Ultraviolet Germicidal Irradiation (UVGI) for Air Disinfection
History, Theory, Efficacy, Safety

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Part 1: Principles and Theory of Upper Room UVGI
Applications of UVGI

- **UV in a box – Room Air Cleaners**
  - Advantages: simple - just plug it in
  - Disadvantages: difficult to move enough air through the box to achieve high Eq ACH

- **UV in the ventilation system**
  - Advantages: out of sight and no safety concerns
  - Disadvantages: Disinfects air only after it leaves the room, and limited by ventilation system

- **Whole Room UV air disinfection**
  - Advantages: good for operating/autopsy room with protective clothing
  - Disadvantages: not useful to disinfect unoccupied rooms

- **Upper room UVGI**
  - Advantages: uses entire upper room as disinfection chamber
  - Disadvantages: not simple to design system for safety and efficacy
UV in ventilation ducts or portable room air disinfection devices
Upper Room UV Air Disinfection uses the entire room as a duct

- UV-C
- 7 ft.
- Disinfected air displaced
- Warm contaminated air rises
- Paddle fans assure good air mixing
Current upper room UVGI usage

- Used in hospital waiting rooms, clinics, emergency rooms, isolation and procedure rooms
- Used in shelters, jails, prisons, homeless shelters
- *Not considered a substitute for 6-12 ACH ventilation or for negative pressure isolation* (CDC)
Current UVGI fixtures (louvered)

Narrow beam
OTHER BOOKS BY THE SAME AUTHOR

2. Light and Shade and Their Applications, 1916.
3. The Lighting Art, 1917.
4. The Language of Color, 1918.
5. Artificial Light, Its Influence Upon Civilization, 1920
8. The Book of The Sky, 1922.

ULTRAVIOLET RADIATION
ITS PROPERTIES, PRODUCTION, MEASUREMENT, AND APPLICATIONS

BY
M. LUCKIESH
DIRECTOR OF APPLIED SCIENCE, NELA RESEARCH LABORATORIES
NATIONAL LAMP WORKS OF GENERAL ELECTRIC CO.


NEW YORK
D. VAN NOSTRAND COMPANY
EIGHT WARREN STREET
1922
OTHER BOOKS BY THE AUTHOR

LIGHT, VISION AND SEEING, 1944
READING AS A VISUAL TASK (WITH FRANK K. MOSS), 1942
TORCH OF CIVILIZATION, 1940
COLOR AND COLORS, 1938
THE SCIENCE OF SEEING (WITH FRANK K. MOSS), 1937
SEEING AND HUMAN WELFARE, 1934
SEEING—A PARTNERSHIP OF LIGHTING AND VISION (WITH FRANK K. MOSS), 1931
ARTIFICIAL SUNLIGHT, 1930
LIGHT AND HEALTH, 1926
LIGHTING FIXTURES AND LIGHTING EFFECTS, 1925
FOUNDATIONS OF THE UNIVERSE, 1925
PORTABLE LAMPS, 1924
LIGHT AND WORK, 1924
LIGHT AND COLOR IN ADVERTISING AND MERCHANDISING, 1923
ULTRAVIOLET RADIATION, 1922
THE BOOK OF THE SKY, 1922, 1933
VISUAL ILLUSIONS, 1922
LIGHTING THE HOME, 1920
ARTIFICIAL LIGHT, 1920
THE LANGUAGE OF COLOR, 1918
THE LIGHTING ART, 1917
LIGHT AND SHADE AND THEIR APPLICATIONS, 1916
COLOR AND ITS APPLICATIONS, 1915, 1921

Applications of Germicidal, Erythemal and Infrared Energy

BY

MATTHEW LUCKIESH, D.Sc., D.E.
Director, Lighting Research Laboratory
General Electric Company
Nela Park, Cleveland

NEW YORK
D. VAN NOSTRAND COMPANY, Inc.
250 FOURTH AVENUE
1946
Ultraviolet Germicidal Irradiation (UVGI) – key concepts:

- 254 nm UV easily produced
  - by mercury vapor lamps (same as ordinary fluorescent lamps with special glass)
- Low skin/eye penetration
  - because it is so reactive – absorbed by outer layers – nucleic acids protected
- Microbes are vulnerable
  - because of their tiny size – nucleic acids are exposed
UVGI Occupational Exposure Limit

- Bactericidal
- Photokeratitis
- Skin cancer
- Skin erythema

Wave length (nm)

Relative effectiveness
Microbial Inactivation

Microbial inactivation characterized by survival curves, based on target theory.

