

Spring 6-2022

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The Effect of Media and Filtration in Inducing the Oxidative Stress Response in *Escherichia coli*

by

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An undergraduate honors thesis submitted in partial fulfillment of the requirements for the

degree of

Bachelors of Science

in

University Honors

and

Biology

Advisor

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Portland State University

2022

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ACKNOWLEDGEMENT

I would like to express my sincerest thanks to my thesis adviser, Dr. Justin Courcelle, for allowing me the opportunity to conduct undergraduate research in his lab. His character and enthusiasm over the knowledge he teaches is what made me want to study in his lab. This experience gave me crucial insight into laboratory research as a career, and ignited my passion for science. I would also like to thank Dr. Charmain Courcelle for being a guide and mentor. Her intellect and understanding of the subjects I was researching was inspiring. From her I learned about lab etiquette, how to conduct experiments, and write research papers, all things I will take with me into the future. Next, I would like to thank my lab mates who set good examples for me. Together we shared in the stresses of college and life, yet their dedication to their work is something I will always admire. Finally, I would like to thank my family and friends for pushing me to strive toward my goals, and encouraging me every step along the way. It is because of all these people that I have succeeded.

ABSTRACT

Escherichia coli grown in complex medium (LB), but not defined medium (DGC), arrest DNA replication when collected on membrane filters and resuspended in fresh medium. The arrest is similar to that observed when cells are challenged with hydrogen peroxide. Yet, the reason behind this arrest is unknown.

I hypothesized that the arrest in replication in complex medium after filtering might be due to oxidative shock, and therefore cells grown in complex medium and filtered should induce an oxidative stress response similar to cells treated with hydrogen peroxide. Utilizing the indicator dye H₂DCFDA, which fluoresces in response to reactive oxygen species, I established an assay to measure levels of oxidative stress in *E.coli* cultures treated with hydrogen peroxide and compared them to cells grown in complex medium and filtered. Using a deletion mutant in *oxyR*, which is sensitive to oxidative stress and unable to induce a cellular response to hydrogen peroxide, I assessed the fraction of fluorescent-positive *oxyR* cells grown in complex or defined media and filtered, to *oxyR* cells treated with hydrogen peroxide. Contrary to what I hypothesized, I found that filtration of cells grown in complex medium does not significantly induce oxidative stress. I discuss alternative reasons as to what may be causing replication to arrest, such as the lack of divalent metals like iron and manganese, osmotic stress and dehydration, the sensitivity of H₂DCFDA, and the difference in medium makeup.

INTRODUCTION

Reactive oxygen species (ROS) such as superoxide anions, hydrogen peroxide, and hydroxyl radicals are produced in organisms from all three domains of life (11, 15, 23, 25, 26). They can be generated as a byproduct of a cellular response to stressors such as bacteria and cytokines, or of aerobic metabolism (9, 16, 28). Cells encode multiple defense mechanisms to process excess reactive oxygen species. However, when a cell is unable to maintain homeostasis due to excess ROS, oxidative stress occurs (11, 25, 27, 28). Excess ROS occurs from endogenous sources or environmental exposure, and can damage proteins, lipids, and nucleic acids. Damage to DNA can result in a range of base and sugar modification products which negatively affects replication (15, 23, 25, 26). ROS have been linked to many age-associated diseases in humans such as mitochondrial dysfunction, cancer, cardiovascular diseases, and neurodegenerative diseases (10, 21, 23, 27, 29).

Reactive oxygen species also affect replication in bacteria such as *Escherichia coli*. Hydrogen peroxide can damage the integrity of the bacterial chromosome by oxidizing bases, causing lesions including 8-oxo-guanine, which mispair during replication or transcription, and thymine glycol, which block some RNA and DNA polymerases and can result in lethality (1, 2, 3, 14, 22). Such oxidized bases are normally repaired via the base excision repair pathway, which is initialized by 8-oxoguanine DNA glycosylase, endonuclease III, exonuclease III, or endonuclease IV (3, 14, 22).

In *E.coli*, the *oxyR* regulator is induced in the presence of certain reactive oxygen species such as free radicals. Another regulator, induced in the presence of superoxide free radicals, is the SoxR/S regulator (9, 11, 16). There is relatively little functional overlap between the stress

response pathways regulated by these two genes, though their respective stressors are chemically related. When activated by oxidative stress, these regulators induce transcription of several genes associated with DNA repair and other protective roles in removing and limiting oxidative damage in the cell (9, 11). Ferric Uptake Regulator, encoded by *fur*, is one gene that is activated by OxyR and SoxS. Fur is a transcription factor which responds to iron availability to control iron metabolism. OxyR binds to the *fur* promoter and SoxS to the upstream *fldA* promoter, to induce Fur expression and limit damage caused by the interaction of iron with hydrogen peroxide (9, 32, 35).

Iron acts as a cofactor for many enzymes involved in multiple metabolic pathways within the cell. It is vital for processes such as metabolism and ribonucleotide biosynthesis (6, 18, 25, 30, 31). However, iron is toxic in excess, due to its propensity to react with hydrogen peroxide via the Fenton reaction, the byproduct of which can severely damage cellular DNA (6, 18, 19, 24, 25, 30, 31). In contrast, manganese is capable of ameliorating the toxic effects of iron, since it is not readily oxidized by hydrogen peroxide and is able to remetallate a subset of iron-dependent enzymes following hydrogen peroxide-induced oxidative stress (5, 6, 18, 31). In addition, *E.coli* encodes several functionally redundant manganese-dependent enzymes that can catalyze iron-cofactored reactions inactivated by hydrogen peroxide (5, 6, 31).

