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CELLULAR RESPONSES TO LOW-GRAVITY: PILOT STUDIES ON SUBORBITAL ROCKETS AND ORBITING SPACECRAFT

Submitted by
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SUMMARY

The allocated funding supported, in part, experiments conducted on two Consort sounding rockets and five Shuttle flights. The primary parameters investigated were signal transduction in response to various mediators, cellular differentiation and metabolism in microgravity and effect of microgravity on cytoskeletal morphology. Achievements include: demonstration of effect of spaceflight on the actin cytoskeleton in mouse osteoblasts (collaborator, M. Hughes-Fulford) and frog cells (collaborator, R. Gruener); confirmation that the T cell receptor-mediated signal transduction pathway in T lymphocytes is not affected by low-gravity compared to non-TCR-mediated stimulation (Con-A) which classically does not promote proliferative response; indication that microgravity may allow separation of proliferative signaling and secretory function in lymphocytes (collaborator, M.A. Principato); demonstration that T lymphocytes and bone cells utilized less glucose indicating a shift in metabolism and confirming Spacelab results with WI-38 cells which used significantly less glucose, during spaceflight; confirmation that activation of human splenic B cells with a number of different mediators is not affected during spaceflight (collaborator, G. Neil); demonstration of increased prostaglandin synthesis during reduced bone cell growth suggesting an effect of microgravity on prostaglandin-induced mitogenesis (collaborator, M. Hughes-Fulford).

The funding contributed significantly to the database described above and resulted in submission of six collaborative abstracts (attached) in 1993 (five to the ASGSB Annual Meeting and one to the ASCB Annual Meeting). Two abstracts were presented at the 1992 ASGSB Annual Meeting in Tucson. In addition, several peer reviewed papers are being generated and data will be included as background in preparation of future proposals, which hopefully will allow us to continue this type of extremely productive collaborative research.

(Note: Achievements resulting from collaboration with selected investigators is described in the text):
INTRODUCTION

This final report describes the activities conducted during the one year plus one year extension granted by NASA Headquarters Life Sciences for the purpose of acquiring additional data from flight experiments flown in 1991, 1992 and 1993. A summary of all flight results and cell response data obtained from this $10,000 grant is included. This funding supported significant cell biology research, allowed me to coordinate specific collaborations to achieve research goals, and maximize capability to conduct basic research on space flights already available through my position in the Consortium for Materials Development in Space (CMDS) at the University of Alabama in Huntsville (UAH). Through my collaborations with selected investigators and their "in kind" support, this funding was greatly expanded to provide very significant low-gravity cellular response data. The primary advantage of this enhanced co-operative activity is frequent access to space, collaboration with investigators in related research areas leading to rapid acquisition of data, sufficient flight opportunities to allow confirmation of data and adequate replication of experimental parameters.

The obvious wealth of information, gained in part from this two-year funding, illustrates the extreme value of co-operative interaction between NASA's Life Science Program and the NASA Centers for Commercial Development of Space (CCDS). The CCDS program provided repeated access to space for multiple experiments, multiple replicates, and multiple collaborative investigations. These factors led to a rapid database expansion for a variety of cell types by maximizing low-g access and providing relatively low-cost, frequent, multiple-user opportunities. The benefit to the CMDS is expansion of the cell biology database on low-gravity response to identify target products and processes which can lead to commercial space bioprocessing and enhanced quality of life on Earth. The benefit to NASA's life sciences goals is expansion of the understanding of fundamental cellular processes in altered gravity environments.

PROJECT REPORT

Research Objectives: The primary objective of this research was to advance knowledge of molecular control mechanisms during cellular differentiation and to gain understanding of mechanisms of cellular responses in low-g. The specific objectives were to evaluate cytoskeletal structure in cells exposed to low-g compared to static culture ground-controls and to gain information on early signal transduction events and gene expression. These parameters were selected for investigation because of the reports in the
literature indicating that some low-gravity effects occur within 10 minutes after stimulation of cells. These responses would thus be detectable for cells flown on sounding rockets as well as the Shuttle.

The specific objectives of this pilot study were to maximize rocket and orbital spaceflight opportunities to gain information on mechanisms involved in altered response of human lymphocytes in low-g and to determine if similar mechanisms are also altered in other cell types. Additional objectives were to evaluate the available hardware for this research and to develop procedures to evaluate cells from more detailed experiments planned for future flights.

**Hypotheses tested:** All terrestrial life and Earth-based processes have evolved under unit gravity conditions and are therefore designed to make optimum use of gravity. For instance, the countless single events which occur in a living cell during growth, differentiation and gene expression have all evolved to take advantage of the unit gravity environment on Earth. In theory, pathways of development would have been very different if organisms had evolved in the absence of gravity. This is validated by increasing numbers of reports, as low-gravity research becomes more frequent and sophisticated, that gene expression, metabolism and cellular functions are affected during spaceflight. We hypothesized that alteration in gravity environment would produce detectable changes in the cytoskeleton and signal transduction pathways resulting in altered response of cells to growth mediators during spaceflight.

**Collaborations**

This research has been achieved through collaboration with outstanding investigators who have contributed some reagents and analyses on their equipment in return for opportunities to fly their cells collaboratively with me in order to achieve our common objectives. Obviously the $10,000 funding could not possibly cover all of the work described in this final report; however, the funding made it possible for me to purchase some reagents and materials in support of the cell investigations described and to travel to the ASGSB annual meeting where collaborations were established and plans for research were discussed. The funding also provided some salary support allowing me to maximize already available access to space through the UAH CMDS sponsored by the NASA Office of Advanced Concepts and Technologies (OACT), to gain the utmost science benefit from my spaceflight opportunities. This expanded report is presented to illustrate the volume and good quality of research that can be achieved from combined support of NASA's space commercialization and basic research activities.
Primary collaborators

Millie Hughes-Fulford, Ph.D., Astronaut and Chief, Laboratory for Cell Growth and Differentiation, Department of Veterans Affairs Medical Center, Univ. C.A.San Francisco. (3T3 Mouse bone cell differentiation and growth).