- Number of survivors decreases by a constant fractional amount for a given increment of exposure – involves chance
  - Holds for a single “hit”, but multiple “hits” leads to survival curves with a shoulder – commonly seen experimentally.
Limitation common to all air disinfection strategies

- Similar to ventilation where
  - 1st AC removes 63% of contaminated air
  - 2nd AC removes 63% of what is left
  - 3rd AC removes 63% of what is left, etc.

- Makes it possible to equate ventilation and effects of UVGI

- When UVGI inactivates 63% of infectious organisms in a room, one Equivalent Air Change has occurred.
## UVGI Investigations

<table>
<thead>
<tr>
<th>Type:</th>
<th>Source:</th>
<th>Sample:</th>
<th>Utility:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Bench-scale</td>
<td>BCG aerosol</td>
<td>Mech. A.S. Culture</td>
<td>UV dose humidity</td>
</tr>
<tr>
<td>2. Room-scale</td>
<td>BCG aerosol</td>
<td>Mech. A.S. Culture</td>
<td>Fixtures, Vent/CFD</td>
</tr>
<tr>
<td>3. Hospital ward</td>
<td>Human M. tb</td>
<td>Guinea Pig/RFLP</td>
<td>Hospital room UV efficacy</td>
</tr>
<tr>
<td>4. Epi</td>
<td>Human M. tb</td>
<td>Skin Test</td>
<td>Real world UV efficacy</td>
</tr>
</tbody>
</table>
Small (Bench) Chamber studies

Measure Z value for various microbes
Susceptibility of various microbes
Humidity effects
Bench top chamber for controlled UVGI studies
Determination of UV susceptibility of various airborne organisms

Z value

\[ Z = \frac{\ln N_0/N_{uv}}{\mu\text{Watt} \times \text{sec} \times \text{cm}^{-2}} = \frac{\text{Kill Rate}}{\text{UV Dose}} \]

Z is the slope of the plot of the natural logarithm of colony count against UV dose

Mtb at 50% humidity = 33 (23-42) Erdman

48 (44-55) 199RB

M. bovis BCG

37 (33-39)

Serratia marcescens

214 (183-245)
Humidity protects the organism

% Survival

UV dose (uw.sec/cm²)
Theory: Permutt analysis - 1

\[ Z = 0.0041 = \text{Eq ACH/UV dose} = 15 \text{ Eq ACH/1 } \mu W/cm^2 \]

1 \( \mu W/cm^2 \)

\[ = 15 \text{ ACH} \]

Eq ACH are high. UVGI inactivates in seconds. This is an hour.
Permutt analysis - 2

$Z = 0.0041 = \text{Eq ACH/UV dose} = 15 \text{ Eq ACH/1 } \mu W/cm^2$

- $1 \mu W/cm^2$
- $= 15 \text{ ACH or } 15 \text{ AC/60 min } =$
- $1 \text{ Eq AC/4 min } = \text{conc. reduced by 63%}$
Permutt analysis - 3

\[ Z = 0.0041 = \text{Eq ACH/UV dose} = 15 \text{ Eq ACH/1 } \mu\text{W/cm}^2 \]

<table>
<thead>
<tr>
<th>1 (\mu\text{W/cm}^2)</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Instantaneous mixing</td>
<td></td>
</tr>
</tbody>
</table>

1 Eq ACH = 20 min (5 x 4 min)

= 15 ACH
Permutt analysis - 4

\[ Z = 0.0041 = \text{Eq ACH/UV dose} = 15 \text{ Eq ACH/1 } \mu\text{W/cm}^2 \]

