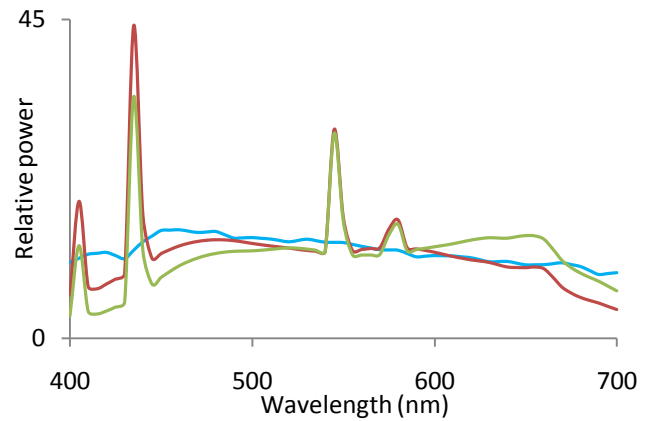


Fig 9: Spectral Power Distribution of common Daylight simulators compared to daylight — overcast sky (6500K) — F7 (6500K, CRI 90) — F8 (5000K, CRI 95)

Colour assessment cabinets

It is not always easy to view our colour match between various light sources or to standardise lamps over time and for these reasons we recommend the use of a colour assessment cabinet.

A colour assessment cabinet can be fitted with specified lamps and dimmer switches. All overhead lighting should be turned off and the patient positioned in front of the cabinet. Ideally the clinician should wait for approximately one minute between changing light sources in order for our eyes to adapt to the new illumination.

We recommend that the cabinet be fitted with a daylight simulator such as D65, a tungsten filament lamp F to represent a common domestic illuminant and at least one fluorescent tube (such as the narrow band triphosphor lamp TL84 or the cool white broad band fluorescent lamp CWF or the Ultralume narrow band triphosphor fluorescent lamp U30).

In order for our visual system to be working at optimum precision, we recommend that the intensity of illumination should be close to that of an overcast sky.

Element 3: The Coloured Silicone and Skin

How surfaces produce colour

If our perception of colour is our brain's response to light stimuli being received from the object then the colour of pigmented silicone or skin can be best understood by investigating the light as it interacts

with the surface. Let us imagine a beam of light hitting the surface of a silicone prosthesis.

As soon as the light meets the silicone surface a small amount of it is reflected away largely unchanged having had no interaction with the colourants within the silicone. The remaining light is refracted upon entering the silicone. Some of this light is absorbed by the colourants and some is scattered and then reflected out. These processes are called refraction, absorption, scattering and reflection and they determine how much light resurfaces from the coloured silicone. The combination of the reflected light from the surface and the refracted light released from within the material provides the stimuli for the colour that we eventually perceive.

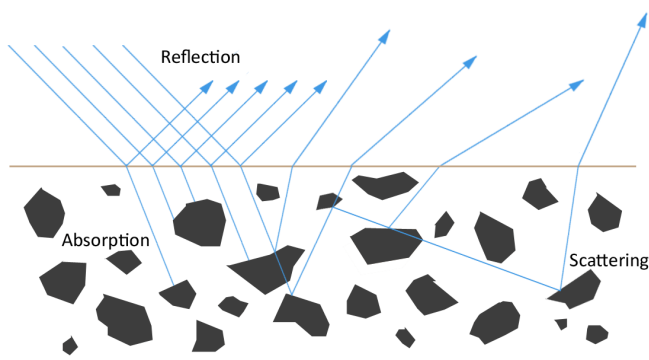


Fig 10: Process by which light is modified by a surface

Surface texture

In order to achieve a successful colour match the sample must be representative of the final material. Colour matching using wet silicone means this is not possible as the surface texture at this stage is different to that of the final cured silicone of the prosthesis.

Surface texture has a profound impact on the appearance of coloured silicone. The wet silicone is highly glossy whilst the final prosthesis has a more matt finish that is similar to real skin. The disparity in colour is a result of what happens to the direction of light that is reflected from these surfaces.

For the smooth wet silicone the reflected light is directional meaning that light is reflected at an equal but opposite direction from the light source. The cured matt silicone reflects light in a diffuse manner that is in many different directions.

