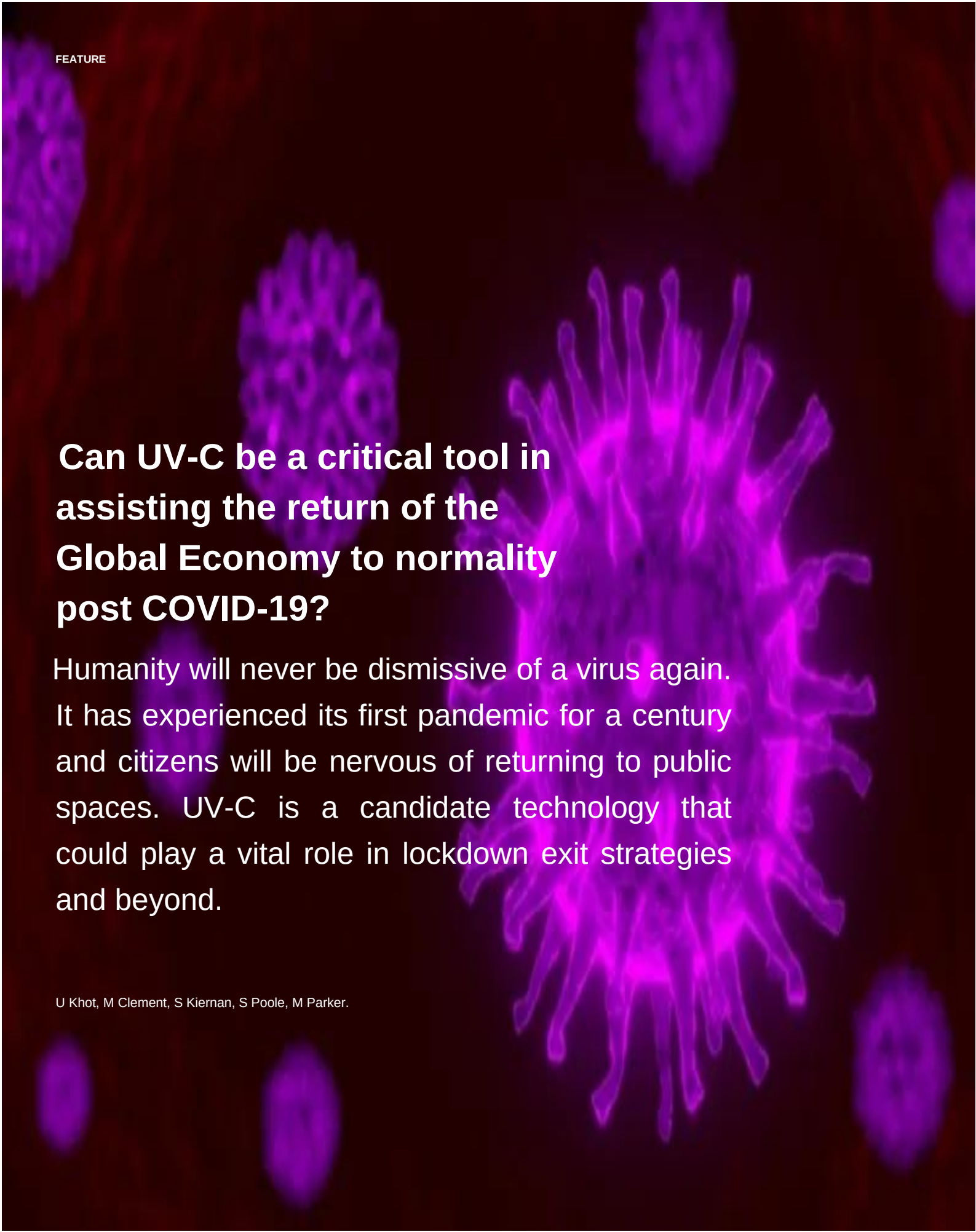


Can UV-C be a critical tool in assisting the return of the Global Economy to normality post COVID-19?

Humanity will never be dismissive of a virus again. It has experienced its first pandemic for a century and citizens will be nervous of returning to public spaces. UV-C is a candidate technology that could play a vital role in lockdown exit strategies and beyond.

U Khot, M Clement, S Kiernan, S Poole, M Parker.

A year ago, one of our authors (MC) was invited to be a speaker at the Chinese Society for Thoracic and Cardiovascular Surgery. The proposed date was in late December 2019 and the venue was the huge InterContinental Hotel and Convention Centre on the banks of the Yangtze River in Wuhan. At the time, few in the West had heard of Wuhan or Hubei province. As it happened MC was not able to travel but his colleague Professor Steve Westaby did attend and present as a keynote speaker.
On his return from Wuhan, Professor Westaby reported that rumours of an unidentified virus were emerging amongst medical experts in the conference. This mysterious illness had appeared in around 30 patients, characterised by fever, cough and pneumonia, seemingly spread by droplets. Some vulnerable patients had already progressed to severe lung failure. The Wuhan Institute of Virology had isolated a novel virus particle that they believed had originated from bats and appeared to be spreading from the vicinity of the fish market. At the date of the conference, 18th December 2019, some ventilated patients had died from hypoxia.

Figure 2 Stephen Westaby on the stage at the convention centre in Wuhan in late December 2019. The same auditorium was transformed into a hospital just three weeks later.