In *E.coli*, oxidative stress induced by hydrogen peroxide treatment transiently inhibits cellular replication. Yet, resumption of replication was observed even in the absence of lesion removal (17, 36). It was observed that restoration of replication relies on the presence of manganese in the growth medium. This demonstrates that the physical disruption to the DNA caused by hydrogen peroxide is not the cause of cellular arrest. Rather, replication is enzymatically inactivated, likely by oxidation of an iron-dependent protein, which requires

manganese to restore synthesis (17). It has also been observed that cell cultures supplemented with manganese recovered DNA synthesis at a faster rate than those supplemented with iron or nonsupplemented (18).

A transient arrest in replication has also been observed in filtered cells grown in complex medium, but not defined medium (Wang, Hackert, Courcelle, unpublished data). This behavior is similar to what is observed following hydrogen peroxide treatment, however, whether filtration is causing oxidative stress and inducing this arrest is unknown. To determine whether filtration of complex medium-grown cells arrest replication as a result of oxidative stress, I established an assay to determine whether the fluorogenic dye, H₂DCFDA, could be used to detect oxidative stress. I then conducted an experiment where I grew cells in complex or defined medium, filtered or mock-treated them, and visualized their levels of fluorescence. I found that filtering cultures grown in complex medium did not significantly increase the percentage of H₂DCFDA-positive cells in the presence of oxidative stress, suggesting the arrest of replication following filtration is not due to the induction of oxidative stress.

MATERIALS & METHODS

Media

Luria-Bertani (LB) was used as the complex medium, and phosphate-buffered Davis medium supplemented with 0.4% glucose and 0.2% casamino acids (DGC), as the defined medium.

Bacterial strains

E. coli K-12 strain BW25113 and its *oxyR* mutant derivative from the Keio collection were used in this study (8).

H₂DCFDA staining following hydrogen peroxide or filtration treatment

Fresh overnight cultures were diluted 1:100 in DGC and grown at 37°C to mid-log. 1-ml aliquots were removed from each culture as mock-treated controls, and the remaining cells were treated with 10mM hydrogen peroxide for 30 minutes. At the end of this treatment time, 1-ml aliquots were removed from the hydrogen peroxide-exposed cultures. Cells from each treatment were collected by centrifugation for 2 minutes at 14,000 rpm, washed once in 1-ml of phosphate-buffered saline (PBS: 137 mM NaCl, 10 mM Na₂HPO₄, 1.8 mM KH₂PO₄, and 2.7 mM KCl), and then resuspended in 1-ml mixture of PBS supplemented with 10 mM H₂DCFDA. Cells were incubated with dye in a 37°C water bath, shaking in the dark for 30 minutes. 0.5-ml aliquots were removed, and cells were collected by centrifugation. Cell pellets were washed once in 1-ml PBS, before resuspension in 100- μ l PBS. 5- μ l aliquots were removed and spotted on agar pads for visualization by microscopy. Cells were observed under 40X magnification, H₂DCFDA fluorescence was observed using a blue light filter (515 nm emittance/ 410-490 nm excitation).

For filtration treatment, fresh overnight cultures were diluted 1:100 in DGC or LB media and grown at 37°C to mid-log. 1-ml aliquots were removed from each culture for mock-treated

controls, while 5-ml of each remaining culture was filtered on 0.45- μ m nitrocellulose membranes and resuspended in 5-ml of the appropriate fresh medium. As a control for H₂DCFDA staining, cells grown in DGC medium were also treated with 10mM hydrogen peroxide for 30 minutes. 1-ml aliquots were collected from the filtered and hydrogen peroxide-treated cultures. Cells from all treatments were collected by centrifugation, then processed and visualized as described above.

RESULTS

H₂DCFDA as an indicator of oxidative stress

Arrest in DNA replication was previously observed in *E.coli* grown in complex medium and filtered (Wang, Hackert, Courcelle, unpublished data). The arrest was similar to that observed when cells were challenged with hydrogen peroxide. I hypothesized that this arrest in replication may be due to oxidative shock. To test this, I developed an assay using H₂DCFDA, an indicator of oxidative stress, to help visualize stress caused by hydrogen peroxide. H₂DCFDA readily diffuses into cells and is oxidized by reactive oxygen species into 2', 7'-dichlorohydrofluorescein (DCF) which is highly fluorescent (4, 10). Wild-type and *oxyR* mutant cells were grown in defined medium to mid-log, treated with 10 mM hydrogen peroxide for 30 minutes, and then stained with H₂DCFDA. The *oxyR* strain lacks the master regulator of the oxidative stress response in *E.coli*. Therefore, *oxyR* cells treated with hydrogen peroxide and dyed with H₂DCFDA should have a high ratio of fluorescing to non-fluorescing cells.

