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SURGICAL SPACE SUITS INCREASE PARTICLE AND MICROBIOLOGICAL EMISSION RATES IN A SIMULATED SURGICAL ENVIRONMENT

ABSTRACT

BACKGROUND: The role of space suits in the prevention of orthopaedic prosthetic joint infection remains unclear. Recent evidence suggests space suits may in fact contribute to increased infection rates, with bioaerosol emissions from space suits identified as a potential cause. This study aimed to compare the particle and microbiological emission rates of space suits and standard surgical clothing.

METHODS: A comparison of emission rates between space suits and standard surgical clothing was performed in a simulated surgical environment during five separate experiments. Particle counts were analysed with two separate particle counters capable of detecting particles between 0.1 and 20 µm. An Andersen Impactor was used to sample bacteria, with culture counts performed at 24 and 48 hours.

RESULTS: Four experiments consistently showed statistically significant increases in both particle and microbiological emission rates when space suits are used compared with standard surgical clothing. One experiment showed inconsistent results, with a trend towards increases in both particle and microbiological emission rates when space suits are used compared with standard surgical clothing.

CONCLUSION: Space suits cause increased particle and microbiological emission rates compared with standard surgical clothing. This finding provides mechanistic evidence to support the increased prosthetic joint infection rates observed in clinical studies.

KEYWORDS: Orthopaedics; space suit; clean air; arthroplasty; prosthetic joint infection; emission rates

INTRODUCTION

Total joint arthroplasty is one of the most successful commonly performed orthopaedic procedures and an effective method of alleviating symptoms associated with hip and knee osteoarthritis [1-3]. Prosthetic joint infection is a concerning complication of total hip and knee replacement, with current rates estimated to be between 2.0% and 2.4% over an eight year period in the USA [4]. This is a marked improvement compared to early arthroplasty series in the 1960s that described rates as high as 10% [5].

This reduction has been attributed to a number of measures that were introduced at the time, including the formulation of the clean air hypothesis which suggested that the prosthetic joint might constitute a system uniquely sensitive to infection by a very small bacterial inoculums derived from airborne particles [5-7]. A multifaceted approach involving both improved room air ventilation systems incorporating laminar flow and modified surgical clothing consisting of body exhaust suits were introduced in an effort to reduce infection rates [5, 6].

Multiple clinical and non-clinical studies supporting the use of body exhaust suits have since been published, leading to their widespread use [8-14]. These studies have used air and wound bacterial and particle counts as surrogate markers for infection, as the number of samples or participants required in a study of statistical significance with the current low prosthetic joint infection rates would be in the thousands and very difficult logistically [10-27]. Body exhaust suits were originally designed with both the air inlet and outlet tubing arranged to create negative pressure inside the gown, ensuring any shed particles are extracted via the outlet tube and released in a controlled manner away from the surgical field, preventing any contamination. However, such tubing is cumbersome, which led to the development of more portable ‘space suit’ systems such as the T4 Steri-Shield (Stryker Instruments, Kalamazoo, MI, USA), the Provision Surgical Helmet (DePuy, Warsaw, IN, USA), and Stackhouse FreedomAire (Stackhouse Incorporated, Palm Springs, CA, USA). With the added benefit of being splash resistant and serving as a form of self-protection for the surgeon, space suits have now become the most common form of clean air clothing systems used [28].

In contrast to the proven effectiveness of body exhaust suits, the impact of space suits on infection rates remains unclear. Recent reports have suggested that space suits appear to cause increased rates of wound contamination and deep infection compared with standard surgical clothing [29]. Various hypotheses have been put forward to explain these increased rates, including decreased spatial awareness, which makes it easier to contaminate oneself, and also the exhaust emissions of space suits.

To date no studies have compared particle or microbiological emission rates between space suits and standard surgical clothing as a potential mechanism to explain the increased rates of infection recently reported.

This study aimed to assess the emissions of space suits and standard surgical clothing in a laboratory based setting by creating a simulated surgical environment, providing a mechanistic rationale for the increased infection rates that have been observed in the literature.

MATERIALS AND METHODS

This study was conducted in a laboratory-based setting at our institution between September 2011 and June 2015. Data was collected prospectively in a novel simulated surgical environment, designed to replicate actual operating theatre conditions and custom-built for the investigation of particle sources during five separate experiments.

The simulated surgical environment consisted of an airtight flow-through chamber with dimensions measuring 2.1 x 0.9 x 0.85 m, with an internal volume of 1.6 m^3. A circular inlet measuring 17cm in diameter in the roof of the chamber was connected to a high efficiency particulate air (HEPA) filtered air supply from a large filter bank and fan unit via aluminium tubing. HEPA filtered clean air was thus introduced into the chamber constantly to ensure there was no confounding influences from ambient room air, and that activities in the chamber were the only source of particles and bacteria. The chamber operated at a slightly higher air pressure than the surrounding room to prevent ingress of room air. A circular outlet was located on the front wall of the chamber adjacent to the floor. With this configuration, the filtered air entered above and exited below the simulated surgical field. No other air ingress or egress pathways were present in the sealed chamber and therefore all emissions from the surgical clothing were captured, free of contamination from other sources. An isokinetic sampling cone attached to electrically conductive rubber tubing measuring 4mm in diameter was attached at the chamber air outlet, and in turn attached to a flow splitter that directed air towards two separate particle counters.

Particle counting was performed with two instruments, the Lasair II 110 optical particle counter (OPC) (Lasair, Korskildelund, Greve, Denmark) and the TSI 3312A ultraviolet aerodynamic particle sizer (UVAPS) (TSI, Shoreview, MN, USA). The use of both these counters has been reported in other similar studies analysing air quality [25-27, 30]. The instruments were used together to ensure the widest possible range of particle sizes was captured. The OPC measured particles between 0.1µm and 5.0µm. The UVAPS measured particles between 0.5µm and 20 µm. Due to the high levels of noise and low detection efficiency of channel sizes below 0.523µm and channel sizes above 15µm for the UVAPS, these measurements were excluded. Measurements were made by both particle counters at 10 second intervals.