Since that date, the world has experienced a global pandemic the like of which has not been seen for a hundred years. Tens of thousands of people have lost their lives and healthcare systems across the globe have

Figure 1 Bridge over the Yangtze River in Wuhan

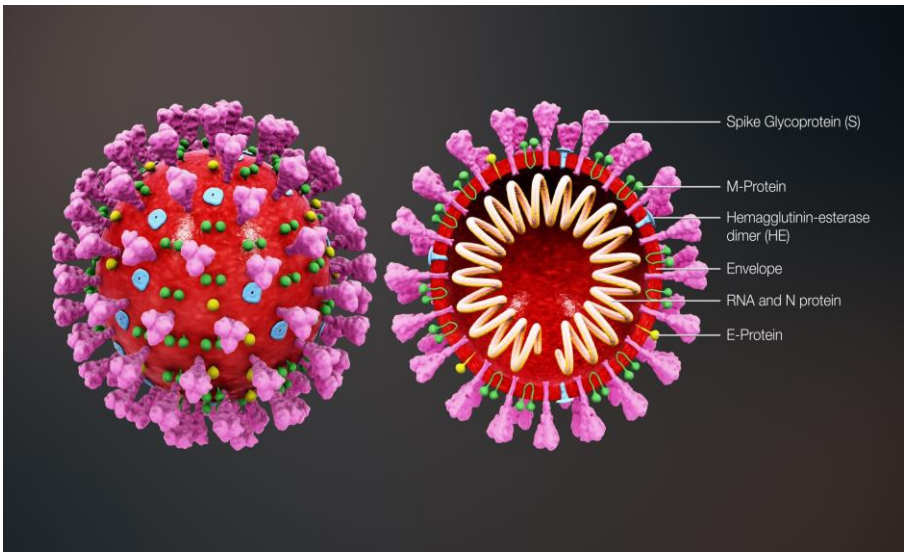
struggled to cope with the pressure on their services.
The crisis became greater due to the absence of infrastructure, technology and personal protection equipment (PPE).
Above all else the pandemic which commenced in Qtr1 2020 was a public health crisis with virtually every community suffering losses.

About COVID-19

COVID-19 is a respiratory disease caused by the SARS-CoV-2 virus. The SARS-CoV-2 is a new variant in the beta coronavirus family (Fisher 2020). It transmits like the related beta coronaviruses SARS, MERS and the four known Human coronaviruses – OC43, 229E, NL63 and HKU1. The majority of infection transmissions are believed to be by droplet spray (aerosol) from coughing and sneezing and by direct contact between humans or contact with fomites and surfaces.
Structurally, this virus is not unique and is similar to other coronaviruses such as severe acute respiratory syndrome (SARS) and Middle East respiratory syndrome (MERS). It can survive on surfaces from 6 hours to 9 days. Coronaviruses are large pleomorphic spherical particles with bulbous surface projections. The average diameter of the virus particles is around 120 nm (0.12 μm). The diameter of the envelope is ~80 nm (0.08 μm) and the spikes are ~20 nm (0.02 μm) long. The envelope of the virus in electron micrographs appears as a distinct pair of electron dense shells. The viral envelope consists of a lipid bilayer where the membrane (M), envelope (E) and spike (S) structural proteins are anchored. A subset of coronaviruses (specifically the members of beta coronavirus subgroup A) also have a shorter spike-like surface protein called hemagglutinin esterase (HE). Inside the envelope, there is the nucleocapsid, which is formed from multiple copies of the nucleocapsid (N) protein, which are bound to the positive-sense single-stranded RNA genome in a continuous beads-on-a-string type conformation. The lipid bilayer envelope, membrane proteins and nucleocapsid protect the virus when it is outside the host cell.
The global COVID-19 pandemic also brought the global economy to its knees. Global stock markets suffered huge losses with the Dow Jones falling from an index high of just over 30,000 in March 2020 to below 20,000 just five weeks later following the US lockdown representing a loss of over 35% of its value. Experts invariably disagree but in the context of the COVID-19 pandemic of 2020, they agree that the way all societies live and function will change irrevocably.
During the pandemic period much has been written about the sterilisation of surfaces exposed to COVID-19 shortly before

noninfected citizens utilise the environment. An example would be an ambulance which has recently transported a COVID positive patient and soon thereafter is required to transport a new patient. Clearly all surfaces should be sterilised before the second patient is transported. There are many other examples of potential surface exposure to the virus shortly before a non-infected individual occupies the space and comes into contact with the surfaces possibly contaminated with the virus.

Figure 3 Coronavirus cell



In the post COVID world many sectors will be confronted with the challenge of sterilising their respective environments allowing citizens and customers to occupy that space safely and come into contact with any solid surfaces. An example could be a cinema where a matinee viewing for a film would conclude, the audience vacate the environment and shortly thereafter the evening audience arrive to occupy the same space and be entertained. The movie industry is extremely worried that its traditional cinema audience will take a lot of persuasion to return to the mass viewings of film in a cinema. There are countless other examples in everyday life, including the use of an elevator, a public toilet cubicle, education classroom, public transport and many, many more.

This paper discusses one technological approach of using germicidal Ultraviolet-C irradiation (UV-C) that may play a significant role in both healthcare and in giving citizens the confidence to return to public spaces.

The entire UV spectrum can kill or inactivate many microorganisms, preventing them from replicating. UVC energy at 253.7 nanometres provides the most effective germicidal results. The application of UVC energy to inactivate microorganisms is also known as Germicidal Irradiation or UVGI.

