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Chronic Benzene Exposure Aggravates Pressure Overload-Induced Cardiac Dysfunction

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ABSTRACT

Benzene is a ubiquitous environmental pollutant abundant in household products, petrochemicals and cigarette smoke. Benzene is a well-known carcinogen in humans and experimental animals; however, little is known about the cardiovascular toxicity of benzene. Recent population-based studies indicate that benzene exposure is associated with an increased risk for heart failure. Nonetheless, it is unclear whether benzene exposure is sufficient to induce and/or exacerbate heart failure. We examined the effects of benzene (50 ppm, 6 h/day, 5 days/week, 6 weeks) or HEPA-filtered air exposure on transverse aortic constriction (TAC)-induced pressure overload in male C57BL/6J mice. Our data show that benzene exposure had no effect on cardiac function in the Sham group; however, it significantly compromised cardiac function as depicted by a significant decrease in fractional shortening and ejection fraction, as compared with TAC/Air-exposed mice. RNA-seq analysis of the cardiac tissue from the TAC/benzene-exposed mice showed a significant increase in several genes associated with adhesion molecules, cell-cell adhesion, inflammation, and stress response. In particular, neutrophils were implicated in our unbiased analyses. Indeed, immunofluorescence studies showed that TAC/benzene exposure promotes infiltration of CD11b⁺/S100A8⁺/myeloperoxidase⁺-positive neutrophils in the hearts by 3-fold. *In vitro*, the benzene metabolites, hydroquinone and catechol, induced the expression of P-selectin in cardiac microvascular endothelial cells by 5-fold and increased the adhesion of neutrophils to these endothelial cells by 1.5-2.0-fold. Benzene metabolite-induced adhesion of neutrophils to the endothelial cells was attenuated by anti-P-selectin antibody. Together, these data suggest that benzene exacerbates heart failure by promoting endothelial activation and neutrophil recruitment.

Keywords: Benzene, heart failure, adhesion molecules, endothelial cells, neutrophils, RNA-seq.

Introduction

Environmental pollution is a health problem worldwide. More than 9 million premature deaths are attributed to pollution every year, out of which 6 million deaths are related to air pollution (1). Nearly half of the air pollution-associated deaths are ascribed to cardiovascular disease (1). Cardiovascular health effects of criteria pollutants (particulate matter_{2.5}, sulfur dioxide, carbon monoxide, nitrogen oxides, ozone and lead) have been extensively studied in the last three decades; however, information about the potential cardiovascular toxicity of other airborne chemicals, such as volatile organic compounds (e.g. benzene, 1,3-butadiene, vinyl chloride, trichloroethylene etc.), is sparse. Benzene, a well-known carcinogen, is abundant in household products, cigarette smoke and automobile exhaust (2-5), and the atmospheric concentration of benzene can exceed 50 ppm, especially near the emission source. People working at gasoline pumping stations or living near hazardous waste sites can be exposed to high levels of benzene. The United States Occupational Safety and Health Administration has set the occupational benzene exposure limit of 1 ppm (6); however, occupational benzene exposure in excess of 100 ppm has been reported in developing countries (7).

Like pollution, heart failure is a pervasive health problem. Heart failure affects more than 6.5 million people in the United States (8) and 26 million people worldwide (9). The lifetime risk for heart failure at 40 years of age is estimated to be 1 in 5 people (10). The pathogenesis of heart failure is also not clearly understood, although a substantial body of literature points to the important role of infiltrating immune cells in the development of left ventricular hypertrophy and cardiac dysfunction (11-18). Therefore, the current focus in finding new therapeutic approaches to delay advanced heart failure includes understanding the molecular mechanisms that govern cardiomyocyte interactions with immune cells (19-21). The innate immune response induced by heart failure initiates the cardiac repair process, and involves infiltration of peripheral neutrophils (22-24).

Recent population based studies have reported that benzene exposure is associated with an increased risk for heart failure (25), and presence of mono-nitrogen oxide and benzene in the air of hospital wards is associated with a higher risk of heart failure morbidity (26). Other studies have linked exposure to benzene with cardiovascular mortality (27, 28); however, direct effects of benzene exposure on heart failure in well-controlled animal studies have not been studied. Here,

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3 we examined the effect of chronic benzene exposure on transverse aortic constriction (TAC)-
4 induced cardiac function and associated immune response in mice.
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8 **MATERIALS AND METHODS**