B. DeSales Lawless, Ph. D., Dept. of Cellular Immunology, Rockefeller Univ. New York (Cellular immunology and flow cytometry).

David W. Sammons, Ph.D., Department of Microbiology, Univ. Arizona, Tucson, AZ (B cell immunology and fixative investigations).

Garry Neil, M.D. Oakdale Research Park, Univ. Iowa, Coralville, IA (Splenic B cell differentiation and immunology).

Raphael Gruener, Ph.D., College of Medicine, Department of Physiology Univ. AZ Med School, Tucson, AZ (Xenopus cytoskeleton morphology and metabolism).

Augusto Ochoa, M.D., Dept, Clinical Immunology, Frederick Cancer Treatment and Dev. Cntr. Frederick MD. (Human T lymphocyte immunology).

Mary Ann Principato, Ph.D., Immunology Branch, Food and Drug Administration, Laurel MD. (Mouse T lymphocyte immunology).
SUMMARY OF ACCOMPLISHMENT OF INDIVIDUAL PROJECT OBJECTIVES ORIGINALLY PROPOSED FOR THIS PILOT STUDY NASA FUNDING

Cytoskeleton Evaluations. Gross morphology of the cytoskeleton was evaluated by immunofluorescent microscopy to determine if the elements are disorganized, if they extend to the cell membrane, if regulatory proteins (i.e. protein kinase C) are associated with cytoskeletal filaments and if stress fibers are visible. This objective was originally intended for human lymphocytes. Because the equipment needed to evaluate the lymphocytes was located at Birmingham and the collaborator accepted a position elsewhere, this part of the intended study was shifted to collaborators working with different cells, i.e. mouse osteoblasts (Millie Hughes-Fulford) and Xenopus cells (Raphael Gruener). The objectives were met in that we showed that the gross morphology of the actin cytoskeleton is significantly altered in low-g in both mouse and frog cells. This objective was accomplished through cooperation with Drs. Hughes-Fulford and Raphael Gruener. We did not evaluate translocation of protein kinase C along the cytoskeletal elements. This remains to be done.

Antigen-antibody binding in low-g. The demonstration of binding of antibodies to cell membranes is significant because it allows us to identify cell surface markers and evaluate membrane binding by ligands in low-g. Mixing cells with antibody specific to a particular cell surface marker to determine if binding is comparable to that in 1-g (i.e. if cell surface receptors are altered by low-g) was achieved on STS-43. (This was attempted on Consort-4, but the hardware anomaly prevented evaluation of this parameter). On STS-43 we demonstrated comparable flight and ground binding of stem cell antigen (SCA-1) antibody and Thy-1 antibody to mouse bone marrow stem cells and also demonstrated that our hardware (the MDA Minilab) is adequate for this type of cell test.

Mechanisms of T lymphocyte response to mitogen activation in microgravity. A primary objective of this research was to determine why cells do not respond well to Con A stimulation during spaceflight. Our experiments with human T lymphocytes confirmed low Con A activation but significant secretion of cytokines. We showed that activators of T cells which are mediated through the T cell receptor (TCR) were not altered in low-g, though Con A response is altered. Thus, we have confirmed by inference that the reduced Con-A activation is a result of early membrane associated reactions, probably involving phospholipase C as suggested by work of Schaffar et al using phorbol esters. The following abstract, submitted to the annual meeting of the American Society for Cell Biology (ASCB) summarizes our lymphocyte investigations.
EFFECTS OF MICROGRAVITY ON LEUKOCYTE GROWTH CONTROL AND FUNCTION. ((M.L. Lewis, M.A. Principato, B.D. Lawless, D.R. Morrison, W.C. Kapp, S.L. Strohl and A.C. Ochoa)) Department of Biology, University of Alabama, Huntsville, AL 35899. Immunology Branch, Food and Drug Administration, Laurel, MD 20708. Department of Cellular Immunology, Rockefeller University, NY, NY 10021. NASA Johnson Space Center, Houston, TX 77058, and Program Resources Inc./DynCorp, Frederick MD 21702.

Spaceflight results in significant reduction in mitogenic activation of human T lymphocytes. Causal mechanisms are not understood though cell contact and macrophage function are implicated. We evaluated microgravity effect on lymphocyte responsiveness, cytokine secretion and signaling through the T cell receptor (TCR) complex. Human or murine T lymphocytes were exposed to: non-TCR binding Con A, an efficient activator of resting T cells in unit gravity but not in microgravity; anti-CD3 plus IL2; and superantigen Staphylococcal Enterotoxin B (SEB) in the presence of Class II presenting feeder layers in unit-gravity and on Space Shuttle flights STS-50, 52, 54, and 56. Cells were exposed to mediators for two to 94 hours followed by fixation of flown cells in microgravity. The human peripheral blood mononuclear cells (hPBMC) exposed to Con-A remained primarily in G1 during spaceflight while ground controls progressed through the replicative cycle. Glucose utilization, significantly lowered in spaceflight, confirmed reduced metabolic activity of Con-A treated cells. However, stimulation of normal hPBMC in flight with anti-CD3+IL2 resulted in activation and appreciable cytokine production (gamma-IFN, GM-CSF, IL-1beta, and IL-6) confirming previous flight results indicating significant changes in cytokine secretion. Stimulation of purified murine splenic T cells through direct engagement of the T cell receptor with the SEB superantigen or via the TCR-associated CD3 molecule using anti-CD3+IL2 was also achieved in microgravity. In both instances, the murine T cell populations transitioned into DNA synthesis (S phase) and mitotic division (G2+M), indicative of cellular proliferation. We conclude that T cell activation via the TCR-mediated pathway is unaffected by microgravity while non-TCR-mediated activation, confirmed by poor proliferative response to Con A, does not promote cell division in microgravity. Our results suggest that microgravity may permit separation of proliferative signaling and T cell responsiveness and thus provide an unparalleled opportunity to investigate basic cellular mechanisms controlling growth and function.