Microbiological sampling was performed in addition to particle counting because particle concentrations alone do not indicate the presence of viable organisms. A Thermo Scientific six-stage viable Andersen cascade impactor (Waltham, MA, USA) was also placed at the test chamber outlet., analysing particles between 0.6µm and 7.0 µm. Air was sampled onto Tryptone soya agar plates on each size stage (Biomerieux, Marcy-l'Étoile, Lyon, France) which have previously been used in similar experiments [25, 27]. Plates were sent immediately for microbiological analysis on the day of the experiment and incubated for 48 hours at 37°C in air. Colony counts were performed at 24 and 48 hours, except for the first experiment where counts were only performed at 24 hours. Bacterial subtyping was also done but only for the first experiment.

A hot-wire anemometer (TSI model 9535, Shoreview, MN, USA) was used to measure the air velocity at the spirometry chamber outlet where the particle and microbiological samples were collected. This allowed the volume flow of air during each test to be calculated in order to determine the mean emission rates of particles and bacteria.

Five experiments were conducted in total over five separate days. Each experiment involved twelve 40-minute cycles conducted sequentially. This in turn consisted of two separate cycle conditions that were tested three times each in a computer randomised order on the day of testing. The two separate cycles tested were identical apart from the type of surgical head gear. For every experiment, the surgeon wore the same pair of cotton surgical scrub trousers/shirts with Work Bistro Vent Clog shoes (Crocs, Niwot, CO, USA) along with for each cycle new sets of:

1) Kimberley-Clark large standard surgical gowns (Kimberley-Clark, Roswell, GA, USA).
2) Ansell Gammex PF surgical gloves (Ansell, Richmond, Victoria, Australia).
3) Sentry Medical shoes covers (Sentry Medical, Eastern Creek, NSW, Aus).
4) Sentry Medical surgical caps (Sentry Medical, Eastern Creek, NSW, Aus).

The two different types of surgical head gear used were either:

1) The combination of a Kimberley Clark Balaclava Hood and Kimberley Clark Fluid-Shield surgical mask (Kimberley-Clark, Roswell, GA, USA) – "Standard Surgical Clothing"
2) The Stryker T3 Sterishield Helmet and Stryker T3 Sterishield Hood Cover (Stryker Instruments, Kalamazoo, MI, USA) – "Space Suits"

A plastic stool was always present in the chamber. In order to best simulate operating theatre conditions, the same set of scrubs and shoes were used during each experiment and cleaned afterwards. All other items of clothing were changed for each cycle. The same space suit helmet was used for all cycles/experiments and was cleaned afterwards.

Prior to each cycle, the chamber was wiped clean with 70% ethanol and also vacuumed. On each separate day prior to commencement of the cycles, the HEPA filter fan unit was allowed to initially run for a total of two hours to flush the test chamber and ensure a steady flow rate. Each cycle involved the surgeon entering the spirometry chamber fully clothed with a particular type of surgical clothing. The chamber was then sealed with the surgeon inside and a total of twenty minutes was allowed to elapse before sampling was commenced to allow particle counts to return to baseline and all external air that had entered from opening of the door to be washed out, as confirmed by the real-time OPC and UVAPS data. Sampling periods lasted twenty concurrent minutes for both particle counters and the impactor. During each twenty minute sampling period, the surgeon would perform a standardised set of upper body movements at one minute intervals for a total of thirty seconds to simulate an actual surgeon's movements.

The mean emission rate (ER) of particles and bacteria was determined for each experiment and condition via the formula:

$$ER = C_{mean}V/t$$

where ER is the mean particle number (particles/sec), or microbiological (bacterial CFU/sec) emission rate, C_{mean} is the arithmetic mean particle number (particles/m^3) or bacterial (CFU/m^3) concentration during the measurement, V is air volume that flowed past the sample point during the measurement (m^3), and t is the duration of the measurement (sec). This formula has been used for similar experiments previously [30]. Statistical analysis of data was performed for each experiment using descriptive analysis and a univariate general linear model in the Statistical Package for the Social Sciences Version 22 (SPSS, IBM, Armonk, NY, USA). Comparisons were made between the space suits and standard surgical clothing. In addition to standard analysis of overall results from both particle counters, a separate analysis of the larger channel sizes (0.5

µm, 1.0 µm and 5.0µm) for the OPC was done, as thissize range includes particles that have been associated with the ability to carry and seed bacteria [31]. Results were analysed separately for each experiment as subtle variations in flow velocities and surgeon particle counts on each experimental day made a combined analysis invalid.

RESULTS

Particle Emission Rates

The results of this study show statistically significant increases in particle emission rates (PER) when space suits are used compared with standard surgical clothing. This was a consistent finding in all experiments, except in experiment one, which showed inconsistent findings trending towards an increase in PER with space suits. Statistical comparisons of PERs between space suits and standard surgical for each particle counter in all the experiments are shown in Figures 1-3.

Microbiological emission rates

The results of this study show statistically significant increases in microbiological emission rates (MER) when space suits are used compared with standard surgical clothing. This was a consistent finding in all experiments, except experiment one, which showed low microbiological counts preventing a statistically significant analysis of results, although the trend was towards increases in microbiological emission rates when space suits were used compared to standard surgical clothing. These microbiological findings are consistent with the particle counts results. The 8 bacterial colonies cultured and subtyped in the first experiment consisted of four coagulase negative staphylococcus species, one gram positive micrococcus species, one gram negative bacillus species and one gram positive corynebacterium species. Statistical comparisons of MER between space suits and standard surgical clothing at 24 and 48 hours in all the experiments are shown in Figures 4 and 5.