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11 **Reagents:** Benzene permeation tubes were obtained from Kin-Tek (La Marque, TX). Primers and
12 probes for real-time PCR were purchased from Integrated DNA Technologies (Coralville, IA) and
13 ThermoFisher Scientific (Waltham, MA). Sources of antibodies used for immunohistochemistry
14 and functional studies were: anti-CD11b (Abcam, cat# ab1333357, RRID:AB_2650514), anti-
15 myeloperoxidase (Abcam, cat# ab9535, RRID:AB_307322); anti-S100A8 (63N13G5)-FITC
16 (Novus, cat# NBP2-25273F); anti-CD90/Thy1 (Sino Biological, cat# 50461-T44); CD62P
17 (Biolegend, cat# 148308, RRID:AB_2565817). Murine cardiac microvascular endothelial cells
18 (CMVEC) were obtained from CellBiologics, Chicago, IL. All other chemicals and enzymes were
19 from Sigma Chemical Co. (St. Louis, MO), or Invitrogen (Carlsbad, CA).
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30 **Animal housing and maintenance:** C57BL/6J male mice obtained from Jackson Laboratory (Bar
31 Harbor, ME) were maintained on normal chow in a pathogen-free facility accredited by the
32 Association for Assessment and Accreditation of Laboratory Animal Care. All procedures were
33 approved by the University of Louisville Institutional Animal Care and Use Committee. We used
34 male mice in our study because multiple studies have shown that rate of benzene metabolism, and
35 consequently benzene toxicity, is significantly higher in male mice than female mice (29-31).
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42 **Animal Surgeries:** For TAC (32), male C57BL/6J mice 12 weeks of age were anesthetized
43 (intraperitoneal injections of 50 mg/kg sodium pentobarbital and 50 mg/kg ketamine
44 hydrochloride), antiseptically prepared for surgery, orally intubated, and ventilated (oxygen
45 supplement to the room-air inlet) with a mouse ventilator (Hugo Sachs). Core body temperature
46 was maintained at 36.5–37.5°C with an automatic, electronically regulated heat lamp. The aorta
47 was visualized following an intercostal incision. A 7-0 nylon suture was looped around the aorta
48 between the brachiocephalic and left common carotid arteries. The suture was tied around a 27-
49 gauge needle placed adjacent to the aorta to constrict the aorta to a reproducible diameter. The
50 needle was removed, and the chest was closed in layers. Mice were extubated upon recovery of
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3 spontaneous breathing. Analgesia (ketoprofen, 5 mg/kg) was provided prior to recovery and by 24
4 and 48 h post-surgery. Sham mice were subjected to the same procedure as the TAC cohort except
5 the suture was not tied.
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10 **Benzene Exposure:** One week after the TAC, mice were exposed to benzene for 6 weeks in
11 bedding-free cages as described before (33). Briefly, benzene atmospheres were generated from
12 liquid benzene (Sigma-Aldrich) in a KIN-TEK Analytical, Inc permeation tube. A carrier gas (N₂)
13 was delivered to the permeation tube at 100 ml/min and diluted with HEPA- and charcoal-filtered
14 room air (3 L/min) and diluted gas directed to an exposure unit. Flow was distributed through a
15 fine mesh screen of a custom cyclone-type top (Teague Enterprises) that distributed air within 10%
16 of the mean concentration at six locations in the cage. Throughout the exposure, benzene
17 concentrations were continuously monitored using an in-line photoionization detector (ppb RAE:
18 Rae Industries) upstream of the exposure unit. Mice were exposed to 50 ppm benzene (6 h/day, 5
19 days/week) for 6 weeks. Mice exposed to HEPA- and charcoal-filtered room air only were used as
20 controls.
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31 **Echocardiography:** At the end of the benzene exposure protocol, mice were anesthetized with
32 2% isoflurane, and echocardiography was performed (VisualSonics Vevo 3100), similar to our
33 previous reports (32, 34). At the end of the experiment, hearts were excised for biochemical and
34 pathological analyses. For mice in the TAC arm of the study, Doppler verification of the stenosis
35 was used. The sonographer was blinded to the specific experimental group.
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41 **RNA Isolation and RNAseq analysis:** Total RNA was extracted from the hearts of mice using
42 TRIzol kit (Thermo Fisher Scientific, MA, USA), and the purity of RNA was analyzed using
43 NanoDrop One (ThermoScientific, MA, USA). RNA quality was measured by Agilent 2100
44 bioanalyzer (Thermo Fisher Scientific, MA, USA) and samples with high RNA integrity were used
45 for subsequent RNAseq analysis. RNA samples were processed by Novogene using mRNA and
46 small RNA sequencing services (Novogene, Beijing, China). The resultant raw reads of the
47 FASTQ files were processed and quality metrics were visualized using FastQC v 0.11.9. The
48 mRNA differentially regulated genes (DEG) and pathway enrichment analysis were performed
49 using the NGS Data Analysis pipeline (35). RNA-seq data has been submitted to the DRYAD
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3 database:[https://datadryad.org/stash/share/aTPKрма2a7Sppu2N3HoVdezhPpVdUncU8PI1cuxz1](https://datadryad.org/stash/share/aTPKрма2a7Sppu2N3HoVdezhPpVdUncU8PI1cuxz1q8)
4 [q8](https://datadryad.org/stash/share/aTPKрма2a7Sppu2N3HoVdezhPpVdUncU8PI1cuxz1q8)
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8 **Histopathology:** Formalin-fixed, paraffin-embedded hearts from Sham and TAC mice were
9 sectioned at 4 μm thickness, and later deparaffinized, and rehydrated according to the appropriate
10 staining method. The histological staining was performed as previously described (36, 37). Picro-
11 Sirius Red staining was used to evaluate tissue fibrosis and general histology, and Alexa Fluor
12 555-conjugated wheat-germ agglutinin (Invitrogen) staining was used to determine the average
13 myocyte area. All images were captured at 20X magnification using the Keyence BZ-X810, all in
14 one fluorescent microscope. Both fibrosis and myocyte area were analyzed using the hybrid cell
15 count feature (BZ-H4C) associated with the Keyence system. Fibrosis was expressed as a
16 percentage of scar tissue divided by the total area of tissue.
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25 **Immunofluorescence:** For immunostaining, deparaffinized and rehydrated sections were
26 incubated for 20 min with 10 mmol/L citric acid pH 6.0 (pH 9.0 for MPO staining). Nonspecific
27 binding was blocked with 5% normal goat serum and 0.05% saponin (Sigma) in PBS (pH 7.4) for
28 30 min. Sections were blocked and then incubated with the appropriate primary antibody in PBS
29 with 1% BSA and 0.05% saponin for 1 h at 37°C against: CD11b (1:100 dilution), S100A8-FITC
30 (1:200 dilution), myeloperoxidase (1:25 dilution), CD90/Thy1 (1:200 dilution). Tissue sections
31 were then incubated for 30 min at room temperature with respective secondary antibodies
32 conjugated with Alexa 488, 555, or 647 (Invitrogen), and counterstained with DAPI to label nuclei.
33 Heart sections stained with non-immune primary antibody or only fluorophore-labeled secondary
34 antibodies served as negative controls. Images were made with a 20x and 60x objective.
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45 **Neutrophils isolation:** Neutrophils were isolated from bone marrow as described previously (38).
46 Briefly, C57BL6/J male mice 10 weeks old were sacrificed using pentobarbital injection. Bone
47 marrow cells were flushed from the femur and tibia and filtered through a 70 μm mesh filter. For
48 a negative selection of neutrophils, we used a Neutrophil Isolation kit from Miltenyi, Auburn, CA.
49 Magnetic sorting was performed using MS columns. Neutrophils presented in flow-through
50 fractions were characterized using flow cytometry and by cytopsin with Diff-Quick staining.
51 Neutrophil purity was always higher than 93%.
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5 **Cell adhesion assay:** Neutrophil adhesion to CMVEC was determined as previously described
6 (39). Briefly, CMVEC (passage 6 to 10) were seeded into 96-well plate at 25,000 cells per well in
7 100 μ l of growth media. Twenty-four hours later confluent monolayer of endothelial cells was
8 exposed to benzene metabolite catechol (5 μ M) for 24 hours. Cells treated with TNF α (100 ng/mL)
9 for 4 hours served as positive controls. Isolated neutrophils labeled with calcein (39) were added
10 to endothelial cells and incubated for 30 min at 37 °C. Cells were rinsed with PBS containing Mg²⁺
11 and Ca²⁺ and the fluorescence was measured with a Synergy H1 (Biotek) fluorescence plate reader
12 (excitation wavelength, 485 nm and emission wavelength, 520 nm). To measure the effect of p-
13 selectin blocking on neutrophil adhesion, CMVEC were incubated with anti-CD62P antibodies
14 (25 μ g/mL) for 30 min prior to the neutrophil adhesion assay. For each assay, 10-12 wells were
15 used.
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25 **Statistical Analyses:** Data are presented as means \pm SEM. Statistical analyses for echo-based
26 parameters were performed after adjustment for body weight and heart rate by two-way ANOVA
27 with Tukey-Kramer corrections. A two-way analysis of variance (ANOVA) with Tukey *post hoc*
28 test was also used for the analyses of RNAseq, histopathology, and immunofluorescence data. *In*
29 *vitro* data were analyzed by one-way ANOVA with Holm-Sidak *post hoc* test to compare
30 differences between multiple experimental groups. P-value of <0.05 indicated statistically
31 significant differences. All analyses were performed using Excel and GraphPad Prism software
32 (GraphPad Software, San Diego, CA).
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41 RESULTS