Evidence for Germicidal UV-C

It is long established that UV light has anti-bacterial and anti-viral properties. In particular, research has shown that light in the UV-C band (100-280nm) is especially effective at killing microbes and deactivating viruses.

UV-C is widely used to disinfect water, food and drink products and in the disinfection of laboratory equipment.

Various approaches to the use of UV-C to disinfect surfaces in rooms have also been proposed. For example, simple room UV sanitisers have been developed for use in the disinfection of hospital wards and operating theatres. Such devices require manual placement and frequently need to be moved in order to disinfect an entire room. This can be time consuming and the disinfection process can take several hours.

Since UV-C light is dangerous to humans, the device operator must vacate the room whilst it is in operation and so will typically return only periodically to move the device. This in turn can compromise the sterility of the environment.

One solution has been to develop complex UV disinfection robots which can move about a room autonomously so as to irradiate the surfaces of the room. Such robots are extremely expensive, slow and require sophisticated control systems in order to map out and navigate a room. UV disinfection robots can be appropriate in certain environments (e.g. operating theatres) but are not suitable for use in smaller spaces such as vehicles or where rapid disinfection is required.

Fixed UV lamps have been proposed for use in smaller spaces which require disinfection such as in ambulances. For example, UV-C lamps can be provided in the ceiling of the ambulance which can be activated when the ambulance is not in use so as to provide some disinfection of surfaces inside the ambulance. However, unless the contents of the ambulance are removed and separately disinfected prior to activation of the UV-C lamps, the efficacy of such an approach is limited due to shadowing of the fixed light sources by the objects present in the ambulance. Removing the contents of the ambulance is very time consuming and renders the ambulance unusable for several hours. This is often unrealistic, especially in epidemic scenarios when ambulances are in high demand and yet there is also an increased need to thoroughly disinfect the ambulance between patients.

What is Ultraviolet C?

Light has been used as a therapeutic tool in healthcare over the centuries. Kaplan and Sharron developed the use of lasers in medicine in Tel Aviv in the 1970's and since then the use of sophisticated light technologies in healthcare has grown dramatically.

Experts often describe photo-medicine as falling into four categories.

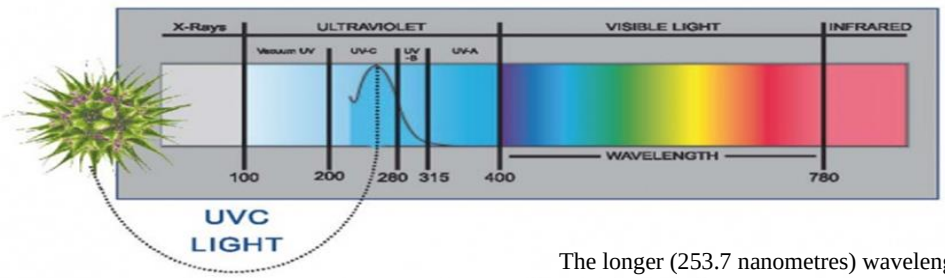
Photo-thermal: Photons in the visible and infrared region of the spectrum are converted to heat on interaction with biological tissue in order to achieve the desired therapeutic end point. Timescales of tissue interaction are in the millisecond range and an example of this would be the removal of vascular lesions by yellow light (585nm).

Photo-acoustic: A beam of light of short pulse duration, in the microsecond range is directed onto tissue in order to achieve a shockwave to destroy structures and achieve therapeutic benefit. An example of this is the use of laser light to remove unwanted tattoos.

Photo-ionisation: In this case, photons are directed onto biological tissue in a pulse of nanosecond duration. The combined energy of the photons in such a short pulse can produce a plasma and achieve the desired therapeutic effect.

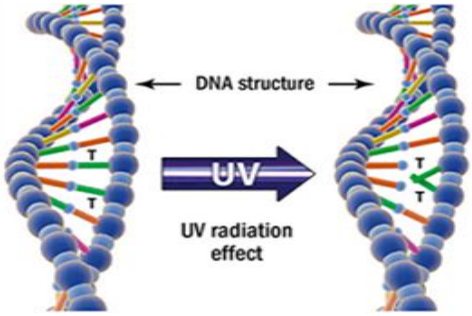
Photo-chemical: In this case the desired therapeutic effect is achieved when a single photon interacts with a chemical bond and initiates a desired change in structure. It is this that is used when UV-C is utilised to neutralise a virus in the process of photo sterilisation.

Figure 4 Light wavelength spectrum



UV-C exposure inactivates microbial organisms such as bacteria and viruses by altering the structure and the molecular bonds of their Deoxyribonucleic acid (DNA)**.** DNA is a **"**blueprint" these organisms use to develop, function and reproduce. By destroying the organism's ability to reproduce, it becomes harmless since it cannot colonise. After UV-C exposure, the organism dies off leaving no offspring, and the population of the microorganism diminishes rapidly.

Figure 5 DNA exposed to UV radiation



When exposing microorganisms to UVC light, the light penetrates through their cell wall and disrupts the structure of their DNA molecules, prohibiting reproduction.

Ultraviolet germicidal lamps provide a much more powerful and concentrated effect of ultraviolet energy than can be found naturally. Germicidal UV provides a highly effective method of destroying microorganisms.