Expression of c-myc and c-fos. This evaluation is based on the report of Reed et al. (1986) that lectin-stimulated mitogenesis of normal human lymphocytes results in sequential expression of protooncogenes and that after stimulation of peripheral blood mononuclear cells with phytohemagglutinin (PHA), a marked increase (within 10 minutes) occurred in levels of mRNA for c-fos and c-myc. Also, a decrease in expression of the fos proto-oncogene in simulated low-g has been reported (Rijken et al.). Evaluation of early gene expression is feasible because the increase in mRNA occurs within 10 minutes, a time easily achieved on rockets. This objective was only partially met. We had difficulty working out the details of the Boehringer non-radioactive technique and found it to be generally unworkable in our laboratory. We are shifting our emphasis to PCR and to in situ detection using a radiolabeling technique. We plan to continue development of the technique for use with cells from our next three Shuttle flights and Consort rocket launches.

Phosphatidylinositol Hydrolysis. An early event in lymphocyte activation after receptor binding is breakdown of phosphatidylinositol-1,4,5-biphosphate (PIP2) to inositol-1,4,5-triphosphate (IP3) and 1,2-diacylglycerol (DAG). Modifications of this assay are in test since timed steps in the assay do not correspond exactly with the possible reagent exposure times in low-g. This technique requires short incubation with specific reagents which we could not accomplish on the Shuttle and by the time the rockets were recovered and samples returned to us, the samples were not testable. We are looking for a more workable technique. Of course, this would be achievable on Space Station where a technician could perform the required activities in real time.
DESCRIPTION OF HARDWARE

MATERIALS DISPERSION APPARATUS (MDA) HARDWARE

Hardware Provider, John M. Cassano, Instrumentation Technology Inc., Exton, PA

The Materials Dispersion Apparatus (MDA) Minilab, (Figure 1) was commercially developed by Instrumentation Technology Associates, Inc. (ITA). The MDA Minilabs are brick-sized units consisting of two sliding blocks with sample wells cut into opposite faces. The blocks, misaligned during launch, slide to bring fluids in the wells of top and bottom blocks into contact during the low-gravity period. For the Type-3 wells, the blocks slide again before re-entry to bring the samples into contact with wells containing a fixative. Volumes in wells vary from 125 to 500 microliters depending on the diameter and depth of the wells required for specific investigations. A block may have as many as 140 well sets and thus adequate replication of test parameters and experimental variables control are easily provided.

Figure 1. The ITA MDA Minilab.

Well configurations (Figure 2) allow mixing of two (Type-2) or three (Type-3) fluids in microgravity. Type 1- wells do not allow mixing of fluids and remain in the same position throughout the mission.
Several science-driven modifications to the MDA's have resulted from my requirement to fly live cells. These modifications include fabrication of blocks using clear material to increase visibility during loading and unloading wells, triple containment to allow flight of NASA-classified catastrophic fluids (chemical fixatives), strip heaters and a precision thermostat to maintain 37°C, and grooves cut into the wells to accommodate small coverslips for anchorage dependent cells. With these adaptations, the area of cell biology research in the MDA's is now possible. Another significant CMDS contribution to the refinement of hardware design to accommodate fluids/particles mixing, was the placement of magnetic discs under bottom wells and addition of magnetized particles with the cells, or other materials, in top wells.

**Bioprocessing Modules (BPM)**

BPM's (Figures 3, 4, 5) are included in the materials dispersion sub-category. The BPM's are simple, manually operated devices. They consist of four syringes interconnected by tubing to a
4-way valve. One syringe contains cells, another contains a growth factor/mediator, and two syringes contain fixative. The valve, turned by the astronaut to pre-selected positions, allows injection of fluids from one syringe into another to mix materials at specified times during the flight. The BPM's provide a larger volume (6 mls) of cells or other fluids but allow for only two samples per BPM rather than the typical MDA which provides up to 120 samples of volumes of 0.125 to 0.5 ml. BPM's are triply contained in flight-certified sealed bags to satisfy NASA safety requirements. Figure 5 shows BPM's on CMIX-1 operated by Lacy Veach.

Figure 4. Bioprocessing Module (BPM) with 4-way valve.

Figure 5. Astronaut, Charles Lacy Veach operating BPM's on STS-52.
**Other Hardware**

As a courtesy and exchange between NASA's CCDSs, I have the opportunity to fly experiments in the Fluids Processing Apparatus (FPA) (Figure 6) of BioServe. To date, this has included experiments on STS-50 and STS-54. The FPA's consist of a glass tube with two by-passes formed along opposite sides to allow fluids to mix between three chambers which are separated by septa. Tubes are placed in lexan cylinders for triple containment. Experiments are activated or fixed by pushing a plunger on a manifold.

![FLUIDS PROCESSING APPARATUS (FPA)](image)

**Figure 6.** The BioServe CCDS Fluids Processing Apparatus (FPA).

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**The Commercial Refrigerator Incubator Module (CRIM)**

CRIM's are made available to the CCDS's through NASA's Office of Advanced Concepts and Technology. This controlled temperature refrigerator/incubator module fits into a Shuttle middeck locker and maintains an approximate set temperature for pre-launch and on-orbit operations. A CRIM carrier, made by ITA, fits inside the CRIM and provides attachment points for the MDA's. The BPM's are stowed in spaces between the MDA's for launch and landing and are de-stowed for on orbit operations. **Figure 7** shows a diagram of the CRIM and **Figure 8** shows the CRIM carrier fabricated by ITA with four MDA's, the controller and BPMs stowed as flown on CMIX-1 and CMIX-2.
3. SUMMARIZED FLIGHT DESCRIPTIONS AND RESULTS

STS-43 (August, 1991): This flight in August 1991 validated the use of ITA's MDA minilabs for cell biology experiments and provided the preliminary information for the FY 1992 experiments. The STS-43 experiments were flown on BIMDA-2 (BioServe sponsored flight of ITA's MDA minilabs) as a joint BioServe/University of Colorado CCDS - ITA payload. On this flight, in addition to ITA experiments, the CMDS flew mouse bone marrow and human lymphocytes which were evaluated after flight for immunologically detectable markers. Results indicated that cells maintained their antigenic identity. The flow cytometry profiles of mouse bone marrow cells fixed after one day in low-g and evaluated to identify the cell type by surface markers show comparable populations of stem cell antigen (SCA-1) and the immune cell marker (Thy-1) positive cells for both Earth-based and spaceflight cells. This significant result validated the MDA's for experiments with live cells. Summarized results of the various experiments flown on the BIMDA Payload are shown in Table 1.
## STS-43 MDA Experiment Results