42 **Benzene exposure exacerbates pressure overload-induced cardiac dysfunction:** As expected,
43 mice in the TAC/Air group developed significant left ventricular dilation as indicated by a
44 significant increase in end diastolic volume (EDV), end systolic volume (ESV) and left ventricular
45 internal diameter in diastole (LVIDd), and diameter in systole (LVIDs), and consequent decrease
46 in fractional shortening (FS) and ejection fraction (EF), as compared with the mice in
47 corresponding Sham/Air (**Fig. 1**). TAC also increased the heart mass, cardiac myocyte size and
48 fibrosis in the heart (**Fig. 1**). This was accompanied with a significant increase in the fluid
49 accumulation in the lung (**Supplemental Fig. 1**). Benzene exposure had no effect on myocyte size
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3 and cardiac function in the Sham group; however, it significantly compromised cardiac function
4 as depicted by a significant increase in EDV, ESV, LVIDd, and LVIDs and resultant decrease in
5 FS and EF, as compared with TAC/Air-exposed mice (**Fig. 1** and **Supplemental Table 1**). The
6 other cardiac function parameters such as left ventricular anterior wall thickness at diastole or
7 systole (LVAWd and LVAWs) and left ventricular posterior wall thickness at diastole or systole
8 (LVPWd and LVPWs), isovolumic relaxation time (IVRT), Stroke Volume (SV), and Cardiac
9 Output (CO) did not significantly change in TAC/Benzene vs TAC/Air groups (**Supplemental**
10 **Table 1**). Cardiac myocyte size and fibrosis in TAC/Benzene-exposed mice were also comparable
11 with the TAC/Air-exposed mice. Collectively, these data suggest that a 6-week benzene exposure
12 exacerbates TAC-induced cardiac dysfunction but does not induce cardiac remodeling in Sham
13 mice.
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25 **RNA-Seq analyses of TAC-benzene-exposed hearts:** To examine the molecular mechanisms by
26 which benzene worsens cardiac function following TAC, we performed deep RNA sequencing on
27 the left ventricle and septum tissues. For these analyses, we used $FDR \leq 0.01$ and $0.5 \leq \text{Log}_2$ (fold
28 change) ≤ -0.5 to examine the differential expression of the genes. As shown in **Fig 2A**, TAC
29 upregulated 671 genes (e.g., genes involved in extracellular matrix organization and collagen
30 formation) and downregulated 351 genes (e.g., genes involved in muscle contraction and cardiac
31 conduction) in the air-exposed mice (see **Supplemental Table 2**). Exposure to benzene in Sham-
32 operated mice did not induce any genes while uteroglobin (*Scgbl1a1*) and surfactant protein C
33 (*Sftpc*) were downregulated by 8.9- and 6.1-fold. However, benzene exposure in TAC mice
34 significantly upregulated 876 genes and downregulated 674 genes as compared with the
35 corresponding Sham-operated controls. Comparison of the gene expression between
36 TAC/Benzene versus TAC/Air mice showed upregulation of 50 and downregulation of 69 genes.
37 **Fig. 2B** illustrates the heat-map of top the 15 upregulated and 10 downregulated genes between
38 these groups as well as the differential expression of these genes in the other experimental groups.
39 Gene ontology of biological process and molecular function enrichment analyses of differentially
40 expressed genes in the benzene-exposed TAC hearts show significant enrichment of the genes
41 associated with the regulation of “neutrophil degranulation”, “signaling by interleukins”,
42 “extracellular matrix organization”, “platelet degranulation”, and heat shock factor-1 (HSF-1) -
43 dependent transactivation etc. (**Fig. 3A**). **Fig. 3B** shows the induction of some representative genes
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3 of these processes, and **Fig. 3C** displays the gene-concept network of select differentially
4 expressed genes associated with the indicated biological pathways including neutrophil
5 degranulation, interleukin signaling, and HSF-1 activation.
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11 **Benzene exposure augments TAC-induced neutrophil infiltration:** Because our RNA-Seq data
12 suggest that benzene exposure affects inflammatory response and neutrophil degranulation
13 processes in TAC hearts, we examined the abundance of inflammatory cells in the TAC/benzene-
14 exposed hearts. As shown in **Fig. 4A**, benzene exposure induced massive infiltration of S100A8-
15 positive granulocytes in the hearts of TAC mice. These cells also co-stained with the pan-myeloid
16 marker CD11b and myeloperoxidase, mostly expressed on neutrophils (**Fig. 4A and 4B**).
17 Quantitative analysis shows >3-fold increase in S100A8⁺ granulocytes, CD11b⁺ myeloid cells and
18 myeloperoxidase⁺ neutrophils in TAC/Benzene vs TAC/Air groups (**Fig. 4C**). The S100A8
19 staining did not co-localize with the markers of CD68⁺ macrophages and Thy1⁺ fibroblasts in
20 TAC-Benzene hearts (**Supplemental Fig. 2**). To examine the mechanisms by which benzene
21 exposure augments neutrophil infiltration in TAC-instrumented hearts, we analyzed the RNA-seq
22 data for the differential expression of adhesion molecules. As shown in **Fig. 4D**, benzene exposure
23 did not affect the levels of adhesion molecules in the Sham-operated hearts, however, it
24 significantly increased the transcription of Intracellular adhesion molecule-1 (*Icam1*), endothelial-
25 selectin (*Sele*), and platelet-selectin (*Selp*) genes in the TAC-instrumented hearts. Expression of
26 vascular cell adhesion molecule (*Vcam1*) in TAC-benzene hearts was comparable with the
27 TAC/Air hearts. Together, these data indicate that chronic benzene exposure enhances the
28 infiltration of neutrophils, possibly by activating adhesion molecules in the myocardial endothelial
29 cells during pressure overload-induced cardiac dysfunction.
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46 **P-Selectin facilitates the adhesion of neutrophils adhesion to the cardiac microvascular**
47 **endothelial cells:** Complimentary *in vitro* experiments with CMVEC showed that benzene
48 metabolites hydroquinone (5 μ M, 24 h) and catechol (5 μ M, 24 h) increased the transcription of
49 P-selectin by 5-fold (**Fig. 5A**) and abundance of P-selectin protein by 1.5-2-fold (**Fig. 5B**).
50 Incubation of CMVEC with catechol for 24 h augmented the adhesion of bone marrow-derived
51 neutrophils to CMVEC (**Fig. 5C**), which was attenuated by pre-incubation of CMVEC with anti-
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3 P-selectin antibody (**Fig. 5D**). Hydroquinone and catechol also increased the expression of
4 interleukin-8 (IL8, **Supplemental Fig. 3**), which can function both as a membrane-bound and
5 soluble activator of neutrophil β_2 integrin-mediated adhesion. Together, these observations suggest
6 that benzene-induced neutrophil infiltration in the TAC hearts could be facilitated, at least in part,
7 by the metabolic conversion of benzene to its active metabolites- hydroquinone and catechol.
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10 11 12 13 **DISCUSSION**