UVV or Vacuum UV light refers to another wavelength in the ultraviolet spectrum. Some UV-C devices also produce light in this wavelength. This shorter (185 nanometres) wavelength of UVV light actually generates ozone. This occurs because UVV light reacts with oxygen to break it into atomic oxygen, a highly unstable atom that combines with oxygen to form O3 (ozone).

The longer (253.7 nanometres) wavelength of UV-C light, by contrast, provides highly effective air and surface disinfection without producing any harmful ozone.

The materials and methods of UV-C lamp construction determine whether a given UV-C device will produce both UV-C and UVV light or only the safer UV-C wavelength. COVID-19 is not the first life threatening respiratory disease to have emerged in recent times.

A disease designated severe acute respiratory syndrome (SARS-CoV) emerged in Guangdong Province China in 2002. According to WHO, 8,098 were diagnosed with SARS-CoV and 774 died of this disease during its initial outbreak of 2003.

Following the SARS-CoV outbreak, concern emerged that accidental exposure could occur in the process of laboratory research. The inactivation of cell cultures became a topic of great interest for that reason and several papers appeared in the learned literature.

Viral inactivation technologies that were researched included gamma irradiation, heat treatment, formaldehyde and glutaraldehyde treatment, pH treatment, infectivity of viral ribonucleic acid (RNA) and detergent-disruptive virions and UV treatment.

The primary interest of this paper is in investigating the potential of UV-C as a tool for virus inactivation or deactivation.

Physicists divide UV light into three categories: UV-A (320-400nm), UV-B (280-320nm) and UV-C (200-280nm). Perdiz et al. 2000 explain that UV-C is absorbed by the DNA and RNA and causes the photochemical fusion of two adjacent pyrimidines into covalently linked dimers which then become non-pairing bases. UV-B can cause a similar effect but is 20-100-fold less efficient than UV-C. UV-A is weakly absorbed by DNA and RNA and is much less effective than UV-C and UV-B.

Darnell concluded that UV-C treatment inactivated the SARS-CoV virus while UV-A had no effect on viability.

UV-C efficacy

Ultraviolet light can be an effective measure for decontaminating surfaces that may be contaminated by the SARS-CoV-2 virus by inducing photo dimers in the genomes of microorganisms. Ultraviolet light has been demonstrated to be capable of destroying viruses, bacteria and fungi in hundreds of laboratory studies (Kowalski 2009). The SARS-CoV-2 virus has not yet been specifically tested for its ultraviolet susceptibility but many other tests on related coronaviruses, including the SARS coronavirus, have concluded that they are highly susceptible to ultraviolet inactivation. This report reviews these studies and provides an estimate of the ultraviolet susceptibility.

It is estimated that the SARS-CoV-2 virus can survive on surfaces for up to 9 days, based on its similarity to SARS and MERS. Standard disinfectants are effective against SARS-CoV-2 but as an extra level of protection and to shield against errors in the manual disinfection process, ultraviolet light can be used to disinfect surfaces and equipment after the manual chemical disinfection process is completed. Ultraviolet germicidal irradiation is one strategy to address COVID-19 disease transmission (ASHRAE 2020).

COVID-19 is highly contagious and so any residual contamination, no matter how small, can pose a threat to healthcare workers and patients. Current manual chemical cleaning only reduces contamination by 36% (Armellino 2020).

Table 1 summarises the results of studies that have been performed on Coronaviruses under ultraviolet light exposure, with the specific species indicated in each case. The D90 value indicates the ultraviolet dose for 90% inactivation (log 1 kill). Although there is a wide range of variation in the D90 values, this is typical of laboratory studies on ultraviolet susceptibility. The range of D90 values for coronaviruses is 0.7-24.1 mJ/cm^2 and the average of all studies is 67 mJ/cm^2. However, the study by Walker (2007) is an airborne study and is an outlier in this set of water-based studies. Also, the studies by Weiss (1986) and Darnell (2004) are outliers on the low and high ends. Excluding outliers, the mean D90 5.1m J/cm^2, should adequately represent the ultraviolet susceptibility of the SARS-CoV-2 (COVID-19) virus.

The key parameter in question is that of energy density measured by most in units of mJ/cm^2. A number of authors have reported energy density values leading to virus inactivation.

Table 1

Microbe	D90 dose (exposure) required for log 1 reduction in mJ/cm^2	Source
Berne virus (Coronaviridae)	0.7 mJ/cm^2	Weiss 1986
Murine Coronavirus (MHV)	1.5 mJ/cm^2	Hirano 1978
Canine Coronavirus (CCV)	2.9 mJ/cm^2	Saknimit 1988
Murine Coronavirus (MHV)	2.9 mJ/cm^2	Saknimit 1988
SARS Coronavirus CoV-P9	4.0 mJ/cm^2	Duan 2003
Murine Coronavirus (MHV)	10.3 mJ/cm^2	Liu 2003
SARS Coronavirus (Hanoi)	13.4 mJ/cm^2	Kariwa 2004
SARS Coronavirus (Urbani)	24.1 mJ/cm^2	Darnell 2004
Coronavirus	0.7 mJ/cm^2	Walker 2007

Table 1 indicates UV-C inactivation rates (D90 dose) for several viruses. The dose rate of D90 translates to a log1 kill rate of 90%. In other words, if the UV-C energy density described falls on a surface then 90% of the active viruses will be rendered inactive. This is time independent which is the phenomenon of the photochemical interaction since it only takes one photon to deactivate a virus.