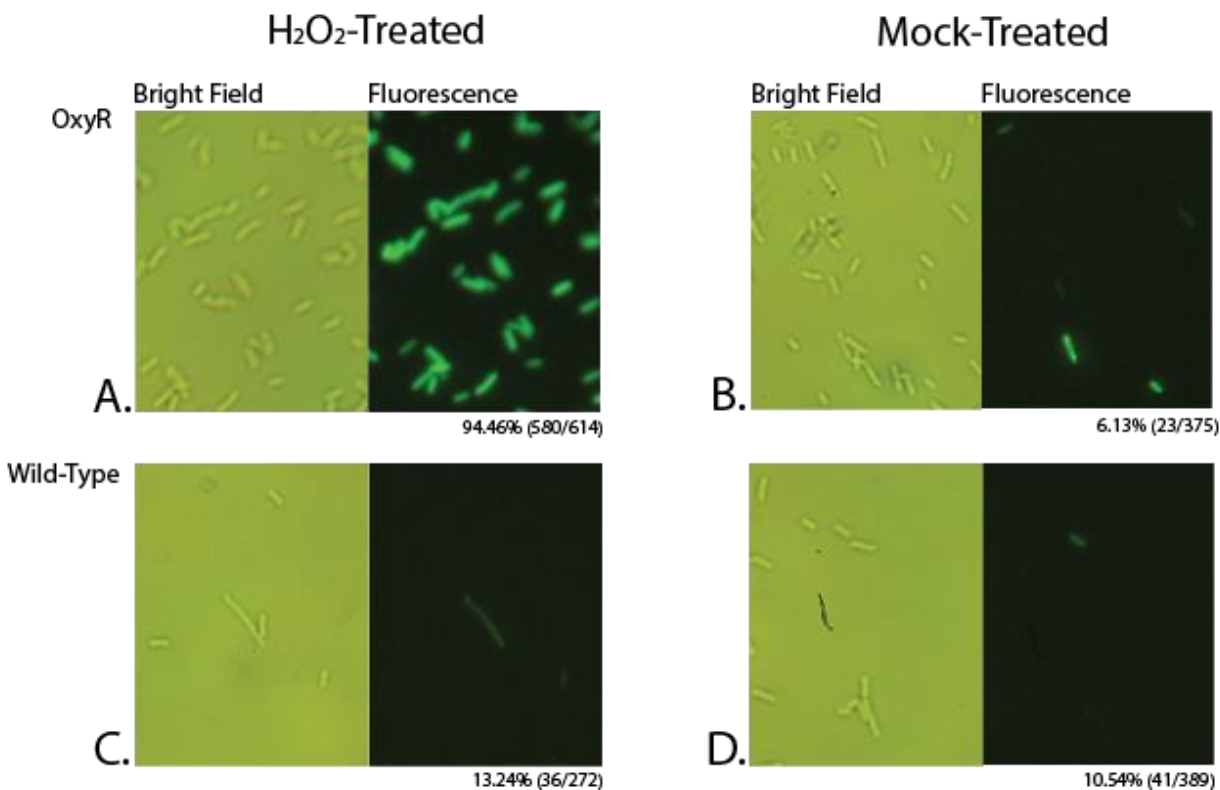


Figure 1: H₂DCFDA as an indicator of oxidative stress. Wild-type and *oxyR* cells were grown to mid-log and either treated with 10mM hydrogen peroxide for 30 min or mock-treated. Cells were collected, stained with H₂DCFDA and visualized by bright field and fluorescence microscopy at 40X magnification. Representative images from hydrogen peroxide- and mock-treated wild-type and *oxyR* cultures are shown. A minimum of 270 cells were evaluated for fluorescence staining. The percentage of fluorescing cells in each population was determined and is shown in the bottom right corner of each fluorescence micrograph.

When mock-treated, 10.54% of wild-type cells were found to fluoresce (Figure 1D). When treated with hydrogen peroxide, 13.24% of wild-type cells were found to fluoresce (Figure 1C). This is expected, because wild-type cells contain the master regulator of the oxidative stress response and therefore are able to process hydrogen peroxide. In contrast, 6.13% of mock-treated, *oxyR* cells were found to fluoresce (Figure 1B). When treated with hydrogen peroxide, 94.46% of *oxyR* cells were found to fluoresce (Figure 1A), more than an eight-fold increase. Therefore, H₂DCFDA is a suitable dye for observing oxidative stress.