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17 The major finding of this study is that chronic benzene exposure exacerbates pressure overload-
18 induced cardiac dysfunction. The TAC/Benzene-induced cardiac dysfunction is accompanied by
19 endothelial activation and enhanced recruitment of granulocytes in the heart and differential
20 regulation of genes involved in neutrophil degranulation, inflammatory signaling, and stress
21 response. These studies corroborate recent reports that occupational and environmental exposure
22 to benzene is associated with an increased risk for heart failure (25).
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28 Inflammatory processes have long been implicated in the manifestation, progression, and
29 consequences of ischemic heart disease (40, 41) and pressure- or volume overload-induced
30 mechanical stress (17, 42-44). Pressure overload induces the expression of *ICAM1* (45) and
31 consequent increase in the recruitment of neutrophils in the heart (42) and subsequent monocyte
32 infiltration (17, 42). It diminishes TAC-induced cardiac hypertrophy and inflammation and
33 sustains cardiac function (42), suggesting that neutrophils play a pivotal role in the manifestation
34 of heart disease, especially heart failure. In mice, increased recruitment of S100A9 positive
35 granulocytes, which co-stained with myeloperoxidase, suggests that TAC/Benzene exposure
36 facilitates the infiltration of neutrophils into the hearts.
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44 This is further supported by RNAseq data of cardiac tissue, demonstrating robust induction in the
45 neutrophil specific *S100A8/A9*, *Mmp8*, *Lcn2*, and *Cxcr2* transcripts. S100A8/A9 is a member of
46 alarmins or damage-associated molecular patterns (DAMPs) that are released by the failing heart
47 (46-48) and subsequently activate resident macrophages, fibroblasts, and endothelial cells to
48 secrete proinflammatory cytokines and adhesion molecules (49) and augment inflammation in the
49 cardiac tissue (21, 23, 50). Systemic administration of S100A8/A9 facilitates the mobilization of
50 neutrophils from the bone marrow (51) while local administration of S100A8/A9 leads to rapid
51 recruitment of monocytes and neutrophils into the site of injury (52). Patients with myocardial
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3 infarction and elevated S100A8/A9 levels have poorer prognosis (53, 54). Overall, increased
4 neutrophil infiltration in the hearts could play a pivotal role in benzene exposure-induced cardiac
5 dysfunction in the pressure overload hearts.
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9 Although precise mechanisms by which benzene exposure exacerbates pressure overload-induced
10 cardiac dysfunction remain unknown, it is plausible that the observed ventricular remodeling of
11 TAC/Benzene mice could, at least in part, be due to the induction of neutrophil gelatinase-
12 associated lipocalin (NGAL or Lcn2) whose expression is regulated by the S100A8/A9 complex
13 (55). Lcn2 plays a central role in the ontogeny of cardiac hypertrophy and heart failure (56-58)
14 and can bind Mmp9 to create a complex to stabilize Mmp9 protein and enhance metalloproteinase
15 activity (59, 60). Such changes could support or promote further ventricular remodeling.
16 Moreover, S100A8/A9 can diminish cardiac myocyte contractility (61). Patients with chronic heart
17 failure have elevated plasma myeloperoxidase levels (62), and pharmacological inhibition of
18 myeloperoxidase diminishes leukocyte recruitment, and limits remodeling following myocardial
19 infarction (63). Therefore, it is conceivable that the augmented neutrophil infiltration with
20 subsequent release of MPO and S100A8/A9 heterodimer from activated granulocytes affects
21 ventricular remodeling in TAC/Benzene mice.
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32 Despite the difference in inflammatory markers and cardiac dysfunction, we did not observe a
33 change in cardiomyocyte size or gross accumulation of fibrosis. Changes in myocardial function
34 do not require changes in cardiomyocyte size. Several factors impact inotropic and lusitropic
35 aspects of cardiac function, and these do not require changes in cardiomyocyte size. Hence, it is
36 not surprising that we observed differences in ejection fraction but no differences in cardiomyocyte
37 hypertrophy. Because all groups of TAC mice retained a similar stenotic insult (i.e., banding), all
38 TAC mice would have similar stimuli for compensatory cardiomyocyte growth. Yet, it is
39 conceivable that, because of the duration of TAC, the hearts have transitioned from concentric to
40 eccentric hypertrophy, which could involve changes in myocyte length; however, we measured
41 only cross-sectional area, which is standard for the field. Regarding the lack of change in fibrosis,
42 there are several caveats to consider. First, endpoints for fibrosis are crude; it is possible that we
43 lacked the sensitivity to detect changes. Second, the TAC model (in contrast to the infarct model)
44 is characterized by relatively modest levels of diffuse, interstitial fibrosis. Third, it is conceivable
45 that fibrosis simply did not change among the groups.
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5 While our *in vitro* studies showed increased transcription of P-selectin on microvascular
6 endothelial cells and neutrophil adhesion to endothelial cells, benzene exposure did not change
7 adhesion molecules' transcription in the naïve (un-instrumented) mice. Nonetheless, it is
8 conceivable that benzene exposure in naïve mice can promote the release of pre-formed adhesion
9 molecules such as P-selectin from storage granules (e.g. Weibel-Palade bodies) and induce
10 endothelial activation. However, in the absence of any significant injury, adhesion of neutrophils
11 to the endothelium is likely to be modest. The pressure overload-induced inflammatory
12 environment and myocardial injury would promote endothelium activation and enhance adhesion
13 of neutrophils to the endothelium in benzene-exposed mice. Increased inflammation in the hearts
14 of mice subjected to pressure overload followed by benzene exposure is further underscored by
15 the increased transcription of chemokines, cytokines, and their receptors (e.g. $Il1\beta$, $Cxcl1$, and
16 $Cxcr2$). Chemokines such as CXCL1 chemokine are well known to facilitate neutrophil migration
17 into inflamed tissues (64), promote angiogenesis (65, 66) and regulate the recruitment of
18 neutrophils and monocytes during cardiac remodeling and inflammation (67). Although the
19 cellular sources (e.g., endothelial cells, granulocytes) of CXCL1 and other chemokines and
20 cytokines in the hearts of TAC/benzene-exposed mice remain unknown, they likely augment
21 neutrophil recruitment and migration. Benzene metabolites have been shown to increase the
22 expression of cytokines and chemokines in the peripheral blood mononuclear cells (68) and
23 endothelial cells (69). Our *in vitro* studies show that in murine cardiac microvascular endothelial
24 cells, benzene metabolites hydroquinone and catechol increase the transcription of chemokine IL-
25 8, which is known to bind to CXCR2 on neutrophils and trigger a signaling cascade that facilitates
26 a firm monocyte adhesion with subsequent intravasation (70). Further studies are required to
27 delineate the sources of chemokines and cytokines and the molecular mechanisms by which these
28 molecules promote inflammatory signaling in the hearts of TAC/Benzene mice.
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47 Induction of heat shock proteins (HSPs) such as *Hspa1a* and *Hspa1b* in Sham/Benzene hearts
48 appears to be an adaptive response to circumvent inflammatory signaling. Induction of HSPs in
49 response to chemical and mechanical stress enhances protein folding, inhibits inflammation and
50 apoptosis, and provides cytoskeletal protection (71). While little is known about the role of HSPs
51 in pressure overload-induced heart failure, heat shock factor 1 (HSF-1), the transcription factor
52 that regulates HSPs is induced by TAC in rats and mice, and constitutive activation of HSF-1
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3 ameliorates TAC-induced cardiac hypertrophy, fibrosis and cardiac dysfunction (72-74).
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5 Conversely, inhibition of HSF-1 impairs cardiac function in the pressure overload subjected hearts
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7 (72, 73). The HSF-1-mediated cardiac adaptation from pressure overload has been attributed, at
8
9 least in part, to myocardial angiogenesis via suppression of p53 and subsequent induction of HSF-1
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11 (75). HSF-1 can also improve endothelial function (76) and prevent inflammatory signaling (77).
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13 Although the contribution of the HSF-1/HSP axis in the etiology of cardiac dysfunction following
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15 TAC/Benzene exposure is unclear, it is likely that these pathways are activated to prevent benzene-
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17 induced endothelial activation. Further studies are required to examine the molecular mechanisms
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19 by which HSF-1-dependent transactivation prevents endothelial activation.