DISCUSSION

This study is the first to examine particle and microbiological emission rates of space suits and standard surgical clothing. Overall, the results show a statistically significant increase in particle and microbiological emission rates when space suits are used compared to standard surgical clothing during simulated operating procedures. These findings support the results of previous studies and provide a mechanistic rationale for the increased rates of wound contamination and deep infection that have been observed [29].

There are a number of limitations to this study. Firstly, large variations exist between particle emission rates of the experiments. This variation is up to tenfold when comparing certain experiments (one and five for example). It is difficult to explain this variation. Causes include varying levels of surgeon skin contamination on the day of each experiment, varying levels of surgical scrub particle content and contamination used for each experiment and varying levels of chamber contamination during each experimental day. Surgeon skin contamination could have been controlled more accurately using a strict and consistent personal hygiene and grooming routine (such as showering/shaving) at the same time on day of the experiment; this was not done. Similarly, varying levels of surgical scrub particle content and contamination could have been standardised by following a regimented laundry regime, which was again not performed. Finally, attempts were made to control levels of chamber contamination during each experimental day with a structured cleaning routine of the chamber, but it is plausible that minor variations in chamber cleaning could have contributed to the varying rates between experiments. However, regardless of these influences because each space suit and standard clothing test was done on the same day, the relative differences between the two should remain. This is bolstered by the observation of a relatively consistent trend showing increased emission rates of space suits compared with standard surgical clothing in all the experiments.

Another limitation of this study is its laboratory based nature. Clinical studies conducted during actual total hip and knee replacements are the current gold standard for investigating factors associated with prosthetic joint infection. The feasibility of performing such studies is limited though due to the current low rates of infection and the large number of participants that would be required for a clinical trial. The correlation between the importance of air quality and infection rates has been proven previously on multiple occasions, and laboratory based studies such as the current study using air particle and bacterial counts as surrogate markers for actual prosthetic joint infection rates still have relevance [8, 9, 31, 32]. Moreover, this study was able to account for the confounding influence of non-clothing particle/bacteria sources by using HEPA filtered supply air. This would be exceedingly difficult under real world operating conditions. The results of the first experiment were not consistent with the other four experiments. There was no consistent statistically significant relationship between the type of clothing and the particle/microbiological emission rate (with particle emission rates at times even showing an opposite effect). The cause of this is unclear, but it may be attributed to the large variations in air velocity found in the first experiment and the high overall velocity, which may have diluted the concentration of particles and bacteria that was able to be detected. This is also reflected by the fact that overall particle counts were much lower in the first experiment compared with the other four experiments. The experience of the first experiment allowed the velocity to be adjusted in prior experiments.

There are a number of explanations for the increased emission rates seen with the use of space suits. The first relates to the positive pressure environment created by the space suit. Space suit systems have an intake valve on the helmet itself, which draws air in from outside using the disposable hood material as a filter. The air is then blown down across the surgeon's face and neck, creating positive pressure inside the surgeon's gown and potentially expelling contaminated particles into the operating environment and onto the surgical field [15].

Another explanation for the increased emission rates may relate to the increased amount of clothing material involved when space suits are used. The hoods on the Stryker T3 hoods (Stryker Instruments, Kalamazoo, MI, USA) measure more than 50 x 70cm. This creates a separate interface for generating particles within the surgical gown that could be responsible for additional particles being emitted, thus leading to increased particle shedding.

The lack of face and head coverage provided by space suits may also have contributed to increased emission rates. Standard surgical headgear used during joint arthroplasty surgery involves a balaclava similar to the one used in this study that covers most of the surgeon's forehead, ears and eyebrows. Space suit helmets and hoods do not routinely cover these areas unless additional headgear is worn. Studies have shown that there are a significant amount of potentially harmful bacteria and squames present on surgeon's foreheads, eyebrows, and ears particularly [34]. The lack of coverage provided by space suits in combination with the positive pressure environment that is created may thus be responsible for the increased emission rates.

A final possible explanation for the increased emission rates relates to spatial awareness issues that arise when space suits are used. Although meticulous attention was paid to the simulated surgeon's surroundings within the spirometry chamber, contact of the surgeons hands with the hood or the sides of the chamber due to decreased spatial awareness may have resulted in additional particles being generated. This concern has been raised by surgeons surveyed previously [33].

Advocates of space suits describe two main reasons for their use, prosthetic joint infection prevention and personal protection. This study and the majority of studies in the literature support either an equivalent or detrimental effect of space suits with regards to infection prevention. The use of space suits for personal protection has more merit, with studies showing a high rate of surgeon and clothing contamination with the surgical site as the primary source during total knee and hip arthroplasty [34, 35]. The recent literature on space suits and their role in the surgical setting has suggested that space suits should be used primarily as a form of self-protection and not as an infection prevention tool [33].

Based on the findings of this study and their potential implications, surgeons who choose to use space suits as a form of self-protection can implement a number of steps to potentially reduce the potential for causing infection. Firstly, all gown interfaces which could serve as an external conduit for emissions, particularly those coming into close contact with the surgical field such as the surgeon's hands (gown/glove interface) should be sealed air tight, and exhaust air routed through a single pathway which is either filtered or discharged such that it cannot contaminate the surgical field. This has been highlighted in the literature recently, with measures such as sealant tape having been recommended [15, 16]. Further headgear should be used to cover as much as the surgeon's face as possible including ears and eyebrows, such as the balaclava used with standard surgical clothing. Surgeons using space suits should also pay meticulous attention to their surroundings and have a heightened sense of spatial awareness.