<table>
<thead>
<tr>
<th>FIELD OF STUDY</th>
<th>APPLICATION</th>
<th>EXPERIMENT</th>
<th>FLIGHT RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomedical/Aging</td>
<td>Bone Homeostasis Development</td>
<td>1 wasp hatched on orb and was alive out of 50 wasp pupae.</td>
<td>Successful bone mineral remoral.</td>
</tr>
<tr>
<td>Biomedical/Aging</td>
<td>Bone Development</td>
<td>1 wasp hatched on orb and was alive out of 50 wasp pupae.</td>
<td>Successful bone mineral remoral.</td>
</tr>
<tr>
<td>Biomedical/Aging</td>
<td>Bone Detrision</td>
<td>1 wasp hatched on orb and was alive out of 50 wasp pupae.</td>
<td>Successful bone mineral remoral.</td>
</tr>
<tr>
<td>Biomedical/Aging</td>
<td>Collagen Assembly on Bone Matrix</td>
<td>1 wasp hatched on orb and was alive out of 50 wasp pupae.</td>
<td>Successful bone mineral remoral.</td>
</tr>
<tr>
<td>Cell Biology</td>
<td>Macrophage Activation</td>
<td>Increased lymphocyte production.</td>
<td></td>
</tr>
<tr>
<td>Cell Biology</td>
<td>Cell Fixation</td>
<td>Inactive worked to preserve certain structures of cells in space.</td>
<td></td>
</tr>
<tr>
<td>Cell Biology</td>
<td>Cell Mixing</td>
<td>Increased lymphocyte production.</td>
<td></td>
</tr>
<tr>
<td>Fluid Sciences/Biomedical</td>
<td>Yeast Diffusion</td>
<td>Diffusion successful.</td>
<td></td>
</tr>
<tr>
<td>Fluid Sciences/Biomedical</td>
<td>Particle Diffusion</td>
<td>Diffusion successful.</td>
<td></td>
</tr>
<tr>
<td>Fluid Sciences/Biomedical</td>
<td>Trypan Blue Diffusion</td>
<td>Diffusion successful.</td>
<td></td>
</tr>
<tr>
<td>Fluid Sciences/Biomedical</td>
<td>Diffusivity of Cells</td>
<td>Diffusion successful.</td>
<td></td>
</tr>
<tr>
<td>Fluid Sciences/Diffusion</td>
<td>Aquous Copper Sulfate Diffusion</td>
<td>Diffusion successful.</td>
<td></td>
</tr>
<tr>
<td>Microbiology/CELSS</td>
<td>Bacteria &amp; Algae Metabolism</td>
<td>Not available.</td>
<td></td>
</tr>
<tr>
<td>Molecular Biology/Pharmaceuticals</td>
<td>Collagen Assembly</td>
<td>Successful collagen polymerization.</td>
<td></td>
</tr>
<tr>
<td>Molecular Biology/Pharmaceuticals</td>
<td>Liposome Formation</td>
<td>Liposomes formed larger than ground controls.</td>
<td></td>
</tr>
<tr>
<td>Molecular Biology/Pharmaceuticals</td>
<td>Virus Assembly</td>
<td>Not available.</td>
<td></td>
</tr>
<tr>
<td>Molecular Biology/Pharmaceuticals</td>
<td>E. Cell Development</td>
<td>E. Cell multiplied faster than controls.</td>
<td></td>
</tr>
<tr>
<td>Molecular Biology/Pharmaceuticals</td>
<td>Cell Lyys</td>
<td>Successful lysis of fibre cots by urokinase.</td>
<td></td>
</tr>
<tr>
<td>Plant Biology/CELSS</td>
<td>Alfalfa &amp; Clover Seed Germination</td>
<td>Some sprouts formed, but overall much less sprouting than on STS-37.</td>
<td></td>
</tr>
<tr>
<td>Protein Crystal Growth</td>
<td>Bacillus Alkalophilic Crystal Growth</td>
<td>No crystals formed.</td>
<td></td>
</tr>
<tr>
<td>Protein Crystal Growth</td>
<td>Lysosome Crystal Growth</td>
<td>No crystals formed.</td>
<td></td>
</tr>
<tr>
<td>Protein Crystal Growth</td>
<td>Double Diffusion Crystal Growth</td>
<td>No crystals formed.</td>
<td></td>
</tr>
<tr>
<td>Protein Crystal Growth</td>
<td>Lysozyme Crystal Growth</td>
<td>No crystals formed.</td>
<td></td>
</tr>
<tr>
<td>Protein Crystal Growth</td>
<td>Bacterial Alkaline Crystal Growth</td>
<td>No crystals formed.</td>
<td></td>
</tr>
<tr>
<td>Protein Crystal Growth</td>
<td>Protein Crystal Growth</td>
<td>No crystals formed.</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- CELSS = Controlled Ecological Life Support Systems (for Space Station, Lunar Base, etc.)
- 1. All MDA's performed successfully, no leakage or cross contamination was seen.
- 2. 21 out of 22 experiments were successful.

Table 1. STS-43 Experimental Results.

**STS-50 BioServe CCDS (June 1992):** (Flown as a CCDS to CCDS courtesy using BioServe Fluids Processing Apparatus {FPA} hardware). Human lymphocytes were flown in collaboration with Dr. Augusto Ochoa of Program Resources, Inc. at the Frederick Cancer Center in Frederick, Maryland. The cells were loaded into the BioServe Fluid Processing Apparatus (FPA) tubes (Figure 6), mixed with a growth mediator for 4 days in microgravity and then mixed with fixative. Results indicated that the cells remained sufficiently viable but did not grow when exposed to the mediator at the low temperature (25°C) on this mission. A subsequent test was conducted in January 1993 at 37°C on STS-54.