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21 Collectively, our studies demonstrate that benzene exposure worsens pressure overload-induced
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23 cardiac dysfunction, which is accompanied by increased influx of neutrophils, alterations in cell-
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25 cell adhesion, and induction of genes associated with inflammation and stress response. These
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27 studies establish the plausibility that benzene exposure is sufficient to exacerbate TAC-induced
28
29 cardiac dysfunction and provide insight about the underlying mechanisms.

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FIGURE LEGENDS:

Figure 1. Effect of benzene exposure on left ventricle function and cardiac remodeling after pressure overload. **A.** Benzene exposure protocol: Transverse aortic constriction or Sham operated male C57BL/6 mice were exposed to benzene (50 ppm, 6 h/day, 5 days/week) or HEPA-filtered air (Air) for 6 weeks. At the end of the exposure protocol, echocardiography was used to measure ejection fraction (**B**), fractional shortening (**C**), end-diastolic volume (EDV; **D**), end-systolic volume (ESV; **E**), left ventricular internal diameter end diastole (LVIDd; **F**) and end systole (LVIDs; **G**). Heart weight:tibial length (TL) are presented in panel **H**. Statistical analyses for echo-based parameters were performed after adjustment for body weight and heart rate by two-way ANOVA with Tukey-Kramer corrections. Panel **I** shows the representative images of Sirius Red-stained mid-ventricular histological sections from mouse hearts with quantitative analysis of fibrosis expressed as percent of fibrous area to total area ratio. Representative images of wheat germ agglutinin (WGA)-stained mid-ventricular histological sections from mouse hearts with quantitative analysis of myocyte area are illustrated in panel **J**. Values are mean \pm SEM. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and **** $p < 0.0001$ represent statistical significance between corresponding groups analyzed by Two-way ANOVA with Tukey *post hoc* test. N=6-11/group.

Figure 2. Differential expression of genes (DEG) in the hearts of TAC/Benzene-exposed mice. **A.** The number of differentially expressed genes (DEG) are depicted by corresponding arrows. The visual representation of DEG for three treatments are presented as volcano plots ($FDR \leq 0.01$). **B.** Heatmap of the top 15 up-regulated and 10 down-regulated (TAC/Benzene vs. TAC/Air) protein-encoding genes in the four experimental groups.

Figure 3. Pathway enrichment analysis of differentially expressed genes in the hearts of TAC/Benzene-exposed mice. **A.** Dot plot of enriched terms for TAC/Benzene vs TAC/Air DEG ($FDR \leq 0.01$). IGF – Insulin-like Growth Factor, IGFBPs – Insulin-like Growth Factor Binding Proteins; **B.** The most upregulated and functionally important genes in TAC/Benzene vs TAC/Air groups. **C.** Gene-concept network depicting the linkage of genes and enriched biological pathways as a network.

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3 **Figure 4. Immune cells infiltration into the heart of TAC/Benzene-exposed mice. A.** Heart
4 sections were stained for S100A8 (green) and CD11b (pink), nuclei (blue); **B.** Co-staining of
5 S100A8 positive cells with myeloperoxidase (MPO) positive cells. **C.** Quantitative analysis of
6 S100A8-, CD11b-, and MPO-positive cells. **D.** Expression levels of adhesion genes in the hearts
7 of exposed mice. Values are mean \pm SEM. * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$ represent statistical
8 significance between corresponding groups analyzed by Two-way ANOVA with Tukey *post hoc*
9 test. N=6/group.