Unnecessary movements generating excess particles should also be avoided. Modification to current space suit instrumentation and other operating room equipment may also potentially help reduce emission rates. Bulky space suit helmets and hoods should be modified, and excessive hood material should be avoided. A translucent hood material may help with a surgeon's spatial awareness. Negative pressure suits with outlet tubing are no longer commercially available but modifications to existing suits such as the implementation of an exhaust fan within the gown that expels emissions towards a specific location away from the surgical field may also be useful. The use of laminar flow systems and similar devices which blow clean air onto and away from the surgical field may also be of benefit. Large clinical studies have shown lower infection rates (1.5% vs 0.56%) when laminar flow is used in conjunction with modified surgical clothing (body exhaust suits) [8, 9]. Recent nationwide registry data has also shown a slight but clinically significant reduction in infection rates when space suits are used in laminar flow theatres compared to conventionally ventilated theatres. A combination of these measures should be employed to limit the effect of the potentially harmful emissions of space suits when they are used.

The potential exists for a number of different areas to be researched based on the findings of this study. A study assessing the flow of particles and bacteria emitted by surgeons and surgical clothing has yet to be performed. While particles derived from the skin and clothing of surgeons have been shown to carry both aerobic and anaerobic skin bacteria capable of causing infections[31], the clinical significance of different thresholds of particle and microbiological emission rates and their impact on prosthetic joint infection rates specifically also requires further research. Finally, a comparison between positive and negative pressure clothing systems (i.e. body exhaust suits and space suits) would be of value, as this is an important mechanism contributing to the results of this study.

CONCLUSION

Orthopaedic prosthetic joint infection rates may be affected by the emissions of orthopaedic surgical clothing. This study compared the emission of space suits to standard surgical clothing, via laboratory based methods of particle and microbiological counting, in a simulated surgical environment. The results of this study consistently showed statistically significant increases in particle and microbiological emission rates when space suits are used compared with standard surgical clothing. These findings provide mechanistic evidence to support the findings of large epidemiological studies reporting higher infection rates, and can be used to inform the choices made by surgeons about their clothing. Surgeons should proceed with caution when using space suits during surgery, particularly total joint arthroplasty.

References

1. Salaffi F, Carotti M, Grassi W. Health-related quality of life in patients with hip or knee osteoarthritis: comparison of generic and disease-specific instruments. Clin Rheumatol 2005; 24 (1): 29-37

2. Jevsevar DS. Treatment of osteoarthritis of the knee: evidence-based guideline, 2nd edition. J Am Acad Orthop Surg 2013; 21 (9): 571-6

3. Tsertsvadze A, Grove A, Freeman K, Court R, Johnson S, Connock M, Clarke A, Sutcliffe P. Total hip replacement for the treatment of end stage arthritis of the hip: a systematic review and meta-analysis. PLoS One 2014; 9 (7): e99804

4. Kurtz SM, Lau E, Watson H, Schmier JK, Parvizi J. Economic burden of periprosthetic joint infection in the United States. J Arthroplasty 2012; 27 (8 Suppl): 61-5.e1

5. Charnley J, Eftekhar N. Postoperative infection in total prosthetic replacement arthroplasty of the hip-joint. With special reference to the bacterial content of the air of the operating room. Br J Surg 1969; 56 (9): 641-9

6. Charnley J. A CLEAN-AIR OPERATING ENCLOSURE. Br J Surg 1964; 51: 202-5

7. Charnley J. Low Friction Arthroplasty of the Hip: Theory and Practice. Berlin: Springer, 1979

8. Lidwell OM. Air, antibiotics and sepsis in replacement joints. J Hosp Infect 1988; 11 Suppl C: 18-40

9. Lidwell OM, Lowbury EJ, Whyte W, Blowers R, Stanley SJ, Lowe D. Effect of ultraclean air in operating rooms on deep sepsis in the joint after total hip or knee replacement: a randomised study. Br Med J (Clin Res Ed) 1982; 285 (6334): 10-4

10. Whyte W, Vesley D, Hodgson R. Bacterial dispersion in relation to operating room clothing. J Hyg (Lond) 1976; 76 (3): 367-78

11. Blomgren G, Hambraeus A, Malmborg AS. The influence of the total body exhaust suit on air and wound contamination in elective hip-operations. J Hosp Infect 1983; 4 (3): 257-68

12. Der Tavitian J, Ong SM, Taub NA, Taylor GJ. Body-exhaust suit versus occlusive clothing. A randomised, prospective trial using air and wound bacterial counts. J Bone Joint Surg [Br] 2003; 85 (4): 490-4

13. Michla Y, Holliday M, Gould K, Weir D, McCaskie A. THE EFFECT OF PERSONAL PROTECTION HELMET SYSTEMS ON BACTERIAL CONTAMINATION OF HIP ARTHROPLASTY WOUNDS. J Bone Joint Surg [Br] 2012; 94-B (SUPP XXI): 30-

14. McGovern PD, Albrecht M, Khan SK, Muller SD, Reed MR. The influence of surgical hoods and togas on airborne particle concentration at the surgical site: an experimental study. J Orthop Sci 2013; 18 (6): 1027-30

15. Young SW, Chisholm C, Zhu M. Intraoperative contamination and space suits: a potential mechanism. Eur J Orthop Surg Traumatol 2014; 24 (3): 409-13

16. Fraser JF, Young SW, Valentine KA, Probst NE, Spangehl MJ. The Gown-glove Interface Is a Source of Contamination: A Comparative Study. Clin Orthop Relat Res 2015; 473 (7): 2291-7

17. Singh VK, Hussain S, Javed S, Singh I, Mulla R, Kalairajah Y. Sterile surgical helmet system in elective total hip and knee arthroplasty. J Orthop Surg (Hong Kong) 2011; 19 (2): 234-7