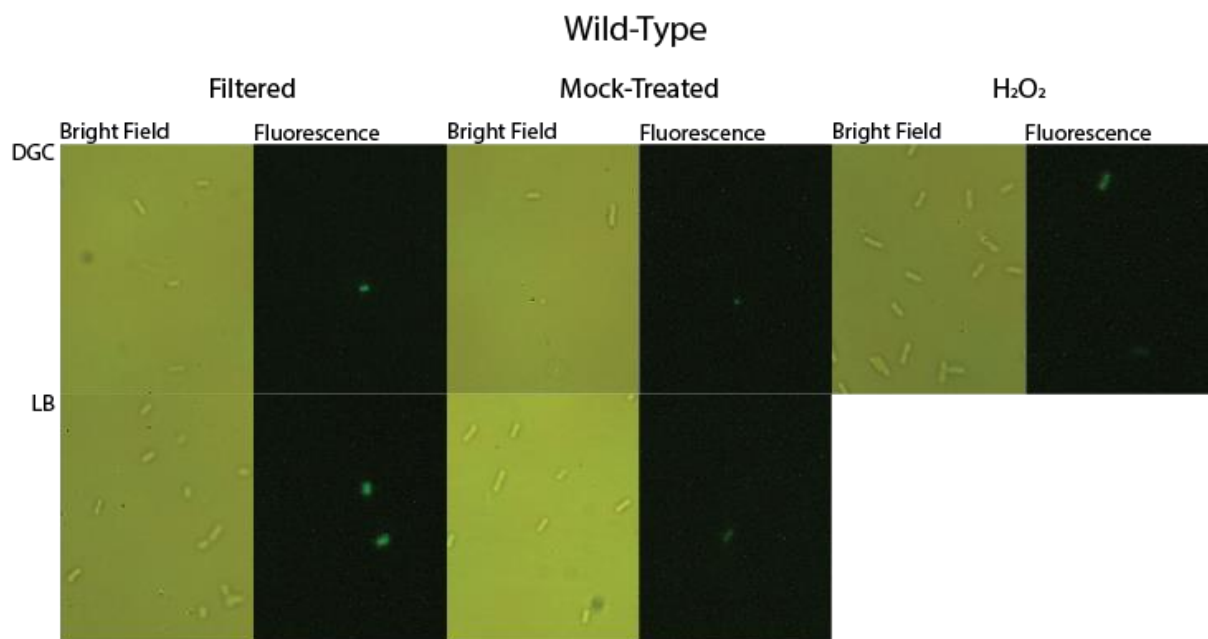


Figure 2A

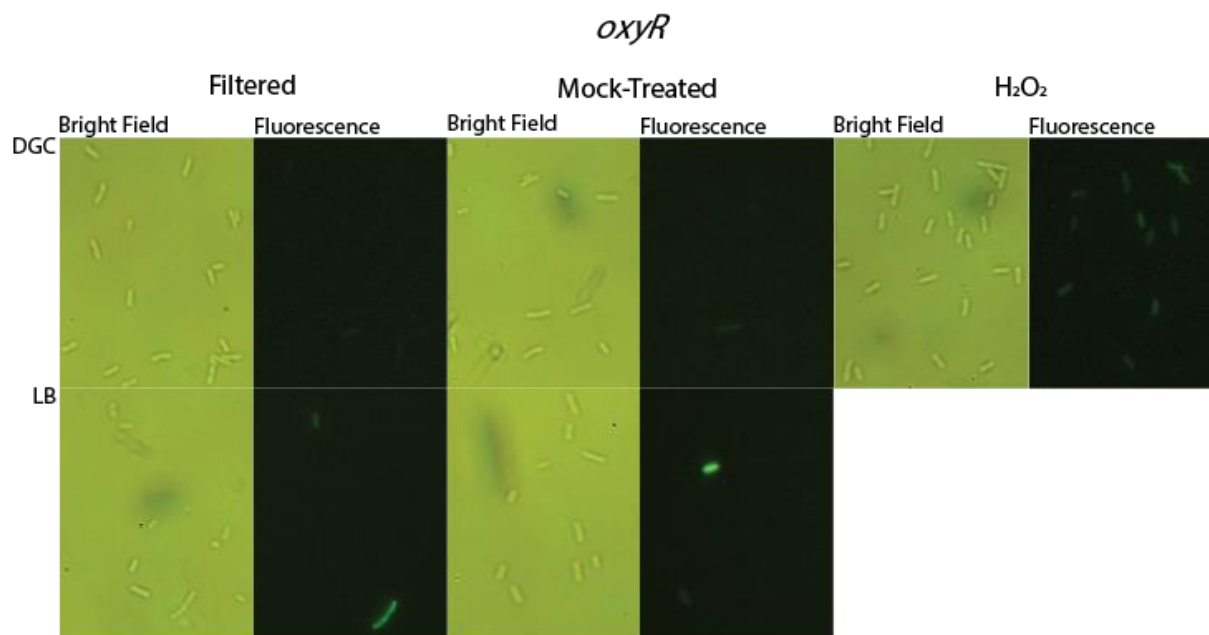


Figure 2B

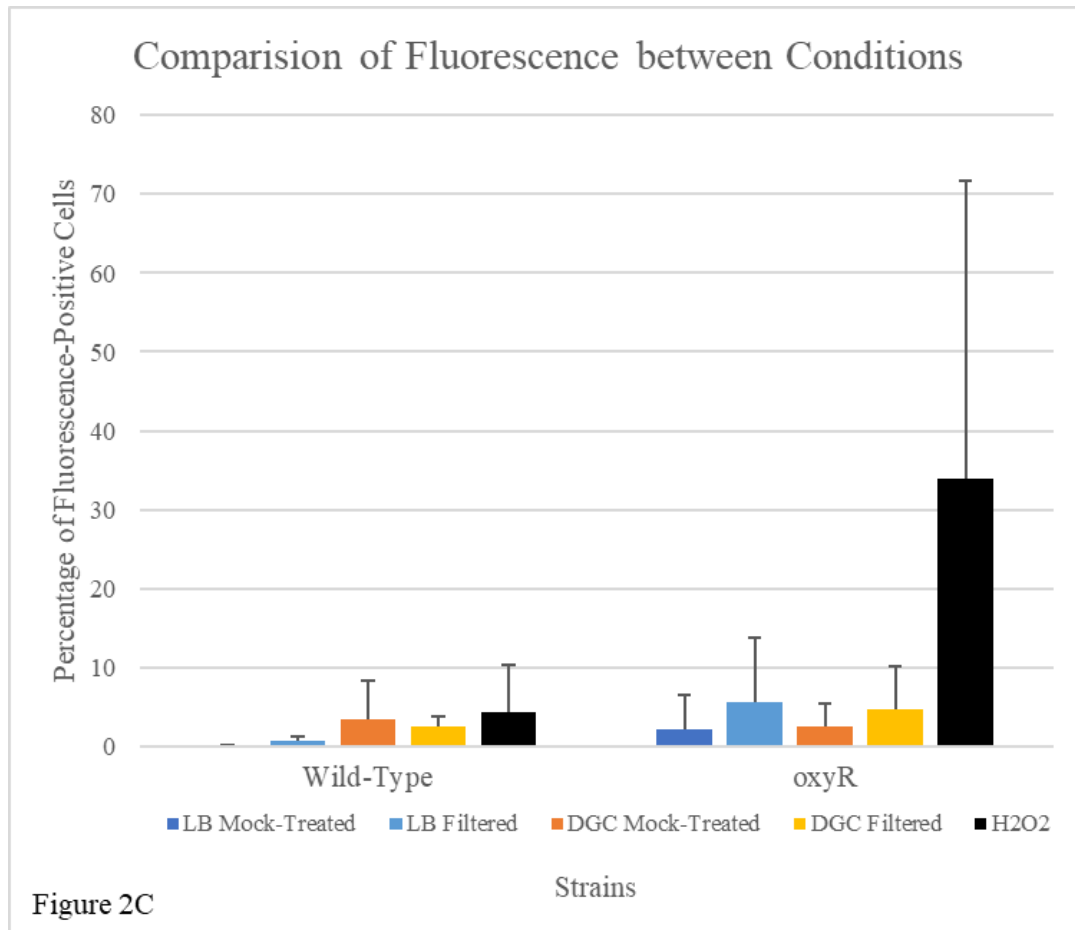


Figure 2: Filtering cells grown in complex medium does not significantly induce oxidative stress. Cells were cultured in either rich or defined growth medium to mid-log, filtered, and resuspended in fresh medium. Aliquots were removed, stained with H₂DCFDA and viewed as for Fig. 1. Representative images for (A) wild-type and (B) *oxyR* cells are shown, along with their respective hydrogen peroxide-treated controls for H₂DCFDA staining. (C) The percentage of fluorescent-positive cells for each growth condition is plotted for wild-type and *oxyR* strains. The bar graphs show an average of at least three independent experiments. Error bars represent plus one standard deviation.

Filtering cells grown in complex medium does not significantly induce oxidative stress

My previous results demonstrated the utility of H₂DCFDA in visualizing oxidative stress following hydrogen peroxide treatment, however it was unknown whether filtration following growth in complex medium induced a similar stress response. To determine this directly, cells were grown in either DGC (defined) or LB (complex) medium, filtered through a nitrocellulose

membrane, and resuspended in fresh growth medium. Treated cells were then stained with H₂DCFDA, and visualized using microscopy as described above. To assess the efficiency of H₂DCFDA staining I also visualized hydrogen peroxide-treated wild-type and *oxyR* cells in every experiment. If filtration causes a similar arrest in cellular replication as oxidative stress induced by reactive oxygen species, then filtered populations grown in LB would be expected to have an increased percentage of fluorescence-positive compared to mock-treated samples or those grown in DGC.

3.36% of wild-type cells grown in DGC and mock-treated were found to fluoresce. When treated with hydrogen peroxide, 4.27% of wild-type cells were found to fluoresce (Figure 2A). 2.5% of cells deficient in OxyR, grown in DGC, and mock-treated were found to fluoresce. When treated with hydrogen peroxide, 33.94% of *oxyR* cells were found to fluoresce (Figure 2B). This is consistent with a role of *oxyR* in responding to oxidative challenge, and demonstrates the efficiency of H₂DCFDA staining in detecting hydrogen peroxide-induced oxidative stress.