<table>
<thead>
<tr>
<th>32 μW/cm² avg. = 480 Eq AC</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Eq ACH/7.2 sec.</td>
<td></td>
</tr>
</tbody>
</table>

Instantaneous mixing

1 Eq ACH = 36 sec

= 100 Eq ACH
Permutt analysis - 5

\[ Z = 0.0041 = \text{Eq ACH/UV dose} = 15 \text{ Eq ACH/1 } \mu W/cm^2 \]

- 100% air disinfection
- 25 ACH between upper and lower room
- = 25 Eq ACH
Permutt analysis - 6

\[ Z = 0.0041 = \text{Eq ACH/UV dose} = 15 \text{ Eq ACH/1 } \mu\text{W/cm}^2 \]

- 32 $\mu$W/cm\(^2\) avg. = 480 Eq AC
- 1 Eq ACH/7.2 sec.
- 25 ACH mixing
- 20 Eq ACH in the lower rm
Permutt analysis - 7

\[ Z = 0.0041 = \text{Eq ACH/UV dose} = 15 \text{ Eq ACH/1 } \mu \text{W/cm}^2 \]

32 \( \mu \text{W/cm}^2 \) avg. = 480 Eq AC

1 Eq ACH/7.2 sec.

100 ACH mixing

50 Eq ACH in the lower rm
Room (large chamber) studies

Interaction of air mixing and UVGI
Room-scale studies:
Riley-Middlebrook, 1976 - aerosolized BCG

- A single 17 W UV lamp added the equivalent of 10 air changes to an unventilated room – air mixing by radiator only
- Silent, safe, no drafts, low energy use, low maintenance
- Established current dosage guideline 30 W fixture per 200 sq ft area.
Airborne Infection Control
- Exposure Chamber: HSPH
**Summary: efficacy of upper room UVGI**

(Large chamber studies)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Microorganism</td>
<td>BCG</td>
<td><em>Mycobacterium parafortuitum</em></td>
<td>BCG</td>
</tr>
<tr>
<td>Particle size (μm)</td>
<td>0.5-3</td>
<td>0.65-2.1</td>
<td>1.1-4.7</td>
</tr>
<tr>
<td>Suspending medium</td>
<td>0.2% BSA</td>
<td>DW</td>
<td>10% FCS</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>n/a</td>
<td>15-35</td>
<td>4-26</td>
</tr>
<tr>
<td>RH (%)</td>
<td>25</td>
<td>50-90</td>
<td>41-69</td>
</tr>
<tr>
<td>Room size (m³)</td>
<td>61</td>
<td>90</td>
<td>46</td>
</tr>
<tr>
<td>Mechanical ventilation</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ACH</td>
<td>2</td>
<td>2-4</td>
<td>0</td>
</tr>
<tr>
<td>Mixing fan (during aerosolization)</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>UV output (W)</td>
<td>17</td>
<td>46</td>
<td>99(28)</td>
</tr>
<tr>
<td>UV output/Room size (W/m³)</td>
<td>0.28</td>
<td>0.75</td>
<td>1.1</td>
</tr>
<tr>
<td>UV fixture type</td>
<td>C₁</td>
<td>C₁&amp;W</td>
<td>CN&amp;C₂</td>
</tr>
<tr>
<td>UV Effectiveness (%)</td>
<td>83</td>
<td>88, 89</td>
<td>98</td>
</tr>
<tr>
<td>UV effect (ACH)</td>
<td>10</td>
<td>18-19, 33</td>
<td>6-16, 19</td>
</tr>
</tbody>
</table>
Room Studies – Miller et al, 2002
University of Colorado at Boulder, NIOSH contract #200-97-2602

- Full scale room studies – 87 m² test chamber
- 5 fixtures, tot. 216 W producing
  - avg. 42 µW/cm² in the irradiated upper zone,
  - only 0.08 µW/cm² at eye level
- 3 test organisms:
  - B. subtilis, M. parafortuitum, and M. bovis.
- 2 types of experiments:
  - constant generation – gives effectiveness
  - decay – gives equivalent room air changes
Miller et al, 2002 (cont.)