18. Kearns KA, Witmer D, Makda J, Parvizi J, Jungkind D. Sterility of the personal protection system in total joint arthroplasty. Clin Orthop Relat Res 2011; 469 (11): 3065-9

19. Newton G, Brown S, Dias J, Bullock D. Can conventional theatre clothing be as effective as the “space suit”. J Bone Joint Surg [Br] 1991; 73 (Suppl II): 170

20. Shaw JA, Bordner MA, Hamory BH. Efficacy of the Steri-Shield filtered exhaust helmet in limiting bacterial counts in the operating room during total joint arthroplasty. J Arthroplasty 1996; 11 (4): 469-73

21. Pasquarella C, Pitzurra O, Herren T, Poletti L, Savino A. Lack of influence of body exhaust gowns on aerobic bacterial surface counts in a mixed-ventilation operating theatre. A study of 62 hip arthroplasties. J Hosp Infect 2003; 54 (1): 2-9

22. Friberg B, Friberg S, Ostensson R, Burman LG. Surgical area contamination--comparable bacterial counts using disposable head and mask and helmet aspirator system, but dramatic increase upon omission of head-gear: an experimental study in horizontal laminar air-flow. J Hosp Infect 2001; 47 (2): 110-5

23. Bohn WW, McKinsey DS, Dykstra M, Koppe S. The effect of a portable HEPA-filtered body exhaust system on airborne microbial contamination in a conventional operating room. Infect Control Hosp Epidemiol 1996; 17 (7): 419-22

24. Miner AL, Losina E, Katz JN, Fossel AH, Platt R. Deep infection after total knee replacement: impact of laminar airflow systems and body exhaust suits in the modern operating room. Infect Control Hosp Epidemiol 2007; 28 (2): 222-6

25. Pankhurst L, Taylor J, Cloutman-Green E, Hartley J, Lai K. Can Clean-Room Particle Counters be Used as an Infection Control Tool in Hospital Operating Theatres? Indoor Built Environ 2012; 21 (3): 381-91

26. Friberg B, Friberg S, Burman LG. Correlation between surface and air counts of particles carrying aerobic bacteria in operating rooms with turbulent ventilation: an experimental study. J Hosp Infect 1999; 42 (1): 61-8

27. Seal DV, Clark RP. Electronic particle counting for evaluating the quality of air in operating theatres: a potential basis for standards? J Appl Bacteriol 1990; 68 (3): 225-30

28. NZOA. The New Zealand Joint Registry Fifteen Year Report. New Zealand. 2014

29. Young SW, Zhu M, Shirley OC, Wu Q, Spangehl MJ. Do 'Surgical Helmet Systems' or 'Body Exhaust Suits' Affect Contamination and Deep Infection Rates in Arthroplasty? A Systematic Review. J Arthroplasty 2016; 31 (1): 225-33

30. Knibbs LD, He C, Duchaine C, Morawska L. Vacuum cleaner emissions as a source of indoor exposure to airborne particles and bacteria. Environ Sci Technol 2012; 46 (1): 534-42

31. Hambraeus A. Aerobiology in the operating room--a review. J Hosp Infect 1988; 11 Suppl A: 68-76

32. Howorth FH. Prevention of airborne infection during surgery. Lancet 1985; 1 (8425): 386-8

33. Hooper GJ, Rothwell AG, Frampton C, Wyatt MC. Does the use of laminar flow and space suits reduce early deep infection after total hip and knee replacement?: the ten-year results of the New Zealand Joint Registry. J Bone Joint Surg [Br] 2011; 93 (1): 85-90

34. Singh VK, Kalairajah Y. Splash in elective primary knee and hip replacement: are we adequately protected? J Bone Joint Surg [Br] 2009; 91 (8): 1074-7

35. Alani A, Modi C, Almedghio S, Mackie I. The risks of splash injury when using power tools during orthopaedic surgery: a prospective study. Acta Orthop Belg 2008; 74 (5): 678-82

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Figure Legends

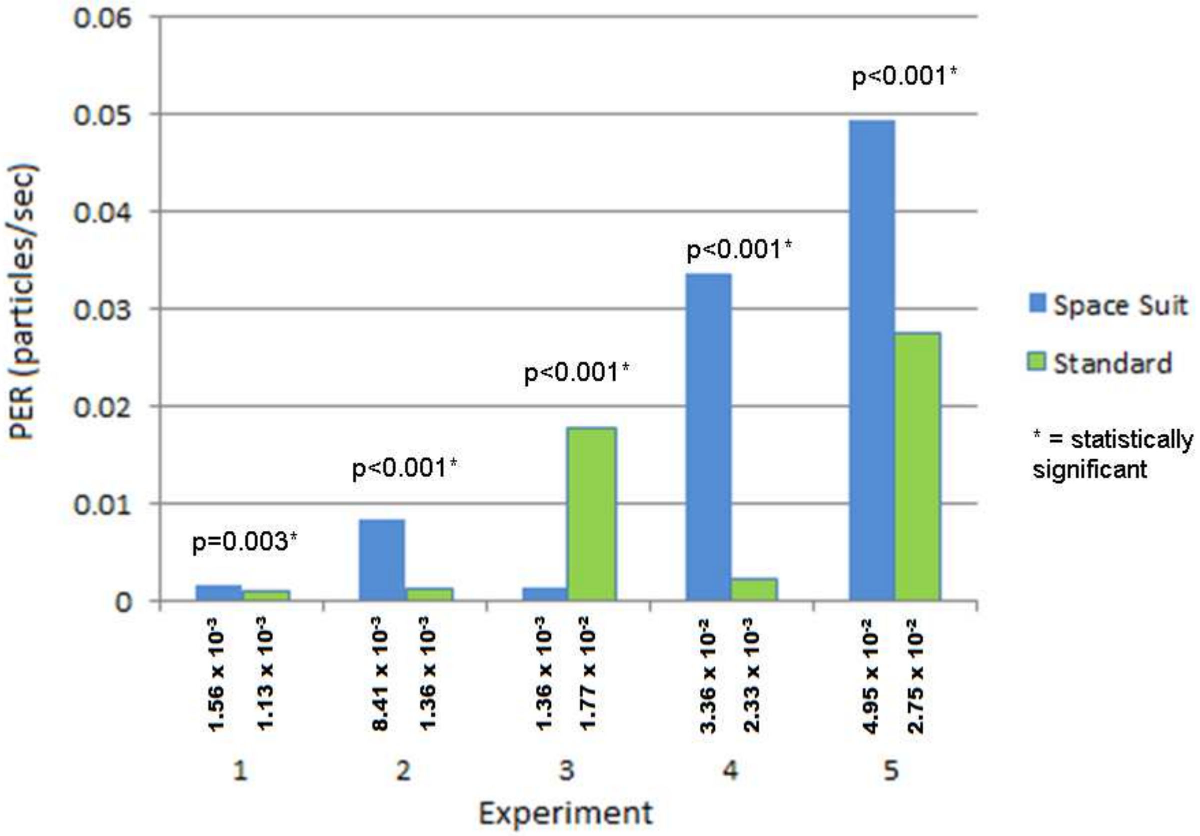
Figure 1: Mean of UVAPS particle emission rates space suit vs standard