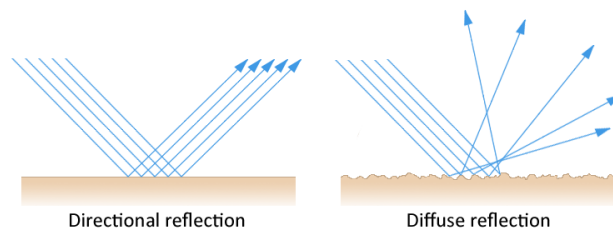


Fig 11: How surface texture affects the direction of reflected light

How surface texture affects colour appearance

When we view wet silicone we tend to angle our viewing in such a way as to avoid the reflected directional light. As the amount of reflected light does not change with a glossy surface this makes the wet silicone appear darker than the matt cured silicone. We cannot avoid the diffuse reflected light on the cured silicone thus making it appear lighter than the wet silicone.

This optical effect results in the cured prosthesis always looking lighter than its wet counterpart.



Fig 12: Shows three typical skin tones in cured silicone. The top half is smooth and glossy, the bottom half has a rougher matt finish. The affect that surface texture has on the direction of light and in turn the colour is clear to see.

The visual assessment of the colouration process is usually done by placing a small amount of the coloured silicone into a clear polythene sheet that is folded over and place against the patient's skin. It is possible to mitigate the effect of changes in surface texture by modifying the surface of a clear polythene sheet. By simply rubbing the polythene sheet lightly with very fine sandpaper the colour matching sheets will better represent the colour of the final cured silicone when viewed wet.

How colourants determine metamerism

Here we consider how we can determine the spectral reflectance of the coloured silicone. At this point it is wise to remind ourselves that the perceived colour of our prosthesis, or in fact any colour, is the result of our visual system aggregating the collective light

energy of each wavelength across the visible spectrum.

As figure 10 shows the light that leaves the layer is the result of how the incoming light has been absorbed or scattered by the colourants within the layer. How the layer absorbs or scatters the light depends on the colourants. Each colourant absorbs and scatters light differently.

It follows that every combination of colourants will have its own spectral reflectance as a result of how each colourant absorbs or scatters the light. Metamerism, as discussed earlier, means that two colours can match under a specified illumination and observer even when they are not spectral matches.

As a general principal, whenever we use different colourants from those used to make the target colour (skin) some metamerism is to be expected. The only way to limit the metamerism is through the choice of colourants used.

Colourant selection

The choice of colourants will have the single biggest impact on the level of metamerism perceived between the patient's skin and the prosthesis.

The only way to eliminate metamerism is to produce a colour match that is also a spectral match. In our situation this can only be achieved by using the exact same colourants to produce the prostheses as are present in real skin. Clearly this is not possible.

Historically, the choice of colourants used in the manufacture of silicone prostheses has, to a large extent, been passed down from one generation to the next. Whilst an excellent system in many ways, it does perpetuate the continuation of myths and misunderstandings. It is our intent to clarify the situation.

Colourant selection the hard way

Let us suppose a diligent clinician wishes to achieve a low metameric match by eye. Our clinician could achieve an accurate colour match under any one illuminant with ease. Our clinician would then assess the same sample colour under a different light source and would notice an unacceptable mismatch. The

clinician finds him or herself in a difficult situation. If they were to attempt to correct the colour for the second illuminant this would inevitably be made worse for the first illuminant.