- Results (50% humidity):
  - Constant generation (effectiveness):
    - *B. subtilis* 46 – 80% @ 216 W
    - *M. parafortuitum* 83 – 98% @ 216 W
    - *M. bovis* 96 – 97% @ 216 W

- Decay (release & mix):
  - *M. parafortuitum* 16 ± 1.2 ACH @ 216 W
    - 6.1 ± 0.8 ACH @ 108 W
    - 19% increase @ 509 W

  
  \[ Z \text{ value} = 1.2 \pm 0.15 \times 10^{-3} \text{ cm}^2 \text{ u.sec}^{-1}\text{sec}^{-1} \]

- Winter conditions (warm air from ceiling): 25% decrease
- Photoreactivation
  - none detected at 40% humidity
  - inconclusive at 100% humidity
Epidemiological studies

Testing UVGI in real world situations
Upper room UVGI effect on measles in day schools, (Wells, Am J Hygiene, 35:97-121, 1942)

**Figure 1.** Measles epidemic in Philadelphia, 1941. Weekly attack rate among susceptibles (home secondaries excluded).
The 1957-58 Livermore Veterans Pandemic Influenza Study

- Livermore, CA Veterans Hospital
  July 1957 – March 1958
  - Upper Room UVC
    - Used in Building 62 but not Building 2
    - Long-term TB patients
    - Patients restricted to assigned building
    - Serology July, November, March

The 1957-58 Livermore Study Results

- **Health Care Workers**
  - 18% attack rate
  - Equivalent exposure to patients in both buildings

- **UV was 90% effective in patients**
  - (95% CI: 73% to 96%)

### Pandemic Influenza Serologically Confirmed Attack Rate Among Patients

<table>
<thead>
<tr>
<th></th>
<th>At Risk</th>
<th>+ Flu</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV</td>
<td>209</td>
<td>4</td>
<td>1.9%</td>
</tr>
<tr>
<td>No UV</td>
<td>395</td>
<td>75</td>
<td>18.9%</td>
</tr>
</tbody>
</table>

Part 2: Experimental Hospital Ward
Riley (Wells) experimental TB ward
Baltimore, 1958 - 1962
Airborne Infection Research Facility

Medical Research Council

HJE Schultz SANTA

in collaboration with

CDC

HARVARD SCHOOL OF PUBLIC HEALTH

CSIR

JAN 29 2005
The Airborne Infections Research (AIR) Facility
Witbank, Mpumalanga Province, SA
• The detailed **fixture specifications** developed for this project, but the following **key performance specifications** were used:

• **Upper room power** - A UV meter reading of not less than 250 µW/cm², one meter out from the face/opening of the fixture, on the horizontal centerline of the UVGI beam.

• **Lower room safety** – A UV meter reading not greater than 0.4 µW/cm² at 2.0 m (6.5 ft) above the floor anywhere in the room. (0.4 µW/cm² at in the lower room is consistent with South African Guidelines)
AIR, Experimental Plan

Guinea Pig Air Sampling

A B
Odd days Even days
3 patient rooms Plus common areas

Intervention on/off on alternative days

UVGI or other intervention 3 patient rooms Plus common areas
Pt. TB RFLP

Guinea Pig TB RFLP
Results

<table>
<thead>
<tr>
<th>UV1</th>
<th>Intervention</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>TST-1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>TST-2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>TST-3</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>TST-4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>UV2</th>
</tr>
</thead>
<tbody>
<tr>
<td>TST-1</td>
</tr>
<tr>
<td>TST-2</td>
</tr>
<tr>
<td>TST-3</td>
</tr>
<tr>
<td>TOTAL*</td>
</tr>
</tbody>
</table>

* p<0.0005

Combined hazard ratio 4.9 (CI.95: 2.8, 8.6) or about 80% effective.