Figure 2: Mean of OPC All particle emission rates space suit vs standard

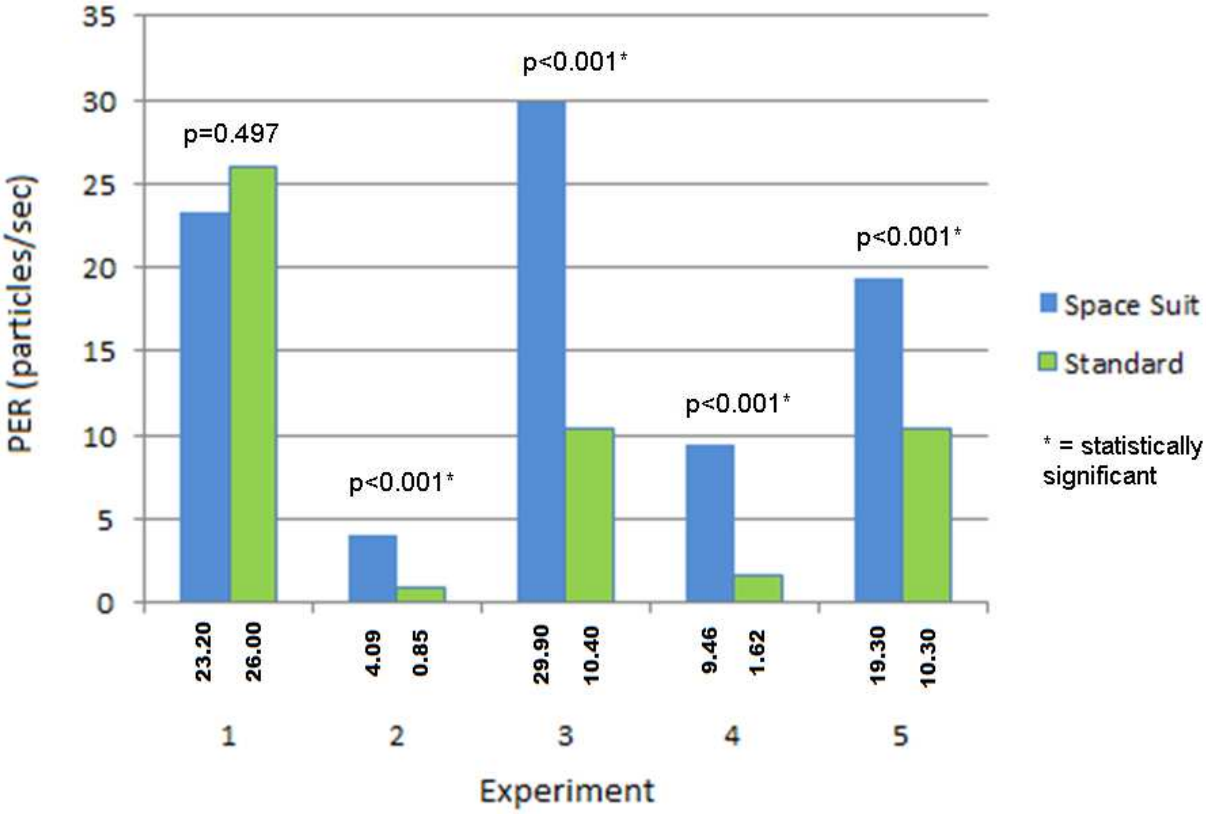
Figure 3: Mean of OPC Large particle emission rates space suit vs standard

Figure 4: Mean of microbiological emission rates at 24 hours

Figure 5: Mean of microbiological emission rates at 48 hours (Experiment 1 not read at 48 hours)



0.06
0.05
0.04
0.03
0.02
0.01
0
PER (particles/sec)
p=0.003*
p<0.001*
p<0.001*
p<0.001*
p<0.001*
1.56 x 10-3
1.13 x 10-3
8.41 x 10-3
1.36 x 10-3
1.36 x 10-3
1.77 x 10-2
3.36 x 10-2
2.33 x 10-3
4.95 x 10-2
2.75 x 10-2
1
2
3
4
5
Experiment
Space Suit
Standard
* = statistically significant