**STS-54 BioServe CCDS (January 1993):** This experiment was a repeat of the STS-50 investigation with the exception that the FPA's were maintained at 37°C, this temperature permitted lymphocyte proliferation. Identification of cell surface markers for activated cells indicated positive human cell activation by OKT-3 monoclonal antibody in the presence of exogenous IL-2 in space and ground controls. Flown cells appeared to be activated less than ground controls but secreted significant levels of specific cytokines into the medium. These results are consistent with other...
data indicating retarded growth of cells in space but inconsistent with data from cells stimulated with another type of mediator (Con A) which produced higher levels of some cytokines (Interferon gamma) in microgravity compared to ground controls (Chapes, S.K., D.R. Morrison, J.A. Guikema, M.L. Lewis, and B. S. Spooner. "Cytokine production by immune cells in space". J. Leukocyte Biol. 52:104-110 (1992)). The difference in the activators used may accounts for the difference in cytokine secretion (See abstract on Page 5).

**Consort-5 Sounding Rocket (September 1992):** Live cell tests flown on Consort 5 indicated that the MDA's adapted to accommodate glass coverslips and maintain 37°C temperature performed flawlessly. The cells, including mouse bone, Xenopus (frog) muscle/nerve co-culture, and CV-1 (monkey kidney cell line), remained attached to the coverslips for the total mission profile. This was an extremely significant evaluation since the MDA's were proven to have a new capability to accommodate attachment-dependent cells to be flown on subsequent Shuttle missions.

**Table 2. CMDS EXPERIMENTS FLOWN IN THE MDA MINILABS ON CONSORT 5**

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>INVESTIGATOR/COLLABORATOR/LOCATION</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary human lymphocytes</td>
<td>M./ UAH</td>
<td>Remained viable, MDA validated</td>
</tr>
<tr>
<td>Monkey kidney cell line</td>
<td>M. Lewis/ L. Binder/ UAB</td>
<td>No cytoskeletal data obtained</td>
</tr>
<tr>
<td>Human B lymphocytes</td>
<td>M. Lewis/ D. Sammons/ U. Arizona</td>
<td>Fixative tests feasibility</td>
</tr>
<tr>
<td>Mouse osteoblasts on cover slips</td>
<td>M. Lewis/ M. Hughes-Fulford/ UCSF</td>
<td>Validation of MDA's for coverslips</td>
</tr>
<tr>
<td>Mouse bone marrow</td>
<td>M. Lewis/ B. Lawless/ Rockefeller Univ.</td>
<td>Validation of MDA, cell viability</td>
</tr>
<tr>
<td>Amphibian cells (Xenopus)</td>
<td>R. Gruener/ U. Arizona</td>
<td>Validation of MDA's for coverslips</td>
</tr>
<tr>
<td>Algae (Diatoms)</td>
<td>P. Nerren/ UAH</td>
<td>Student experiment data obtained</td>
</tr>
<tr>
<td>Copper sulfate</td>
<td>J. Baird/ UAH</td>
<td>Fluids mixing in low-g data</td>
</tr>
</tbody>
</table>

**STS-52 CMIX-1 Payload (October 1992):** The first flight of the Commercial MDA ITA Experiments (CMIX) Program Payload was accomplished in October 1992 on STS-52. Table 3 lists ITA commercial users and Student Space Education Program experiments, UAH CMDS affiliates and experiments, and describes experiment rationale and potential commercial applications for the CMIX-1 Payload. Additional UAH CMDS experiments not listed in Table 3 are shown in Table 4.
CMIX-1 Experiments Conducted in ITA's MDA Minilab Units

<table>
<thead>
<tr>
<th>Experiment Name</th>
<th>PI</th>
<th>Sponsor/Organization</th>
<th>Experiment Relevant to Potential Commercial Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain hardening</td>
<td>Dr. Davis Marksber</td>
<td>University of Colorado, Boulder</td>
<td>Study the effects of strain hardening on metal strength and durability in mechanical components.</td>
</tr>
<tr>
<td>Collagen/Polymer self-assembly</td>
<td>Dr. Robert Fitch</td>
<td>University of California, Berkeley</td>
<td>Investigate the self-assembly of collagen and polymer materials for use in tissue engineering and regenerative medicine.</td>
</tr>
<tr>
<td>Inorganic Assembly</td>
<td>Dr. Joseph Gray</td>
<td>University of Washington, Seattle</td>
<td>Examine the synthesis and characterization of inorganic materials for potential applications in electronics and energy storage.</td>
</tr>
<tr>
<td>Biocatalyst Assembly</td>
<td>Dr. Robert Fitch</td>
<td>University of Colorado, Boulder</td>
<td>Study the catalytic activity of biocatalysts for use in bioremediation and biofuel production.</td>
</tr>
<tr>
<td>Enzyme Assembly</td>
<td>Dr. Joseph Gray</td>
<td>University of Washington, Seattle</td>
<td>Investigate the enzymatic processes for biofuel production and bioremediation.</td>
</tr>
<tr>
<td>Growth promotion</td>
<td>Dr. Robert Fitch</td>
<td>University of Colorado, Boulder</td>
<td>Examine the factors that promote cellular growth and differentiation in tissue engineering applications.</td>
</tr>
<tr>
<td>Immobilization of biocatalysts</td>
<td>Dr. Joseph Gray</td>
<td>University of Washington, Seattle</td>
<td>Study the immobilization techniques for use in biocatalytic processes.</td>
</tr>
<tr>
<td>Transduction</td>
<td>Dr. Joseph Gray</td>
<td>University of Washington, Seattle</td>
<td>Investigate the transduction mechanisms involved in cellular communication.</td>
</tr>
</tbody>
</table>

ITACOMMERCIAL USERS

Table 3. CMIX-1 Experiments Conducted in ITA's MDA Minilab Units on STS-52.
Table 4. Additional UAH CMDS Experiments flown on STS-52 not listed in Table 3.