Note: 6 ACH (mechanical). Doubling to 12 EqACH would reduce risk by about 50%; doubling to 24 EqACH would reduce risk by about 75%; so UVGI added about 24-6 (mechanical) = about 18 EqACH to the AIR facility wards.
Computer Assisted Design (CAD): validated, published and available free.

A computer generated illustration estimating the UVGI "efficacy" distribution in one of the patient rooms in the AIR facility. The upper tri-color distribution is for the "kill zone" whereas the lower "safety" distribution indicates peak UV fluence at eye level.
<table>
<thead>
<tr>
<th><strong>AIR Facility UV Characteristics</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fluence Rate Treatment Zone</strong></td>
<td></td>
</tr>
<tr>
<td>Lower Limit of Treatment Zone</td>
<td>2.18 m</td>
</tr>
<tr>
<td>Average fluence</td>
<td>18.84 µW/cm²</td>
</tr>
<tr>
<td><strong>Upper Room UV Treatment Volume</strong></td>
<td>8 m³ (19% of room volume)</td>
</tr>
<tr>
<td>Coverage at 5.0 µW/cm²</td>
<td>6 m³ (80% of upper room zone)</td>
</tr>
<tr>
<td>Coverage at 10.0 µW/cm²</td>
<td>5 m³ (59% of upper room zone)</td>
</tr>
<tr>
<td>Coverage at 20 µW/cm²</td>
<td>3 m³ (32% of upper room zone)</td>
</tr>
</tbody>
</table>
Safety

<table>
<thead>
<tr>
<th></th>
<th>Avg</th>
<th>Max</th>
<th>Min</th>
<th>Avg/Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluence Rate Eye Level (1.75 m above the floor)</td>
<td>0.22 µW/cm²</td>
<td>0.32 µW/cm²</td>
<td>0.00 µW/cm²</td>
<td>0.7:1</td>
</tr>
</tbody>
</table>

Achieving safe UV levels in the lower, occupied room by tightly-spaced louvers traps much of the useful UV traps much of the useful UV – only 1 -5% of UV lamp output exits the fixture.

Problem: how to use UVGI more efficiently
Upper room UV light for the prevention of airborne tuberculosis transmission

R Escombe\textsuperscript{1,2}, R Ramirez\textsuperscript{3}, RH Gilman\textsuperscript{2,4,6}, M Navincopa\textsuperscript{5}, E Ticona\textsuperscript{5}, P Sheen\textsuperscript{6}, C Noakes\textsuperscript{7}, B Mitchell\textsuperscript{8}, D Moore\textsuperscript{1,2}, JS Friedland\textsuperscript{1}, C Evans\textsuperscript{1,2,4,6}.

\textsuperscript{1} Wellcome Centre for Clinical Tropical Medicine & Department of Infectious Diseases & Immunity, Imperial College London, Hammersmith Hospital Campus, UK.
\textsuperscript{2} Asociación Benéfica PRISMA, Lima, Perú.
\textsuperscript{3} Facultad de Medicina Veterinaria, Universidad Nacional Mayor San Marcos.
\textsuperscript{4} Johns Hopkins University, Baltimore, USA.
\textsuperscript{5} Hospital Nacional Dos de Mayo, Lima, Perú.
\textsuperscript{6} Universidad Peruana Cayetano Heredia, Lima, Perú.
\textsuperscript{7} School of Civil Engineering, University of Leeds, UK
\textsuperscript{8} Agricultural Research Service, USA.
Kaplan-Meier survival based on PPD conversions

UV vs. No intervention: Log rank 46 \[ p<0.0001 \] UVGI reduced TB: 72%

Ionizers vs. No intervention: Log rank 20 \[ p<0.0001 \] Ionisers reduced TB: 58%
UV killing and relative humidity

Relative humidity in Lima 50-95%
Dosing Upper room UVGI

How many fixtures are required and on what basis?
NIOSH 2009 Guidelines

NIOSH. Environmental Control of Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings. 2009

NIOSH Recommendations:
- 30 – 50 µW/cm² average irradiance (hard to predict)
- 6.3 W total UVGI wattage per cubic meter room volume treated (but what about fixture efficiency?)