The probability therefore of the interaction taking place is dependent on the number of photons impingent on the surface. This photon exposure can be intense for a short time or less intense for a longer time.

Caballero et al 2004, quote a UV-C dosage of 140mJ/cm^2 to achieve a Log 3 kill. In other words, a UV-C exposure of 140mJ/cm^2 will kill 99.9% of viruses lying on a solid surface. The same paper quotes a figure of 80mJ/cm^2 for a Log 2 kill and 40mJ/cm^2 for a Log 1 kill. The authors decided to adopt the figure of 140mJ/cm^2 as their fundamental design criterion for the sterilisation of solid surfaces.

Use case: Ambulance

In order to evaluate the potential of the technology and more importantly the practicality of using UV-C to sterilise an ambulance in a realistic time and affordable cost the following design criteria were postulated.

The ideal goal would be to expose all solid surfaces to 140mJ/cm^2 thereby achieving a Log 3 kill.

Quantifying the surface area is challenging, however most ambulances are 3.7 metres long, 2 metres wide and 2.5 metres high.

The environment is cluttered with equipment and there is little space for manoeuvre.

However, if one assumes the space to be a simple cuboid then the total area is 42m^2 (two 9m^2 walls, 6m^2 floor and ceiling and 6m^2 door and cabin wall). The surface area of 42m^2 translates to 42x10^4 cm^2. To achieve a Log 3 kill then a UV-C light source capable of delivering 140mJ/cm^2 x 42x10^4 cm^2 would be required. Therefore, in order to deliver the necessary dosage to the entire area, 58,800J of UV-C light is required.

This gives a UV-C power requirement of 98W. The Wattage can be adjusted pro rata simply be extending or reducing the time, so, for a 15 minute sterilisation 65W is required and for 5 minutes 196W of UV-C light is required. This simple rationale avoids the complex reality of shadowing in the ambulance environment but also does not include the effect of reflective surfaces. Both factors vary tremendously from one environment to another. However, the authors decided to design a UV-C light source with an output of 96W to evaluate the concept.

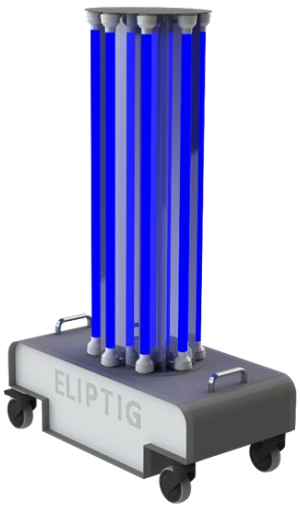
To overcome, at least in part, the effect of shadowing, a UV Orbiting elliptical light

source was designed. An acentric UV Orbit changes the directionality of the light path impingent on any obstructing object. The shadow cast by that object is then reduced by the changing angles of the light path. In addition, the UV-C light source was designed to translate along the length and variable height of the ambulance environment again changing angles and reducing shadows.

Experimental Model

A room was identified with similar dimensions to that of an ambulance, furnishings in the room including tables, chairs, computer monitors etc. which were also typical of those found in an active ambulance.

Figure 6 ELIPTIG®



The UV-C sterilising instrument (hereafter referred to as ELIPTIG®) used for the initial testing had the following specification:

- 8 vertical UV-C lamps each producing 18W of UV-C (total 144W)
- Oval supporting base plate 12in by 8in capable of rotation at variable speed
- Linear translator of 1.2m length capable of translation at variable speed
- Linear translator of adjustable height from ground to 2m

Energy was measured using an Opsytec Dr Grobel RMD Radiometer specifically designed to measure UV-C radiation. RMD features a wide dynamic range and extremely low noise. For this purpose, the sensor contains a multi-stage amplification, an extremely precise analog-to-digital converter and a temperature sensor.

The sensor memory contains all sensor identifications and the calibration history. Two UVGI sensors can be read out simultaneously. The measured data are clearly shown on the graphical display.

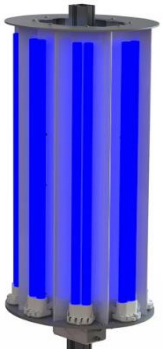
Figure 7 RMD Radiometer

Mapping the stationary optical field

The RMD Radiometer was firstly used to map the optical field of ELIPTIG® in three dimensions while ELIPTIG® was stationary. This was undertaken in two planes, a horizontal plane through the centre of the UV-C tubes of ELIPTIG® with a second plane being perpendicular again through the central axis of ELIPTIG®. All of the measurements were taken with ELIPTIG® at full power, each of the eight lamps emitting 12W of UV-C at 254nm.

The first observation was that the optical emission from the lamps takes some time to settle. At initial ignition of the lamps the output is some 40% of that settled output which is achieved 3 minutes post ignition. The 3 minute settling delay is reduced if the lamps are utilised soon after a previous illumination. This is due to the fact that they retain some thermal energy for a period, for example if reignited within 5minutes then the settling time can be less than 2 minutes. However, for all results quoted in this paper the lamps were ignited 3 minutes before any measurements were taken. This observation will have relevance to the germicidal usage of UV-C lamps. Figure 9 shows the results of the measurements taken to map the UV-C horizontal optical field.