It has been previously shown that wild-type cells grown in defined medium and filtered do not experience the cellular replication inhibition that is seen in filtered, LB-grown cells. This suggests that DGC medium does not trigger the same cellular response as filtration of LB-grown cultures (Wang, Hackert, Courcelle, unpublished data). If filtration after LB, but not DGC, growth induces oxidative stress, then I predicted that both mock-treated and filtered wild-type cells grown in DGC should have similar H₂DCFDA fluorescence levels. 2.44% of wild-type cells grown in DGC and filtered were found to fluoresce, compared to 3.36% H₂DCFDA-positive fluorescence seen in mock-treated, wild-type cells (Figure 2A). This result is consistent with our hypothesis that filtration of wild-type cells grown in DGC does not cause oxidative

stress. When I examined *oxyR* cells grown in DGC and filtered, 4.64% of cells were found to fluoresce, compared to 2.5% H₂DCFDA-positive fluorescence seen in mock-treated *oxyR* cells, similar to what I observed in wild-type cells (Figure 2B).

I predicted that cells grown in LB and mock-treated would have a similar level of fluorescence to that seen in mock-treated cells grown in DGC medium. I also hypothesized that cells grown in LB and filtered would have an increased level of fluorescence over mock-treated cells grown in either type of medium, due to oxidative stress caused by filtration. 0.11% of wild-type cells grown in LB and mock-treated were found to fluoresce. When filtered, 0.64% of wild-type cells were found to fluoresce, about a sixfold increase (Figure 2A). In *oxyR* cells grown in LB and mock-treated, 2.2% of cells were found to fluoresce. When filtered, 5.63% of *oxyR* cells grown in LB were found to fluoresce, about a two-and-a-half-fold increase over its mock-treated counterpart (Figure 2B). While the increase in H₂DCFDA fluorescence following filtration of LB-grown cultures over mock-treatment appears to support my hypothesis that filtration is causing oxidative stress, I observed wide variation in the percentage of fluorescence-positive cells between experimental populations, as shown by the error bars included in my graphs (Figure 2C). Therefore, it is unlikely that filtration is causing significant oxidative stress in LB-grown cells.