<table>
<thead>
<tr>
<th>Discipline</th>
<th>Experiment</th>
<th>Potential Commercial Application</th>
<th>Investigator Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Immunology</strong></td>
<td>T lymphocyte activation</td>
<td>Therapeutics</td>
<td>D. Morrison, NASA/JSC Houston</td>
</tr>
<tr>
<td><strong>Immunology</strong></td>
<td>T lymphocyte different</td>
<td>Therapeutics</td>
<td>M. Lewis, UAH</td>
</tr>
</tbody>
</table>

**Additional MDA Experiments not listed in Table 3.**

- **Cell differentiation**
  - Bone marrow cell growth
  - Transplantation: B. Lawless, Rockefeller U., NY

- **Oxygen regen.**
  - Algae/diatom growth
  - Closed life support: P. Nerren, UAH

- **Fluid dynamics**
  - Diffusion
  - Materials processing: J. Baird, UAH

Four MDA's were flown in the Commercial Refrigerator/Incubator Module (C-RIM); two were filled with CMDS investigators and affiliates and two contained ITA's commercial customer samples. Table 5 lists the CMIX-1 hardware flight configuration.

**FLIGHT CONFIGURATION ON CMIX-1, STS-52**

1. Four MDA units plus controller and CRIM carrier in CRIM* at 20°C
   - Controller provides power and commands to operate MDA units

2. MDA units are qualified for 2 levels of containment

3. MDA-4 will be heated to 37°C and be in a lexan 3rd containment vessel for UAH cell research experiments

4. MDA controller is velcroed to CRIM carrier for easy removal of BioProcessing Modules (BPM's)

5. MDA's 1, 2, and 3 have the capability for manual override contingency on-orbit operations

6. The four MDA units will provide more than 300 separate data points on STS-52

Table 5. Flight Hardware Configuration on CMIX-1.
Unfortunately, due to an elevated temperature in the carrier (the NASA provided CRIM), a temperature excursion occurred causing an overtemp by several degrees during the first days of the CMIX-1 Payload operations. Because of this anomaly, much of the data obtained from this flight were inconclusive. Post-flight analyses determined that the higher than acceptable temperature was due to a derating of the CRIM fan to run 50% slower in order to meet Shuttle acoustic requirements. In addition, the CMIX-1 Payload was placed near the galley and water heater which appear to generate significant heat to proximally located Shuttle middeck payloads. Modifications to the CRIM and location of the CMIX Payload far away from the galley and water heater were beneficial results of the lessons learned from this first mission. These modifications were incorporated in the second flight of CMIX on STS-56.

Ten BPMs, (Figure-4) were also flown on STS-52. The BPMs, removed from the CRIM and attached by Velcro to a beta cloth bag placed on the flight deck, were maintained at ambient Shuttle temperature. The BPM experiment, in collaboration with Dennis Morrison, NASA/Johnson Space Center, included human and mouse lymphocytes mixed with different growth mediators and fixed at selected times during flight. The cells survived with viabilities of 70-80% and provided information for the design of the subsequent CMIX-2 Payload.

**STS-56 CMIX-2 Payload April (1993):**
CMIX-2 was essentially a repeat of the CMIX-1 Payload. Tables 4 and 6a list experiments conducted in the ITA MDA Minilabs. The payload was launched on STS-56 on April 8, 1993 and returned after a nominal nine-day mission. CMIX-2 carried four MDA's and consisted of 35 separate experiments (25 commercial or student-affiliated investigations for ITA and ten cell biology experiments conducted by UAH CMDS and collaborating investigators). Approximately 400 data points were obtained from the four MDA minilabs.

![Figure 9. Astronaut Ken Cockrell activating MDA's.](image)
Figure 9 shows Astronaut Kenneth Cockrell switching the MDA controller to activate CMIX-2 experiments on STS-56.
### CMIX-2 Experiments Conducted in ITA's MDA Minilab Units