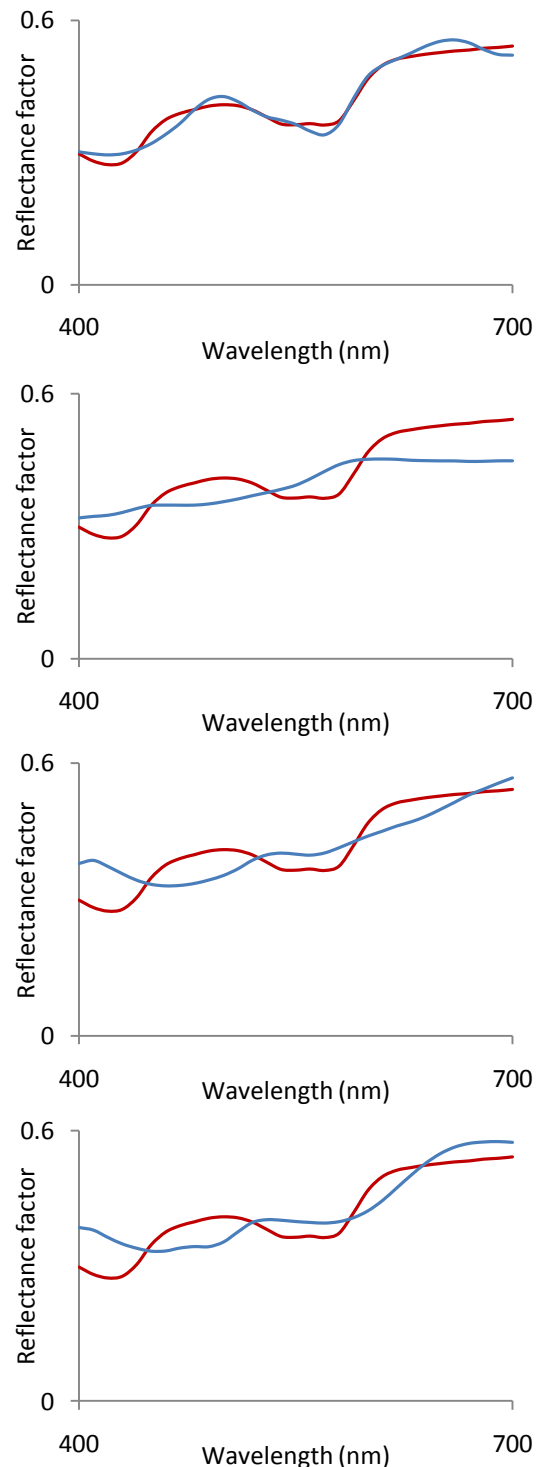


Fig 13: Shows the spectral reflectance curves for four – colourant recipes using different combinations of commonly used colourants. Each recipe matches the – target skin colour exactly for a daylight light source and standard observer. Notice how each colourant combination has substantial differences in spectral reflectance. The top graph shows the spectral reflectance curve using Spectromatch Reality Series.

At this point our clinician has no choice but to start the process from square one using a different combination of colourants to see whether a better match under both lighting conditions is achieved. The process is further complicated by the fact that more than just two light sources should be considered.

With experience our clinician may start to notice that some colourants always lead to better results but that different skin types may require completely different combinations of colourants.

Although an experienced clinician may have some ideas as to the best colourants to use, the method is generally one of trial and error and can be long and wasteful. This is clearly a very impractical situation and would be very frustrating for both clinician and patient.

Colourant selection the easy way

The process illustrated above shows us how difficult and time consuming it is to achieve low metameric matches using trial and error alone. Here instrumental measurement and digital techniques can simplify and massively speed up the selection process.

Spectromatch colour matching systems model each colourant's absorption and scattering properties as well as the strength of each colourant. This data enables the software to predict the spectral reflectance for any and every combination of colourants.

In order to find the best colourant recipe, the software uses every available combination of colourant to mathematically match the measured spectral reflectance of skin. Using trichromatic theory we calculate how well each combination of colourants matches the target skin colour under several different lighting conditions and amongst different observers.

The costs of the Spectromatch systems are sometime prohibitive to some clinics and NHS trusts. However we have utilised the powers of this technology to develop a new system of matching by eye that produces the best results short of using instrumentation and software. It is called the Reality Series and consists of ready mixed skin tone base shades.

The Reality Series base shades have been selected from a database of hundreds of measured skin tones. This enabled us to select our base shades so that they produce accurate starting points for any skin tone.

Using our recipe prediction engine we have formulated the perfect blend for each Reality Series base shade from our Expert Series pigments. This allows us to mimic the optical properties of real skin so the match is maintained when viewed under different lighting conditions and by different observers, thus greatly reducing metamerism.

Summary

We consider this a working document based on questions we have been asked when visiting clinics and talking to clinicians. We imagine that with further discussions and developments in the field of colour technology that modifications and extra information will be added periodically.

We hope that we have provided a complete practical framework for the colouration of silicones for medical prosthesis based on a sound scientific understanding of colour science. The advice and solutions we recommend have been tried and tested in clinical practice and will inform clinicians of all experience levels.

If you would like more information and practical explanation to the topics covered Spectromatch will be running courses in Colour Science for Silicone Prosthetics. Please visit our website at www.spectromatch.com to register your interest and for information on course dates.

If you have any questions relating to any of the topics covered including suppliers of recommended equipment and materials please contact charlie@spectromatch.com.

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