DISCUSSION

Filtration of *E.coli* grown in complex medium leads to a temporary arrest in cellular replication that is restored approximately 15 minutes after the culture is resuspended in fresh medium (Wang, Hackert, Courcelle, unpublished data). The filtration effect on replication is similar to what is observed after oxidative shock due to peroxide species (6, 18, 25, 26). In my thesis I addressed the question, does filtration of LB-grown cells induce oxidative stress? I filtered LB-grown cells and compared the percentage of cells staining positive for the ROS-responsive dye H₂DCFDA to those seen in mock-treated, LB-grown cells. I found that there was no difference in the percentage of fluorescent-positive cells in filtered versus mock-treated cultures grown in LB.

There are several possible reasons that H₂DCFDA did not induce fluorescence in the filtered cells. While I cannot rule out the possibility that modest oxidative stress is induced during filtration sufficient enough to inhibit replication, such levels may be below the threshold of detection when using H₂DCFDA as an indicator. The most likely interpretation of my results is that filtration simply does not induce oxidative stress inside cells. If this is the case, then the inhibition of replication could be caused by one of several other possible variables between the complex and defined media. These might include differences in divalent metal concentrations- such as iron and manganese in the cell, differences in the osmotic stress and dehydration induced by these media due to potassium and magnesium concentrations, or possibly other differences of potentially a rare or minor component found in the complex media that is absent in minimal, defined media.

Iron plays a vital role in the metabolism of many organisms. It acts as a nutrient, functioning as a cofactor for multiple enzymes involved in metabolic pathways (6, 7, 18, 25, 30,

31). It also acts as an electron acceptor, extending the viability of cells for cultivation in both aerobic and anaerobic conditions (7). However, excess or unbound iron poses a potential threat to a cell. When in contact with hydrogen peroxide, a natural byproduct of cellular metabolism, iron can generate reactive oxygen species such as hydroxyl radicals via the Fenton Reaction (6, 18, 25, 30, 31). This can damage the integrity of various lipids, proteins, and DNA (6, 18, 25, 30, 31). To prevent oxidative damage to iron-associated enzymes, manganese, which does not react with hydrogen peroxide, may be used in place of iron to restore the function of certain proteins (6, 18, 25, 31).

Levels of iron and manganese are regulated within a cell to allow for the optimal presence and function of metal-dependent enzymes (18, 25, 30). If *E.coli* has too much iron, it could be toxic to the cell. If *E.coli* are lacking such metals, it may not be able to activate certain metal-dependent enzymes crucial for the functionality of the cell (18, 25, 30, 31). DGC and LB have different concentrations of iron and manganese. DGC contains 117.04 μM manganese and 489.75 μM iron. LB contains 184.21 μM manganese and 4,326.98 μM iron (18). Filtration may deplete intracellular metal concentrations, and it's possible that cells grown in DGC are better adapted to the minimal levels of iron and manganese present. Therefore, filtration may not cause as great a shock to them as to cells grown in LB. Filtration may also have the same effect on LB as if the cell was being starved of nutrients. If this is the case then cells grown in DGC, because it lacks other nutrients in the same concentration as LB, may also be more adapted to filtration (20).

The act of filtration may also lead to osmotic stress in *E.coli*. High-salt or high-solute environments lead to osmotic stress and dehydration in bacteria such as *Bacillus subtilis* and *Escherichia coli* (12, 13, 34). It has been proposed that increases in cytoplasmic potassium is the

main regulatory signal that activates other osmotically controlled responses (12). In *B. subtilis*, one response to high salt stress is to transiently raise the level of potassium ions, resulting in bacteriostasis (34). It has been shown that with the influx of potassium follows an efflux of intracellular magnesium, and this depletion of magnesium is the rate-limiting factor in the resumption of growth. Without magnesium import to compensate, *B. subtilis* is not able to counter the effects of a high-salt or high-solute environment, and the resumption of growth does not occur (34). DGC contains 392.1 μM magnesium, whereas LB contains 81.87 μM magnesium (33). It may be that filtration affects DGC-grown cells less due to the higher levels of magnesium in the medium. Since LB medium contains lower levels of magnesium, when filtered, LB-grown cells may not be able to import enough of the ion to restore it to a biocompatible level. This may lead to sustained osmotic stress, and an arrest in replication (34).

Finally, H₂DCFDA may not be sensitive enough to detect low levels of oxidative stress. It is possible that a certain threshold of reactive oxygen species needs to be present to activate H₂DCFDA. If the dye was unable to be altered from a non-fluorescent chemical to a fluorescence one, then the level of fluorescence observed may be inaccurate to the amount of stress the cells were experiencing. It may also be that filtration decreases cell permeability. If this is the cause, then H₂DCFDA would not be able to enter the cell and detect ROS, resulting in low fluorescence levels.

Future studies examining osmotic stress, supplementation with different metals, or use of a different oxidative stress dye will be required to determine the effects of filtration on replication progression.