Need better guidance
- Fogarty Grant
- December, 2011 International Meeting, HSPH, “Toward International UVGI Guidelines”
2. The germicidal fixture manufacturer shall provide photometric data for each available fixture showing:

A. The size and shape of the effective treatment area in the horizontal plane (50 µw-sec/cm² at 254 and 1 ips) and the size and shape of the area whose minimum dosage is 25 µw-sec/cm² at 254 nm and 1 ips.
3. As a guideline, the effective treatment area shall occupy at least 65% of the irradiated zone above the occupied space.
### AIR Facility conditions:

<table>
<thead>
<tr>
<th>Fluence Rate Treatment Zone</th>
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## Safety

<table>
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<tr>
<th></th>
<th>Avg</th>
<th>Max</th>
<th>Min</th>
<th>Avg/Max</th>
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<td>0.22 $\mu$W/cm$^2$</td>
<td>0.32 $\mu$W/cm$^2$</td>
<td>0.00 $\mu$W/cm$^2$</td>
<td>0.7:1</td>
</tr>
</tbody>
</table>
### UVGI Dosing Criteria:

<table>
<thead>
<tr>
<th></th>
<th>30 W (nominal) Per 200 sq ft floor area</th>
<th>Does not take fixture efficiency into account</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riley</td>
<td>30 – 50 µW/cm(^2) average irradiance</td>
<td>Hard to predict Hard to measure</td>
</tr>
<tr>
<td>NIOSH</td>
<td>6.3 W total UVGI wattage per cubic meter room volume</td>
<td>Does not take fixture efficiency into account</td>
</tr>
<tr>
<td>Boehme</td>
<td>Effective treatment area in the horizontal plane: 50 µw-sec/cm(^2) at 254 and 1 ips Overlapping 25 µw-sec/cm(^2)</td>
<td>65% of irradiated zone (area?, vol?)</td>
</tr>
<tr>
<td>AIR Facility</td>
<td>Avg UV flux (zone) : 18.84 µW/cm(^2)</td>
<td>32% zone at 20 µW/cm(^2) 60% zone at 10 µW/cm(^2)</td>
</tr>
</tbody>
</table>
A new dosing strategy for upper room UVGI

1. Determine the total output of the fixtures being used. (Rudnick approach).
2. Based on the AIR facility study which achieved 80% efficacy, apply UV per room volume. **Total UV dose per room vol.**
3. Will be published soon - GHDonline
Part 3: Upper Room UVGI Safety
Critical parameters determining upper-room UVGI effectiveness

• Good UV fixture design
  – Flood the upper room with enough 254 nm
  – Low levels of UV in the occupied space

• Good air mixing between the lower and upper room
  – A slow paddle fan is essential

• Good maintenance of fixtures.

Not all fixtures being sold are well-designed for their application.
Upper room UVGI safety

- TLV for UVGI (UV-C, 254 nm)
  - 6.0 mJ/cm² for 8 hr. exposure (dose)
    - Continuous staring for 8 hrs. at intensity of > 0.2 µW/cm² will cause photokeratitis and skin erythema
    - Will not cause lens cataracts or skin cancer because of limited penetration
  - Compare to 240 µW/cm² for 2 hrs peak sunbathing outside.
### % Skin Penetration of UV

<table>
<thead>
<tr>
<th>Depth, ( \mu \text{m} )</th>
<th>Skin Layer</th>
<th>254 nm UV-C</th>
<th>297 nm UV-B</th>
<th>365 nm UV-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Surface</td>
<td>100 %</td>
<td>100 %</td>
<td>100 %</td>
</tr>
<tr>
<td>10</td>
<td>St. corneum</td>
<td>42</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>18</td>
<td>25</td>
<td>64</td>
</tr>
<tr>
<td>30</td>
<td>Viable layer</td>
<td>5</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>50</td>
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<td>0.4</td>
<td>6</td>
<td>31</td>
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<tr>
<td>70</td>
<td></td>
<td>0.03</td>
<td>2</td>
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</tbody>
</table>