Figure 8 ELIPTIG® lamp configuration



As one might expect the field is circularly symmetrical. Four “optical isobars” were selected to illustrate the power density within the fields namely 1.67mW/cm^2, 0.48mW/cm^2, 0.28mW/cm^2 and 0.17mW/cm^2 which coincide with the level of illumination at 0.5m, 1m, 1.5m and 2m respectively from the outer surface of the ELIPTIG® perimeter.

Further measurements along the 0^0 line with the RMD Radiometer measuring accumulated energy density gave the following results.

Table 2

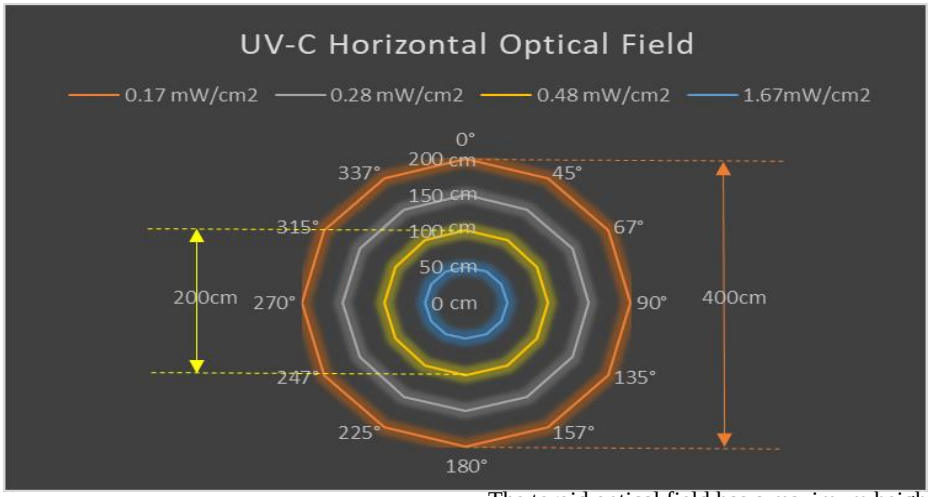
Distance cm	Power mW/cm^2	Time to Cumulative Energy seconds			
		60 mJ/cm^2	100 mJ/cm^2	120 mJ/cm^2	140 mJ/cm^2
50	1.67	38	62	74	86
100	0.48	132	220	264	309
150	0.28	226	377	453	530
200	0.17	372	621	745	872

The results show that any surface 50cm from the centre of the outer envelope of ELIPTIG® would receive the Log 3 germicidal dose in 86s. A surface 1m distant from the centre of the outer envelope of ELIPTIG® would achieve the same Log 3 germicidal effect in 309s i.e. a little more than 5 minutes.

If ELIPTIG® itself has a minimum radius of 10cm then all surfaces within a radius of 60cm will be sterilised within 1 minute and 26s and all surfaces within a radius of 1.1m will be sterilised within 5 minutes and 9s.

If one assumes that a Log 2 kill can be achieved with 80mJ/cm^2 and if that threshold were acceptable then the sterilisation of a

Figure 9 UV-C Horizontal Optical Field



radius of 0.6m could be achieved within 50s, 1.1m in 2 minutes and 56s and a radius of 1.6m in 5 minutes and 1s.

In the case of a Log 1 kill assuming the germicidal threshold to be 40mJ/cm^2, then a 1.6m radius could be sterilised in 2minutes and 30s and even 2.1m in 4minutes and 8s.

The results of the measurements taken to map the vertical optical field are shown in Figure 10.

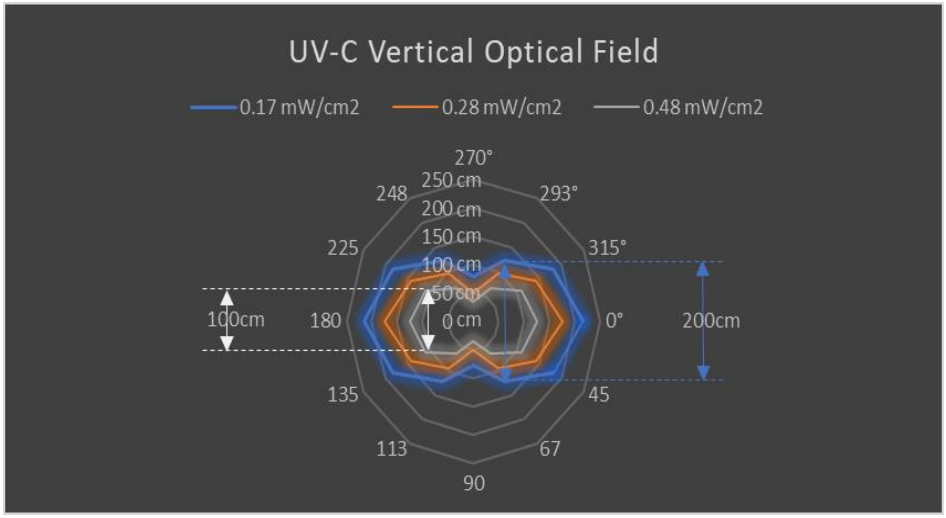
The measurements demonstrate the toroidal nature of the field when viewed in the vertical plane. In this case three power density optical isobars are shown namely 0.48mW/cm^2, 0.28mW/cm^2 and 0.17mW/cm^2 .

ELIPTIG® itself is 50cm high but the results show that the optical field extends above and beneath the extremities of the device.