REFERENCES

1. Aguiar, P. H., Furtado, C., Repolês, B. M., Ribeiro, G. A., Mendes, I. C., Peloso, E. F., Gadelha, F. R., Macedo, A. M., Franco, G. R., Pena, S. D., Teixeira, S. M., Vieira, L. Q., Guarneri, A. A., Andrade, L. O., & Machado, C. R. (2013). Oxidative stress and DNA lesions: the role of 8-oxoguanine lesions in *Trypanosoma cruzi* cell viability. *PLoS neglected tropical diseases*, *7*(6), e2279. <https://doi.org/10.1371/journal.pntd.0002279>
2. Alanazi, M., Leadon, S. A., & Mellon, I. (2002). Global genome removal of thymine glycol in *Escherichia coli* requires endonuclease III but the persistence of processed repair intermediates rather than thymine glycol correlates with cellular sensitivity to high doses of hydrogen peroxide. *Nucleic acids research*, *30*(21), 4583–4591. <https://doi.org/10.1093/nar/gkf588>
3. Allgayer, J., Kitsera, N., von der Lippen, C., Epe, B., & Khobta, A. (2013). Modulation of base excision repair of 8-oxoguanine by the nucleotide sequence. *Nucleic acids research*, *41*(18), 8559–8571. <https://doi.org/10.1093/nar/gkt620>
4. Ameziane-El-Hassani, R. and Dupuy, C. (2013). Detection of Intracellular Reactive Oxygen Species (CM-H₂DCFDA). *Bio-protocol* *3*(1): e313. DOI: 10.21769/BioProtoc.313
5. Anjem, A., & Imlay, J. A. (2012). Mononuclear iron enzymes are primary targets of hydrogen peroxide stress. *The Journal of biological chemistry*, *287*(19), 15544–15556. <https://doi.org/10.1074/jbc.M111.330365>
6. Anjem, A., Varghese, S., & Imlay, J. A. (2009). Manganese import is a key element of the OxyR response to hydrogen peroxide in *Escherichia coli*. *Molecular microbiology*, *72*(4), 844–858. <https://doi.org/10.1111/j.1365-2958.2009.06699.x>

7. Appenzeller, B. M., Yañez, C., Jorand, F., & Block, J. C. (2005). Advantage provided by iron for *Escherichia coli* growth and cultivability in drinking water. *Applied and environmental microbiology*, *71*(9), 5621–5623. <https://doi.org/10.1128/AEM.71.9.5621-5623.2005>
8. Baba, T., Ara, T., Hasegawa, M., Takai, Y., Okumura, Y., Baba, M., Datsenko, K. A., Tomita, M., Wanner, B. L., & Mori, H. (2006). Construction of *Escherichia coli* K-12 in-frame, single-gene knockout mutants: the Keio collection. *Molecular systems biology*, *2*, 2006.0008. <https://doi.org/10.1038/msb4100050>
9. Chiang, S. M., & Schellhorn, H. E. (2012). Regulators of oxidative stress response genes in *Escherichia coli* and their functional conservation in bacteria. *Archives of biochemistry and biophysics*, *525*(2), 161–169. <https://doi.org/10.1016/j.abb.2012.02.007>
10. Eruslanov, E., & Kusmartsev, S. (2010). Identification of ROS using oxidized DCFDA and flow-cytometry. *Methods in molecular biology (Clifton, N.J.)*, *594*, 57–72. https://doi.org/10.1007/978-1-60761-411-1_4
11. Farr, S. B., & Kogoma, T. (1991). Oxidative stress responses in *Escherichia coli* and *Salmonella typhimurium*. *Microbiological reviews*, *55*(4), 561–585. <https://doi.org/10.1128/mr.55.4.561-585.1991>
12. Gunasekera, T. S., Csonka, L. N., & Paliy, O. (2008). Genome-wide transcriptional responses of *Escherichia coli* K-12 to continuous osmotic and heat stresses. *Journal of bacteriology*, *190*(10), 3712–3720. <https://doi.org/10.1128/JB.01990-07>
13. Guo, Y., Winkler, J., & Kao, K. C. (2017). Insights on Osmotic Tolerance Mechanisms in *Escherichia coli* Gained from an *rpoC* Mutation. *Bioengineering (Basel, Switzerland)*, *4*(3), 61. <https://doi.org/10.3390/bioengineering4030061>

14. Hagensee, M. E., & Moses, R. E. (1989). Multiple pathways for repair of hydrogen peroxide-induced DNA damage in *Escherichia coli*. *Journal of bacteriology*, *171*(2), 991–995. <https://doi.org/10.1128/jb.171.2.991-995.1989>
15. Halliwell, B., & Whiteman, M. (2004). Measuring reactive species and oxidative damage in vivo and in cell culture: how should you do it and what do the results mean?. *British journal of pharmacology*, *142*(2), 231–255. <https://doi.org/10.1038/sj.bjp.0705776>
16. Herb, M., & Schramm, M. (2021). Functions of ROS in Macrophages and Antimicrobial Immunity. *Antioxidants (Basel, Switzerland)*, *10*(2), 313. <https://doi.org/10.3390/antiox10020313>
17. Hoff, C.A., Schmidt, S. S., Hackert, B. J., Worley, T. K., Courcelle, J., & Courcelle, C. T. (2021). Events associated with DNA replication disruption are not observed in hydrogen peroxide-treated *Escherichia coli*. *G3 Genes/Genomes/Genetics*, Volume 11, Issue 4, April 2021, jkab044, <https://doi.org/10.1093/g3journal/jkab044>
18. Hutfilz, C. R., Wang, N. E., Hoff, C. A., Lee, J. A., Hackert, B. J., Courcelle, J., & Courcelle, C. T. (2019). Manganese Is Required for the Rapid Recovery of DNA Synthesis following Oxidative Challenge in *Escherichia coli*. *Journal of bacteriology*, *201*(24), e00426-19. <https://doi.org/10.1128/JB.00426-19>
19. Imlay, J. A., Chin, S. M., & Linn, S. (1988). Toxic DNA damage by hydrogen peroxide through the Fenton reaction in vivo and in vitro. *Science (New York, N.Y.)*, *240*(4852), 640–642. <https://doi.org/10.1126/science.2834821>
20. Jenkins, D. E., Schultz, J. E., & Matin, A. (1988). Starvation-induced cross protection against heat or H₂O₂ challenge in *Escherichia coli*. *Journal of bacteriology*, *170*(9), 3910–3914. <https://doi.org/10.1128/jb.170.9.3910-3914.1988>