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17 **Figure 5. Benzene metabolites induce neutrophil adhesion to the cardiac microvascular**
18 **endothelial cells. A.** Transcription of P-selectin (*Selp*) in cardiac microvascular endothelial cells
19 (CMVEC) treated with benzene metabolites hydroquinone (HQ; 5 μ M, 6 h) and catechol (5 μ M,
20 24 h). **B.** HQ (5 μ M, 24 h)- and catechol (5 μ M, 24 h)-induced upregulation of P-selectin protein
21 in CMVEC. **C.** Adhesion of bone marrow-derived calcein-labeled murine neutrophils to CMVEC
22 pretreated with HQ (5 μ M) and Catechol (5 μ M) for 24 hours. **D.** Inhibition of neutrophil adhesion
23 to HQ (5 μ M, 24 h)- and catechol (5 μ M, 24 h)-stimulated CMVEC by anti-P-selectin antibody.
24 Values are mean \pm SEM. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and **** $p < 0.0001$ between
25 corresponding groups analyzed by One-way ANOVA with Holm-Sidak *post hoc* test.
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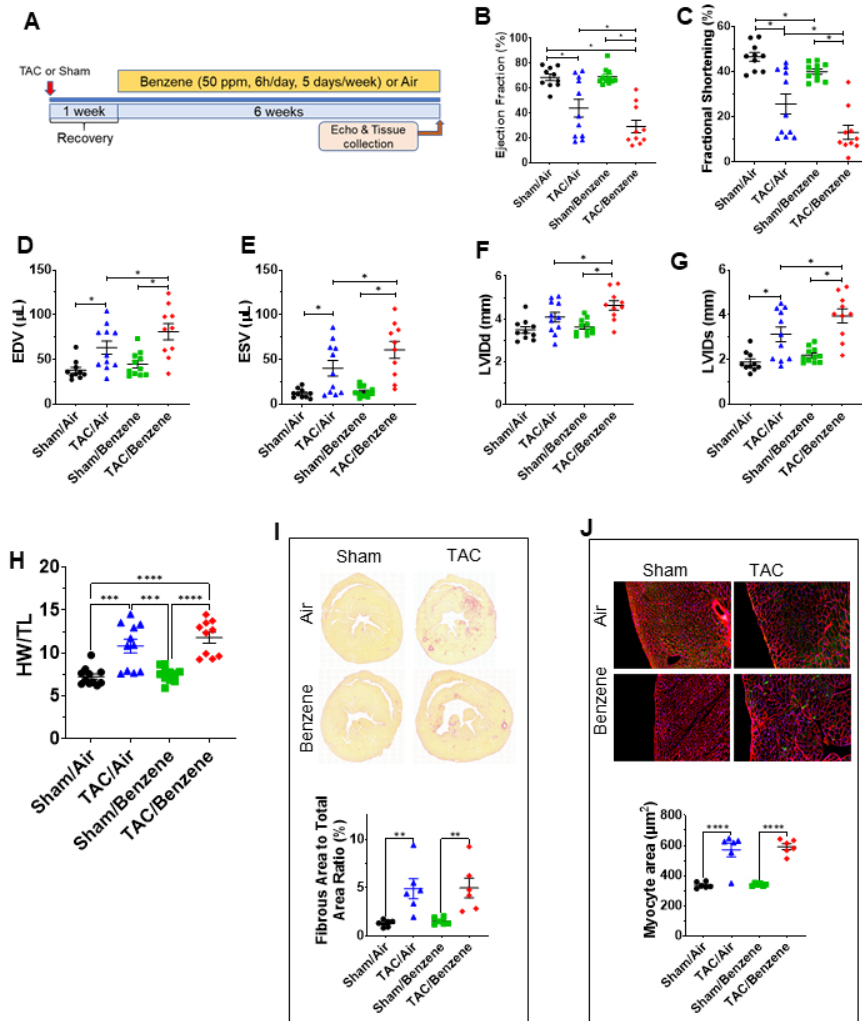
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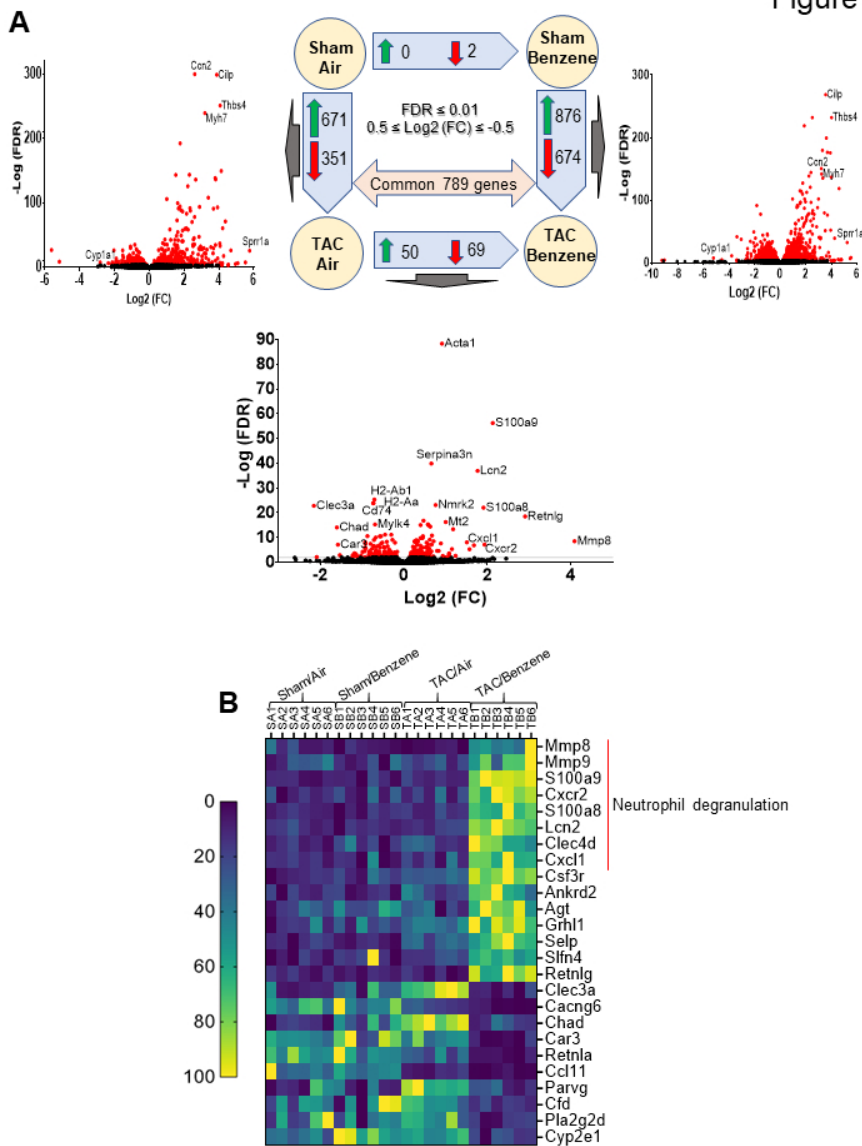
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Figure 1



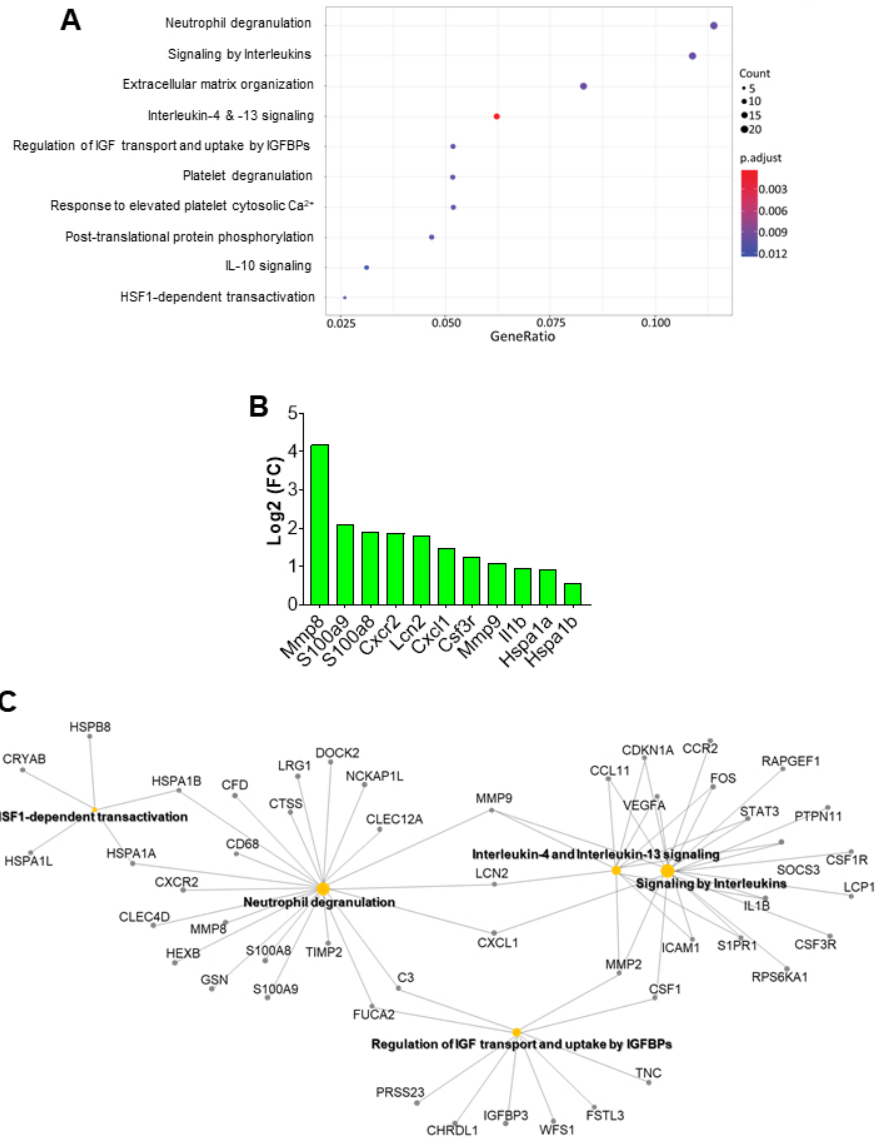
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Figure 2