35
30
25
20
15
10
5
0
PER (particles/sec)
p=0.497
p<0.001*
p<0.001*
p<0.001*
p<0.001*
23.20
26.00
4.09
0.85
29.90
10.40
9.46
1.62
19.30
10.30
1
2
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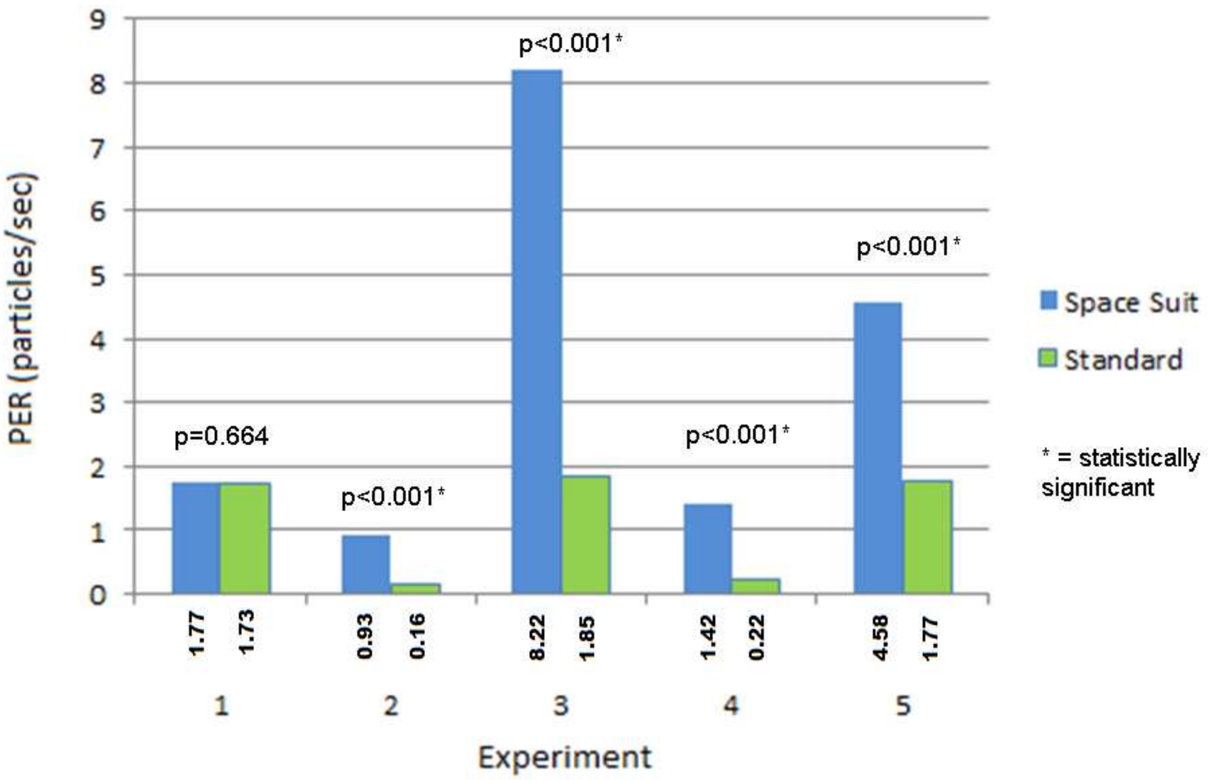
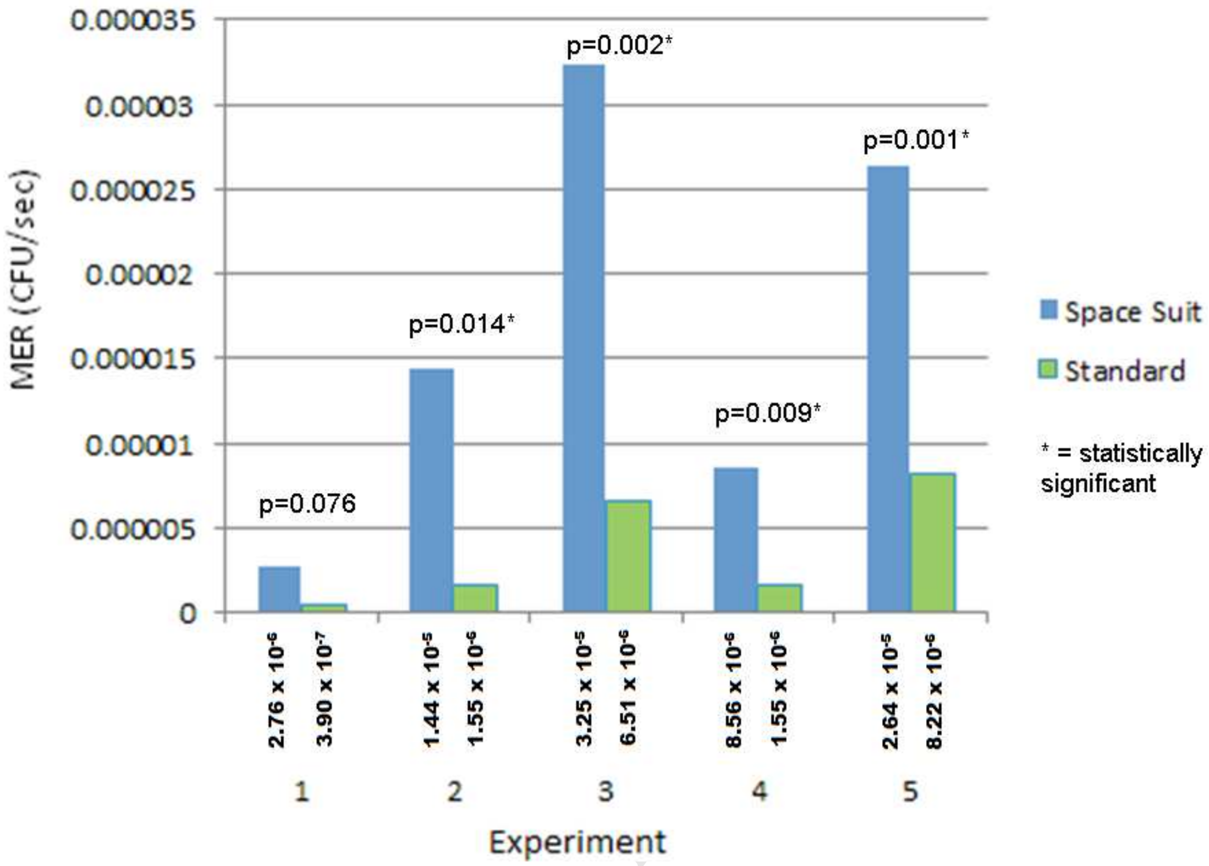
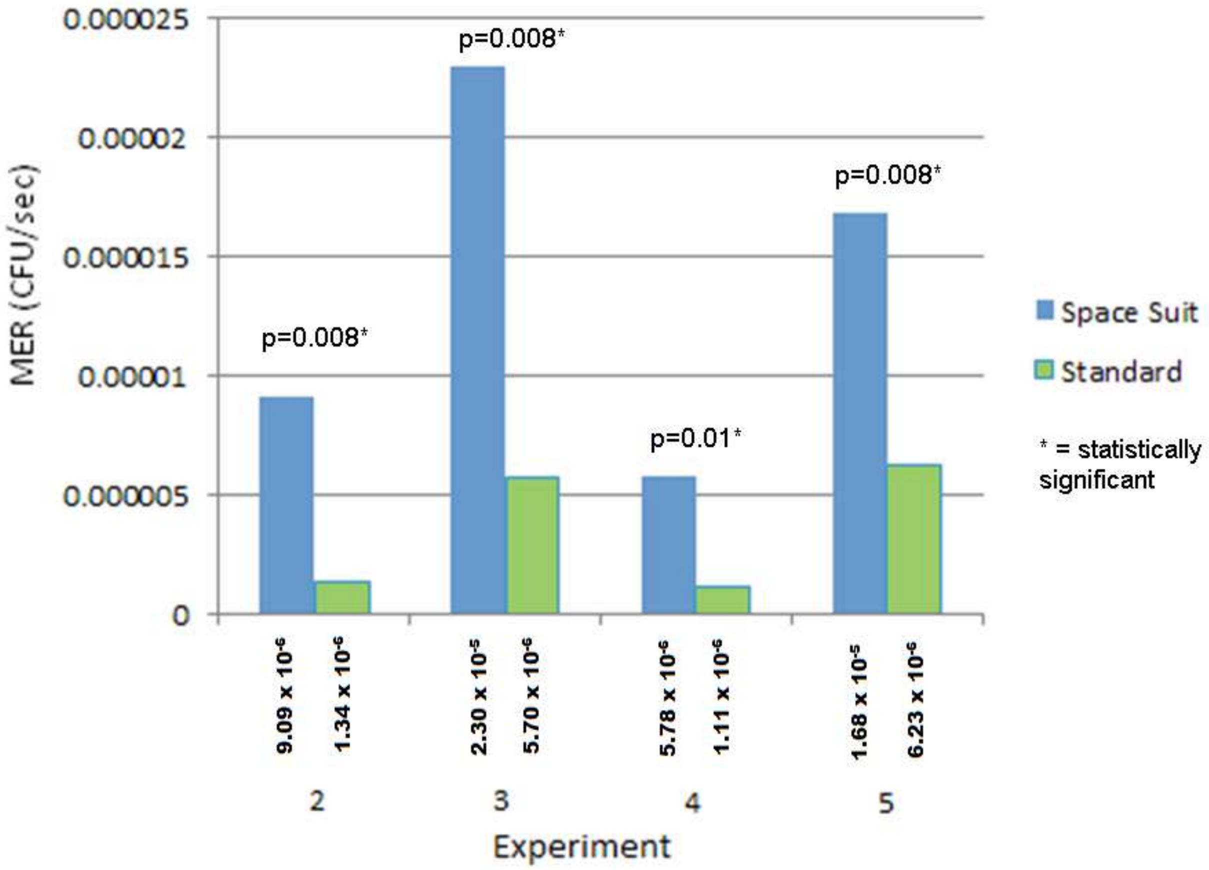
5
Experiment
Space Suit
Standard
* = statistically significant