The toroid optical field has a maximum height of 200cm for the 0.17mW/cm^2 optical isobar and 100cm for the 0.48mW/cm^2 optical isobar. A key feature of this result is the significant extension of the optical field beyond the plane of ELIPTIG® both above and below. This is because of the nature of the light emitted from the UV lamps which are neither coherent or columnated as would be the case in a laser for example.

The result is that this optical field topography allows sterilisation of the floor beneath the plane of ELIPTIG® and the sterilisation of the hidden surface beneath a table or gurney/stretcher when ELIPTIG® is positioned close to the ground. Furthermore, when ELIPTIG® is positioned let us say at shoulder level, then the same optical field

Figure 10 UV-C Vertical Optical Field



configuration sterilises the surface of a desk or the bed of the gurney/stretcher whilst also illuminating and sterilising the ceiling.

In this case ELIPTIG® was placed with its baseplate 5cm above the floor with its lamps positioned vertically. The RMD Radiometer was positioned on the floor looking vertically upward in order to quantify the germicidal effect of the UV-C illumination on any virus resting on the surface of the floor. Initially ELIPTIG® was stationary and not rotating. The direct illumination of the floor experiment gave the following results.

Table 3

Distance cm	Power mW/cm^2	Time to Cumulative Energy seconds			
		60 mJ/cm^2	100 mJ/cm^2	120 mJ/cm^2	140 mJ/cm^2
25	1.3	50	82	98	114
50	0.55	118	194	232	270

The results show that any floor surface receives significant illumination despite being at an angle to the ELIPTIG® plane. A point on the floor 25cm beyond the outer envelope of ELIPTIG® and 5cm below the baseplate receives 1.3mW/cm^2 of UV-C light. A Log 3 germicidal effect can be achieved at that 25cm point in 114s. A floor surface 50cm beyond the outer envelope of ELIPTIG® would achieve the same Log 3 germicidal effect in 270s i.e. 4 minutes and 30s.

If ELIPTIG® itself has a minimum radius of 10cm then the floor would be sterilised to a distance of 60cm on both sides of ELIPTIG® within 4 minutes and 30s.

It is important to note that not only does ELIPTIG® illuminate at an angle downwards towards the floor but also upwards sterilising underneath surfaces that maybe horizontal, such as tables, chairs and stretchers/gurneys.

This experiment was then repeated with ELIPTIG® both translating horizontally and rotating about its axis. The RMD Radiometer was placed on the floor looking vertically upward 25 and 50 cm perpendicular to the centre of the linear translator.

In this experiment the RMD Radiometer is placed at a fixed position on the floor. ELIPTIG® starts at one end of the translator and then progresses horizontally past the RMD

Radiometer to the other end of the translation path before returning to complete a cycle. Two translation speeds were tested. Firstly, the speed of translation was 0.5m in 18.6s and the following results were achieved.

Table 4

Distance cm	Power mW/cm² Average	Time to Cumulative Energy seconds			
		60 mJ/cm²	100 mJ/cm²	120 mJ/cm²	140 mJ/cm²
25	1.05	62	108	125	151
50	0.41	159	267	320	376

Secondly, translation speed of 0.5m in 90s and the following results were achieved.

Table 5

Distance cm	Power mW/cm² Average	Time to Cumulative Energy seconds			
		60 mJ/cm²	100 mJ/cm²	120 mJ/cm²	140 mJ/cm²
25	1.10	59	108	121	150
50	0.43	152	266	309	374

Any point on the floor receives a germicidal dose in a longer time period than that achieved by a stationary ELIPTIG® directly perpendicular to that point. This is clearly the case since the translating ELIPTIG® at some point in its pathway is further away from the point of interest. However, the average power does not decrease as much as one might expect. ELIPTIG® would give optimal power of 1.3mW/cm² when stationary and perpendicular to the point of measurement compared to an average power of 1.1 mW/cm2 when making multiple passes through that perpendicular point. It is also important to note that the speed of translation has minimal effect.

These results hold not only for ELIPTIG® translated close to the floor but also for the situation where the translator might be 2m off the ground where the angular light is sterilising the ceiling. Figure 11 illustrates ELIPTIG® in full extension mode.

A further experiment placed the RMD Radiometer at an angle to the direction of translation of ELIPTIG® in order to mimic surfaces that are not perpendicular to the direction of travel or illumination.

Figure 11 ELIPTIG® in full extension mode.

ELIPTIG® was translating at the speed of 0.5m in 18.6s and rotating at 1 rotation every 30s. The following results were achieved.

Table 6

Distance cm	Power mW/cm²		Time to Cumulative Energy seconds			
	Max	Min	60 mJ/cm²	100 mJ/cm²	120 mJ/cm²	140 mJ/cm²
95	0.39	0.33	211	369	429	569
100	0.45	0.35				
124	0.20	0.15				

In this worst case example, a surface inclined at an angle to the translating and rotating ELIPTIG® and 1m distant from its centre point receives the 140 mJ/cm² log 3 germicidal dosage in 9 minutes and 29s.

Discussion and Conclusions

The key parameter which dictates both the efficacy and practical applicability of UV-C as a solution to the rapid and safe sterilisation of spaces is the germicidal threshold measured in mJ/cm². This threshold is dependent on the prescribed kill rate for the environment in question. This study has assumed that a Log 3 kill rate is the desired outcome and that the target germicidal threshold is therefore 140mJ/cm².