After Bruls, Photochem Photobiol, 1984
ACGIH: 6.0 mJ/cm² for 8-hour period

= 0.2 μW/cm² for 8-hour continuous eye-level exposure – but it is not continuous!!!!!
UVGI – poor design and installation
MDR TB Hospital – South Africa
3 UV detectors:
- Biofilm
- Chemical photometer
- Electronic UV meter
Monitoring Human Exposures to Upper-Room Germicidal Ultraviolet Irradiation
Melvin W. First, Robert A. Weker, Shojiro Yasui, and Edward A. Nardell


Old style fixtures
- intensity 10 x 0.2 µW/cm²

Unventilated bldg.

Drug-resistant TB patients

No worker infections
Pt. B - always in bed

Patient B 11/30/01

Peak 1.49E-01 uW/cm²
Mean 5.69E-02 uW/cm²
### Summary - UV exposure

<table>
<thead>
<tr>
<th></th>
<th>Peak $\mu$W/cm²</th>
<th>Mean $\mu$W/cm²</th>
<th>Ratio P/M</th>
<th>Duration/8-hr</th>
<th>Exposure mJ/cm²</th>
<th>8-hr exp. mJ/cm²</th>
<th>% TLV (6 mJ/cm²)</th>
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</thead>
<tbody>
<tr>
<td>Pt. A</td>
<td>0.124</td>
<td>0.0454</td>
<td>0.37</td>
<td>0.83</td>
<td>1.1</td>
<td>1.3</td>
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<tr>
<td>Pt. B</td>
<td>0.149</td>
<td>0.0569</td>
<td>0.38</td>
<td>0.54</td>
<td>0.9</td>
<td>1.6</td>
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<tr>
<td>Pt. C</td>
<td>0.190</td>
<td>0.0815</td>
<td>0.43</td>
<td>0.83</td>
<td>2.0</td>
<td>2.2</td>
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<td>Pt. D</td>
<td>0.767</td>
<td>0.0356</td>
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<td>0.87</td>
<td>0.9</td>
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<td>0.0323</td>
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<td>Pt. E</td>
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<td>0.75</td>
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<td>0.0141</td>
<td>0.02</td>
<td>0.60</td>
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</tbody>
</table>
Where are we going?

- UVGI needs:
  - Better, more efficient fixture designs
  - Wider availability of expertise, UV technology, and maintenance
  - CAD to plan UVGI installations
    - License available for free (enardell@gmail.com)
Domodedovo Airport Moscow
Domodedovo Airport Moscow
The “Eggcrate” UV Concept
Novel approaches to UVGI

Also testing LED UV but technology is expensive and early in development
Eggcrate UV: A Whole Ceiling Upper room Ultraviolet Germicidal Irradiation System for Air Disinfection in Occupied Rooms

Authors

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Affiliations

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\textsuperscript{2}Division of Global Health Equity, Brigham and Women’s Hospital, Boston, MA 02115

\textsuperscript{3}Harvard Medical School, Boston, MA 02115

*Correspondence to: Edward Nardell, enardell@gmail.com
Figure 1: Schematics of (A) conventional wall mounted UVGI fixture, (B) the bare UV lamp with electrical components mounted on aluminum plate (right) and suspended eggcrate panels (left).
Figure 2: Measurement grid within the experimental chamber. Locations of lamps for eggcrate UV are at locations B3 (single UV lamp location) and B2 and F4 (two UV lamp locations). Conventional UVGI fixtures were located adjacent to A2 and C4. Radiometer measurements were made at each of the 35 circles (O) within the grid. Anemometer measurements were made at each of the 12 bold circles (O) within the grid.
Germicidal Efficacy, fraction inactivated

Figure 3: Germicidal efficacy of conventional fixtures and the eggcrate UV system at inactivating (A) B. strophaeus and (B) M. parafortuitum in steady-state conditions. Error bars indicate standard deviations. * indicates p < 0.0005. ** indicates p < 0.001.
Germicidal Efficacy, equivalent air changes