<table>
<thead>
<tr>
<th>Experiment Name</th>
<th>PI</th>
<th>Sponsor/Organization</th>
<th>Experiment Rationale / Potential Commercial Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collagen Reconstitution</td>
<td>Dr. Kenneth E. Hughes</td>
<td>Battelle, Ohio</td>
<td>Studies of hard growth in microg. Applications include unique &amp; complex products for implants</td>
</tr>
<tr>
<td>Urokinase Protein Crystal Growth</td>
<td>Dr. Dennis Morrison &amp; John Cavanagh &amp; Dr. Paul Todd</td>
<td>NASA &amp; University of Colorado, Boulder, PA</td>
<td>Grow crystals of urokinase to study design drugs to combat spread of breast, brain, and other cancers</td>
</tr>
<tr>
<td>Macropinocytosis</td>
<td>Dr. BenjГ¼n Mossavar &amp; Dr. Dennis Morrison</td>
<td>Institute for Research, Houston, TX</td>
<td>Macropinocytosis of drugs for drug delivery techniques. Applications to improve chemotherapy drug delivery.</td>
</tr>
<tr>
<td>Inorganic Assembly</td>
<td>Dr. Robert Shaw &amp; Dr. Jon Deering</td>
<td>Environmental Technology &amp; Telecommunications (ET&amp;T), NY</td>
<td>Inorganic assembly studies</td>
</tr>
<tr>
<td>Bacterial Adenine Crystal Growth</td>
<td>Dr. Jan Schott &amp; Dr. Jon Deering</td>
<td>University of Montreal, Canada</td>
<td>Determine 3D structure of inhibitors for understanding of enzyme catalysis. Studies may allow understanding of genetic effects associated with defects in the structure of the inhibitors.</td>
</tr>
<tr>
<td>Rabbits Muscle Adenine Crystal Growth</td>
<td>Dr. clich Schott &amp; Dr. Jon Deering</td>
<td>University of Montreal, Canada</td>
<td>Obtain attoliter crystals to determine how this enzyme interacts with DNA.</td>
</tr>
<tr>
<td>HIV Reverse Transcriptase</td>
<td>Dr. Paul Todd &amp; Dr. Richard Korzen</td>
<td>University of Colorado, Boulder, PA</td>
<td>Obtain small-scale crystals for study of triple positive function of MDA units.</td>
</tr>
<tr>
<td>Methylenediphtheric Acid Growth</td>
<td>Dr. Paul Todd &amp; Dr. Richard Korzen</td>
<td>University of Colorado, Boulder, PA</td>
<td>Obtain small-scale crystals for study of triple positive function of MDA units.</td>
</tr>
<tr>
<td>Glycogen Protein Crystal Growth</td>
<td>Dr. Paul Todd &amp; Dr. Richard Korzen</td>
<td>University of Colorado, Boulder, PA</td>
<td>Obtain small-scale crystals for study of triple positive function of MDA units.</td>
</tr>
<tr>
<td>Metallogenic Protein Crystal Growth</td>
<td>Dr. Paul Todd &amp; Dr. Richard Korzen</td>
<td>University of Colorado, Boulder, PA</td>
<td>Obtain small-scale crystals for study of triple positive function of MDA units.</td>
</tr>
<tr>
<td>Dye Diffusion/Magnetic Mixing</td>
<td>Dr. Paul Todd</td>
<td>Cold Spring Harbor Laboratory, Cold Spring Harbor, New York</td>
<td>Obtain small-scale crystals for study of triple positive function of MDA units.</td>
</tr>
<tr>
<td>Yeast Cell Diffusion</td>
<td>Dr. Paul Todd</td>
<td>Cold Spring Harbor Laboratory, Cold Spring Harbor, New York</td>
<td>Obtain small-scale crystals for study of triple positive function of MDA units.</td>
</tr>
<tr>
<td>Human stem cell cytoskeleton</td>
<td>Dr. David Baldor</td>
<td>NASA, Huntsville, AL</td>
<td>Obtain small-scale crystals for study of triple positive function of MDA units.</td>
</tr>
<tr>
<td>Human T cell cytoskeleton</td>
<td>Dr. David Baldor</td>
<td>NASA, Huntsville, AL</td>
<td>Obtain small-scale crystals for study of triple positive function of MDA units.</td>
</tr>
<tr>
<td>Cell Research</td>
<td>Dr. Bill Eaves &amp; Dr. Marwan Lewis</td>
<td>NASA, Huntsville, AL</td>
<td>Obtain small-scale crystals for study of triple positive function of MDA units.</td>
</tr>
<tr>
<td>Gene Synthesis Development</td>
<td>Dr. Valerie Cavanagh, Dr. Valera Hernandez &amp; Dr. Paul Todd</td>
<td>NASA, Huntsville, AL</td>
<td>Obtain small-scale crystals for study of triple positive function of MDA units.</td>
</tr>
<tr>
<td>Inorganic Assembly</td>
<td>Dr. John Cavanagh &amp; Dr. Valera Hernandez &amp; Dr. Paul Todd</td>
<td>NASA, Huntsville, AL</td>
<td>Obtain small-scale crystals for study of triple positive function of MDA units.</td>
</tr>
<tr>
<td>Engineering Tools</td>
<td>Dr. Ted Mullen &amp; Dr. Jonathan Duker &amp; Dr. Paul Todd</td>
<td>NASA, Huntsville, AL</td>
<td>Obtain small-scale crystals for study of triple positive function of MDA units.</td>
</tr>
<tr>
<td>Magnetic Residual Tests</td>
<td>Dr. Ted Mullen &amp; Dr. Jonathan Duker &amp; Dr. Paul Todd</td>
<td>NASA, Huntsville, AL</td>
<td>Obtain small-scale crystals for study of triple positive function of MDA units.</td>
</tr>
</tbody>
</table>
## ITA Student Space Education Program

### CMIX-2 Experiments Conducted in ITA's MDA Minilab Units

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Investigator(s)</th>
<th>Institution/Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brassica Rape Reproduction</td>
<td>Dr. Susan Weather, Dr. David E. Harmon</td>
<td>School District of Lancaster, PA for J. P. McCaskey High School</td>
</tr>
<tr>
<td>Fish Egg Hatching</td>
<td>Dr. Charles A. Poole</td>
<td>Pennsyville Memorial School, Pennsyville, New Jersey</td>
</tr>
<tr>
<td>Heart Cells in Culture</td>
<td>Dr. Robert Carter, Dr. Keith M. M. Brown, Dr. Robert A. Rouse</td>
<td>STI 61C Center, the Paddock School, New Jersey</td>
</tr>
<tr>
<td>Mushroom Mycelium Growth</td>
<td>Dr. Helen E. Moore, Dr. Heather D. Sweare, Dr. E. Brown, Dr. Susan H. Moore</td>
<td>University High School, John B. Sweare Company</td>
</tr>
<tr>
<td>Seeds in space</td>
<td>Dr. Peter W. Wood, Dr. John M. Wallihan</td>
<td>International Space University (ISU)</td>
</tr>
<tr>
<td>Human Red Blood Cell Morphology</td>
<td></td>
<td>University of Alabama, Huntsville, Alabama (UAH), UCLS</td>
</tr>
<tr>
<td>Bone Cell Differentation</td>
<td>Dr. M. Lees, Dr. M. Hughes-Fulford</td>
<td>Consortium for Material Development in Space (CMDS) at the University of Alabama, Huntsville, Alabama (UAH), UCLS</td>
</tr>
<tr>
<td>Immunocyte Stem Cell Expansion</td>
<td>Dr. M. Lees, Dr. B. D. Landis</td>
<td>Veterans Administration Medical Center, CMDS at UAH, Rockville University, New York</td>
</tr>
<tr>
<td>Human Cell Response</td>
<td>Dr. M. Lees, Dr. Gary Nell, M. D.</td>
<td>UCSC, University of Iowa</td>
</tr>
<tr>
<td>Adipose Cell Response</td>
<td>Dr. M. Lees, Dr. R. Spangrider</td>
<td>CMDS at UAH, University of Arizona</td>
</tr>
<tr>
<td>Fat and Muscle Cellի Interaction</td>
<td>Dr. Brian Spencer, Dr. Jen Gushan</td>
<td>University of Arizona</td>
</tr>
<tr>
<td>Toxicity and Various Genotypes</td>
<td>Dr. Philip Harmet</td>
<td>CMDS at UAH</td>
</tr>
<tr>
<td>Endocrinology</td>
<td>Dr. James Bond</td>
<td>CMDS at UAH</td>
</tr>
</tbody>
</table>