9
8
7
6
5
4
3
2
1
0
PER (particles/sec)
p=0.664
p<0.001*
p<0.001*
p<0.001*
p<0.001*
1.77
1.73
0.93
0.16
8.22
1.85
1.42
0.22
4.58
1.77
1
2
3
4
5
Experiment
Space Suit
Standard
* = statistically significant



0.000035
0.00003
0.000025
0.00002
0.000015
0.00001
0.000005
0
MER (CFU/sec)
p=0.076
p=0.014*
p=0.002*
p=0.009*
p=0.001*
2.76 x 10-6
3.90 x 10-7
1.44 x 10-5
1.55 x 10-6
3.25 x 10-5
6.51 x 10-6
8.56 x 10-6
1.55 x 10-6
2.64 x 10-5
8.22 x 10-6
1
2
3
4
5
Experiment
Space Suit
Standard
* = statistically significant



0.000025
0.00002
0.000015
0.00001
0.000005
0
MER (CFU/sec)
p=0.008*
p=0.008*
p=0.008*
p=0.01*
Space Suit
Standard
* = statistically significant
9.09 x 10-6
1.34 x 10-6
2.30 x 10-5
5.70 x 10-6
5.78 x 10-6
1.11 x 10-6
1.68 x 10-5
6.23 x 10-6
2
3
4
5
Experiment