B. strophaeus

M. parafortuitum

Figure 4: Equivalent air exchange rate provided by conventional fixtures and the eggcrate UV system for B. atrophaeus spores and M. parafortuitum at steady-state conditions. Error bars indicate standard deviations. * indicates $p < 0.00005$, ** indicates $p < 0.05$. 98x153mm (150 x 150 DPI)
Lower room safety, UV Irradiance

Figure 5: Lower room irradiance measurements of eggcrate UV and of conventional fixtures. Boxplots show the 25th and 75th percentile as the box boundaries with the middle line indicating the median (50th percentile) measurement value. Minimum and maximum values are marked by the whiskers.

Detector upright
- Top of head

Detector horizontal
- Eye exposure

Next steps: optimization, testing in the AIR facility, commercialization
Fogarty Frame Innovation Award

• 5 year, multi-institutional, multidisciplinary project
• Collaborators:
  – Architecture: U. Pretoria, S. Africa (3 fellows),
  – Engineering: Harvard SPH, Boston (1 fellow)
  – Medical: Hospital Nacional Hipolito Unanue, Lima, Peru (1 fellow)

• Proposal: “Sustainable Airborne Infection Control”
• Questions:
  • Architecture– what makes a successful building design?
  • Engineering – optimize UVGI application in low income settings
  • Medical – test of F-A-S-T strategy, i.e., rapid diagnosis and effective treatment impact on HCW transmission
Translational Clinical Research at the AIR Facility:

- CFAR/NIH Inhaled Drugs for TB IC (Colistin)
- RO1 5-yr Rapid Impact of Effective treatment on MDR TB Transmission
- BMGF Vaccine trial And characterization Of airborne Mtb
- NIOSH RO1 (4 years): Testing Novel Interventions
- Fogarty Project (5 years) Research training
- FAST Initiatives*
- VOC Dx

TB Infection Control

- Stop TB Partnership (Sub-Working Group)
- USAID (TB Care 1 & 2)
- CDC, WHO
- PEPFAR
- GFATM
- GHDonline (BWH based)

BIG PICTURE – Where our research fits in

- Design for Health*: Online casebook of building designs
- TB Design Roster*: Finding consultants through GHDonline
- Harvard Course for Architects & Engineers
- Pretoria Course Vladimir Courses

Interrelated TB Infection Control initiatives

Ed Nardell, Ashwin Dharmadhikari
BWH, Harvard Medical School
Innovative Interdisciplinary Approaches to Sustainable Airborne Infection Control
Ed Nardell, MD, PI, Brigham & Women’s Hospital

Goal: to build global capacity in airborne infection control research

1. Architecture – 3 Fogarty architects – defining what makes a successful building design. Based at U. Pretoria School of Architecture, CSIR (South Africa), and eventually including the Kigali Institute of Science and Technology – School of Architecture


FAST Initiatives
TB Care 1 & 2
Implementation: Zambia, Bangladesh, Vietnam, Russia (Lilly Foundation), Peru (Fogarty)

Refocusing TB IC on the key administrative components of TB IC:

Goals: Eliminate undiagnosed TB cases
       Eliminate undiagnosed MDR-TB

- Find cases Actively through cough surveillance
- Separate until effective treatment starts
- Treat based on molecular DST

FAST is not an educational campaign like hand washing or cough hygiene

It is an implementation strategy at the health care facility level requiring:
- administrative buy-in and investment
- hiring and training cough monitors
- laboratory capacity: Xpert TB (rapid turn around time)

Impact: process indicator: monitor time for each step:

Entrance point cough surveillance -> sputum collection -> laboratory -> Xpert result -> clinician – > effective treatment
Conclusions:

- UVGI is an old technology with new applications
- Scientifically sound
- Safe for room occupants
  - Need consensus on dosing upper and lower room
- Clinical trials are difficult
- Applications
  - Poor countries – TB, influenza
  - Rich countries – influenza, bioterrorism, future airborne threats
- Research: improved fixture designs and dosing strategies underway
  - CAD program now available