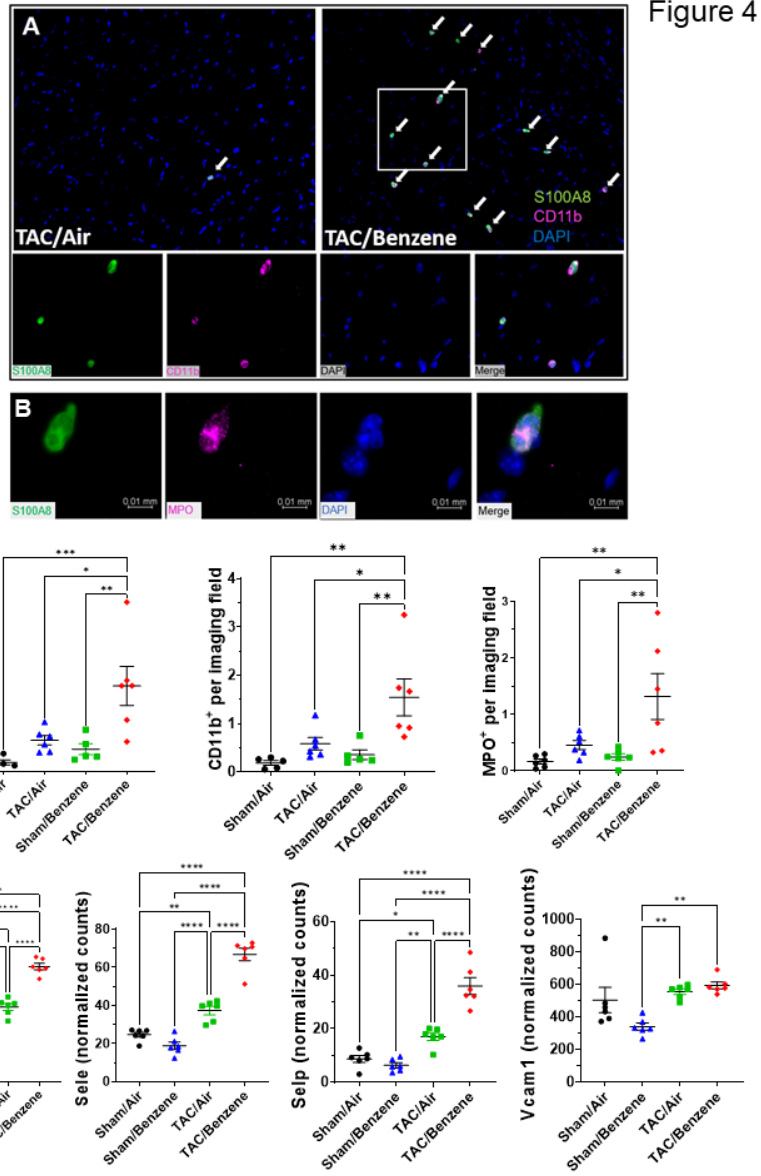


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Figure 3

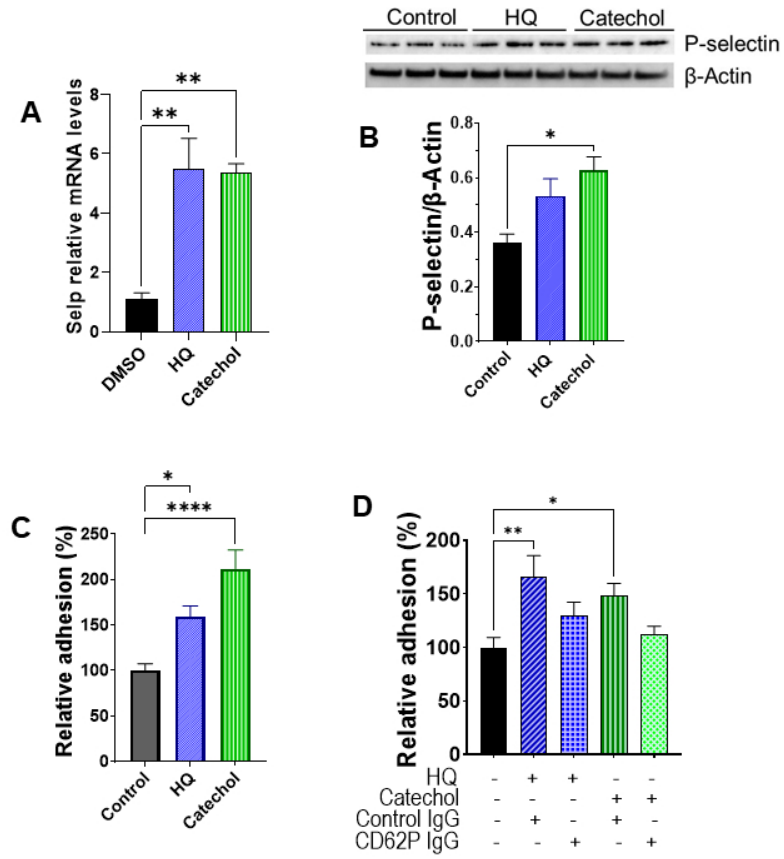


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Figure 5



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