It is questionable whether or not traditional methods have been validated scientifically and indeed as mentioned earlier *"Current manual chemical cleaning only reduces contamination by 36% (Armellino 2020)"*.

During the COVID-19 pandemic of 2020 and particularly as the first wave of the crisis started to ebb, many workers turned their attention to technologies that could assist the "new world order".

Fischer et al, in a preprint made available in April 2020, describe how they studied the sterilisation of materials contaminated with high concentrations of SARS-CoV-2 with UV-C illumination. They concluded that a N95 FFP mask required 18mJ/cm² to kill the virus to a point of being undetectable. Fischer et al further concluded that a dose of 3.6mJ/cm² rendered the virus undetectable on a stainless-steel surface. Fischer however warns the reader that extra time might be needed to disinfect curved surfaces.

In CDC's recently published guidelines http://www.iuva.org/iuva-covid-19-faq dosage value for viruses comparable to COVID-19 in the same SARS virus family are quantified as 10-20mJ/cm² at a wavelength of 254 nm. CDC's guidelines recognise that this dosage achieves 99.9% disinfection (i.e. inactivation) under controlled laboratory conditions.

It appears that coronaviruses are very UV sensitive. The upper limit determined for the log-reduction dose (90% reduction) is approximately 10.6 mJ/cm² (median), while the true value is probably only 3.7 mJ/cm² (median).

It would appear therefore that the threshold set by the authors of 140mJ/cm² according to the guidance emerging during the 2020 pandemic might be a factor of 14-40 times too high.

Heßling et al, recently concluded that since coronaviruses do not differ structurally to any great extent, the SARS-CoV-2 virus – as well as possible future mutations – will very likely be highly UV sensitive, so that common UV disinfection procedures will inactivate the new SARS-CoV-2 virus without any further modification.

Nevertheless, the authors feel it prudent to discuss the efficacy and practical applicability of the technology in the context of 140mJ/cm² threshold, recognising that a lower threshold would reduce sterilisation times or give greater assurance of appropriate levels of sterilisation.

Turning to the technology and its evaluation in the experiments described.

Measurements show that ELIPTIG® when stationary produces a toroidal optical field which extends significantly beyond the plane of the device. This is easily explicable due to the nature of the discharged lamps as a light source. Such optical surface produce light that is divergent and contrasts with, for example, a laser source which is monochromatic, coherent and columnated. The light from the lamps diverges widely and for the application under consideration here is very helpful.

When stationary the toroidal optical field extends significantly outside the envelope of the device itself. Taking for example a power density of 0.17mW/cm^2 (chosen to illustrate the point since such a power density would achieve a germicidal threshold of 140mJ/cm^2 in 824s i.e. less than 14mins which is possibly the limit of practical acceptability) then ELIPTIG® produces in the horizontal plane a field 4.2m in diameter. The toroidal field has a height using the parameters above of 2m. In a conservative scenario therefore, assuming a 140mJ/cm^2 germicidal threshold, ELIPTIG® could sterilise a space 4.2m in diameter and 3m in height in 28mins with one vertical relocation i.e. for example a 14mins sweep 0.5m from the floor and a second sweep of 14mins at a height of 1.5m.

All of the above measurements are quoted for a stationary ELIPTIG® which is neither translating or UV Orbiting. Placing the RMD Radiometer at a fixed position and measuring the power density in mW/cm^2 with a stationary non- rotating ELIPTIG® and subsequently measuring the power density with ELIPTIG® rotating every 30s and translating at a maximum speed of 0.5m in 18.6s gave two measurements of 0.55mW/cm^2 and 0.41mW/cm^2. The translating and rotating ELIPTIG® therefore illuminated any surface with 81% of the energy density impingent on that surface from a stationary non-rotating ELIPTIG®. This compromise in reducing effective dosage is worthwhile in the context of reducing shadows and enhanced coverage in terms of surface area and volume.

Applying the 81% discount leads to the conclusion that any surface 1m from ELIPTIG® will receive the 140mJ/cm^2 in 310s.

The torus can be swept through a space on a linear translator 1.2m long whilst rotating in symmetrical manner in order to eliminate shadow and sterilise the surfaces of interest. This movement maps out a volume which is "sausage" in shape 5.2m long 4.2m wide and 2m in height, if one defines the outer surface of the space as an optical isobar reflecting 0.17mW/cm^2 . Such a volume could be sterilised in 1020s i.e. 17mins when one assumes that any point in space receives 81% of the maximum power on average.

If Fischer et al are correct and the germicidal threshold is not 140mJ/cm^2 but 3.6mJ/cm^2 then a two location sterilisation methodology could be achieved not in 28mins but in 43s. Applying the CDC maximum germicidal threshold of 20mJ/cm^2 then the two location sterilisation methodology would take 4mins. The use of the dynamic ELIPTIG® with a 1.2m translation length and an optical rotational path would seem on this basis both efficient and practical in the case of a sterilisation of an ambulance.

For use in other spaces then, the volume to be sterilised can be varied through changing the power rating of the lamps, extending the time and where necessary for larger spaces relocating ELIPTIG® or extending the translational path length. For much larger spaces other mechanical approaches may be adopted including for example a cable cam system.

The authors conclude that in principle UV-C sterilisation is a viable candidate as a technology to aid the return of human interaction and economic activity safely into spaces that may require change of personnel and hence the possibility of infection.

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