21. Kudryavtseva, A. V., Krasnov, G. S., Dmitriev, A. A., Alekseev, B. Y., Kardymon, O. L., Sadritdinova, A. F., Fedorova, M. S., Pokrovsky, A. V., Melnikova, N. V., Kaprin, A. D., Moskalev, A. A., & Snezhkina, A. V. (2016). Mitochondrial dysfunction and oxidative stress in aging and cancer. *Oncotarget*, 7(29), 44879–44905.
<https://doi.org/10.18632/oncotarget.9821>
22. Laspia, M. F., & Wallace, S. S. (1988). Excision repair of thymine glycols, urea residues, and apurinic sites in *Escherichia coli*. *Journal of bacteriology*, 170(8), 3359–3366.
<https://doi.org/10.1128/jb.170.8.3359-3366.1988>
23. Liguori, I., Russo, G., Curcio, F., Bulli, G., Aran, L., Della-Morte, D., Gargiulo, G., Testa, G., Cacciatore, F., Bonaduce, D., & Abete, P. (2018). Oxidative stress, aging, and diseases. *Clinical interventions in aging*, 13, 757–772.
<https://doi.org/10.2147/CIA.S158513>
24. Lloyd, R. V., Hanna, P. M., & Mason, R. P. (1997). The origin of the hydroxyl radical oxygen in the Fenton reaction. *Free radical biology & medicine*, 22(5), 885–888.
[https://doi.org/10.1016/s0891-5849\(96\)00432-7](https://doi.org/10.1016/s0891-5849(96)00432-7)
25. Mendoza-Chamizo, B., Løbner-Olesen, A., & Charbon, G. (2018). Coping with Reactive Oxygen Species to Ensure Genome Stability in *Escherichia coli*. *Genes*, 9(11), 565.
<https://doi.org/10.3390/genes9110565>
26. Pizzino, G., Irrera, N., Cucinotta, M., Pallio, G., Mannino, F., Arcoraci, V., Squadrito, F., Altavilla, D., & Bitto, A. (2017). Oxidative Stress: Harms and Benefits for Human Health. *Oxidative medicine and cellular longevity*, 2017, 8416763.
<https://doi.org/10.1155/2017/8416763>

27. Poljsak, B., Šuput, D., & Milisav, I. (2013). Achieving the balance between ROS and antioxidants: when to use the synthetic antioxidants. *Oxidative medicine and cellular longevity*, 2013, 956792. <https://doi.org/10.1155/2013/956792>
28. Ray, P. D., Huang, B. W., & Tsuji, Y. (2012). Reactive oxygen species (ROS) homeostasis and redox regulation in cellular signaling. *Cellular signalling*, 24(5), 981–990. <https://doi.org/10.1016/j.cellsig.2012.01.008>
29. Richter, C., Park, J. W., & Ames, B. N. (1988). Normal oxidative damage to mitochondrial and nuclear DNA is extensive. *Proceedings of the National Academy of Sciences of the United States of America*, 85(17), 6465–6467. <https://doi.org/10.1073/pnas.85.17.6465>
30. Sepúlveda Cisternas, I., Salazar, J. C., & García-Angulo, V. A. (2018). Overview on the Bacterial Iron-Riboflavin Metabolic Axis. *Frontiers in microbiology*, 9, 1478. <https://doi.org/10.3389/fmicb.2018.01478>
31. Sobota, J. M., & Imlay, J. A. (2011). Iron enzyme ribulose-5-phosphate 3-epimerase in *Escherichia coli* is rapidly damaged by hydrogen peroxide but can be protected by manganese. *Proceedings of the National Academy of Sciences of the United States of America* vol. 108,13 (2011): 5402-7. <https://doi.org/10.1073/pnas.1100410108>
32. Troxell, B., & Hassan, H. M. (2013). Transcriptional regulation by Ferric Uptake Regulator (Fur) in pathogenic bacteria. *Frontiers in cellular and infection microbiology*, 3, 59. <https://doi.org/10.3389/fcimb.2013.00059>
33. Varghese, S., Wu, A., Park, S., Imlay, K. R., & Imlay, J. A. (2007). Submicromolar hydrogen peroxide disrupts the ability of Fur protein to control free-iron levels in

Escherichia coli. *Molecular microbiology*, 64(3), 822–830.

<https://doi.org/10.1111/j.1365-2958.2007.05701.x>

34. Wendel, Brian M., Hualiang, P., Krüger, L., Herzber, C., Stülke, J., & Helmann, J. D.

(2022). A Central Role for Magnesium Homeostasis during Adaptation to Osmotic

Stress. Edited by Mark S. Turner, *American Society for Microbiology*.

<https://journals.asm.org/doi/full/10.1128/mbio.00092-22>.

35. Zheng, M., Doan, B., Schneider, T. D., & Storz, G. (1999). OxyR and SoxRS regulation

of fur. *Journal of bacteriology*, 181(15), 4639–4643.

<https://doi.org/10.1128/JB.181.15.4639-4643.1999>

36. Zhou, R. Z., Blanco, L., Garcia-Diaz, M., Bebenek, K., Kunkel, T. A., & Povirk, L. F.

(2008). Tolerance for 8-oxoguanine but not thymine glycol in alignment-based gap filling

of partially complementary double-strand break ends by DNA polymerase lambda in

human nuclear extracts. *Nucleic acids research*, 36(9), 2895–2905.

<https://doi.org/10.1093/nar/gkn126>