**Description:**

- **Brassica Rape Reproduction**: Dr. Susan Weather and Dr. David E. Harmon will be growing Brassica rapa in the MDA Minilab units. The aim is to propagate the plant and assess the effects of space travel on the plant's growth and development.
- **Fish Egg Hatching**: Dr. Charles A. Poole will be hatching fish eggs in the MDA Minilab units. The objective is to study the effects of space travel on the hatching success and development of the fish eggs.
- **Heart Cells in Culture**: Dr. Robert Carter, Dr. Keith M. M. Brown, and Dr. Robert A. Rouse will be culturing heart cells in the MDA Minilab units. The goal is to study the effects of space travel on heart cell function and viability.
- **Mushroom Mycelium Growth**: Dr. Helen E. Moore, Dr. Heather D. Sweare, and Dr. Susan H. Moore will be growing mushroom mycelium in the MDA Minilab units. The objective is to study the effects of space travel on mushroom growth and mycelium formation.
- **Seeds in space**: Dr. Peter W. Wood and Dr. John M. Wallihan will be growing seeds in the MDA Minilab units. The goal is to study the effects of space travel on seed germination and plant growth.
- **Human Red Blood Cell Morphology**: Dr. M. Lees and Dr. M. Hughes-Fulford will be studying human red blood cell morphology in the MDA Minilab units. The objective is to study the effects of space travel on red blood cell morphology.
- **Bone Cell Differentiation**: Dr. M. Lees and Dr. B. D. Landis will be studying bone cell differentiation in the MDA Minilab units. The objective is to study the effects of space travel on bone cell differentiation.
- **Immunocyte Stem Cell Expansion**: Dr. M. Lees and Dr. B. D. Landis will be studying immunocyte stem cell expansion in the MDA Minilab units. The objective is to study the effects of space travel on immunocyte stem cell expansion.
- **Human Cell Response**: Dr. M. Lees and Dr. Gary Nell, M. D. will be studying human cell response in the MDA Minilab units. The objective is to study the effects of space travel on human cell response.
- **Adipose Cell Response**: Dr. M. Lees and Dr. R. Spangrider will be studying adipose cell response in the MDA Minilab units. The objective is to study the effects of space travel on adipose cell response.
- **Fat and Muscle Cell Interaction**: Dr. Brian Spencer and Dr. Jen Gushan will be studying fat and muscle cell interaction in the MDA Minilab units. The objective is to study the effects of space travel on fat and muscle cell interaction.
- **Toxicity and Various Genotypes**: Dr. Philip Harmet will be studying toxicity and various genotypes in the MDA Minilab units. The objective is to study the effects of space travel on toxicity and various genotypes.
- **Endocrinology**: Dr. James Bond will be studying endocrinology in the MDA Minilab units. The objective is to study the effects of space travel on endocrinology.

**Table 6a.** CMIX-2 Experiments (continued).
The objectives of UAH CMDS CMIX-2 investigations on mouse, human, amphibian and algal cell cultures, and ITA non-proprietary investigators on collagen assembly, seed germination, microencapsulation, fluid dynamics and protein crystal growth were to expand knowledge of low-g response and to identify potential processes and products which can benefit form space bioprocessing. One MDA was adapted for cells on coverslips, 37°C incubation and triple containment. Three MDA's operated at 20°C for plant and amphibian cells, protein crystal growth and other bioprocessing experiments.

Significant information was obtained on mechanisms of bone and immune cell growth and function. Altered cytoskeletal morphology in both mammalian (Figure 10) and amphibian cells (Figure 11) confirmed cytoskeletal sensitivity to gravity.

In collaboration with Millie Hughes-Fulford, we showed that the actin cytoskeleton of the flown mouse osteoblasts appears bunched and the cell shape is drastically different from the ground control. This data indicates that the cytoskeleton in these cells is extremely gravity sensitive. Implications are that cellular function may also be drastically affected in low-g. We also confirmed results of Skylab experiments which reported reduction in glucose use during spaceflight. Our future experiments will utilize this mouse bone cell model system to test compounds supplied by a leading pharmaceutical company which are designed to prevent or control space osteoporosis.

Similar results were obtained with the Xenopus muscle cells of Raphael Gruener. Flown cells showed decreased actin filament linearity and increased actin filament "cabling" as shown in Figure 11. These data are interpreted to mean that the cytoskeleton may be involved in grav-sensing by single cells.

Figure 10. Mouse bone 3T3 cells grown on coverslips in the MDA wells in ground-based (Top) and flight (STS-56) (Bottom). (Photographs, provided by Dr. Millie Hughes-Fulford, UCSF).
In typical ground control tests, frog cells utilize yolk platelets as a source of energy as they grow. The flown cells were smaller in size and had an over-abundance of yolk platelets indicating a significant slowing of development in space flown cells (Figure 12). These data imply significantly altered development on nerve and muscle cells in low-g and may serve as a model for drug testing and cellular mechanism definition.

Figure 11. Xenopus actin cytoskeleton of control (Top) and flown cells (Bottom)

Figure 12. Xenopus cells from ground (Top) and flown cells (Bottom).

(Xenopus photographs courtesy of Dr. Raphael Gruener, University of Arizona, Tucson, AX)

Human lymphocytes flown in the BPM's maintained high viability (Figure 13) but the flown cells did not increase in number (Figure 14) and were shown by flow cytometry to remain mostly in a non-growth state, whereas the ground control cells responded to mitogenic stimulation and increased in number. In a related experiment using the MDA with mouse T lymphocytes in collaboration with Dr. Mary Ann Principato of the Food and Drug Administration, we determined that the T-cell receptor is not affected by low-g, however; non-T cell mediated activation (Con-A) is severely blunted in low-gravity.
Figure 13. Viability of human T lymphocytes in the Bioprocessing Modules on STS-56. Viabilities of flight and ground cells were approximately the same during the test.

Using the ITA MDA we have thus defined a tool for the study of mechanisms of growth regulation and can now begin to manipulate growth factors and mediators to expand the database on cellular signaling. This can be important to research in the area of cancer and other immune cell disease states.

The CRIM hardware functioned well on CMIX-2. The temperature remained within acceptable limits as shown by plots obtained from data from the thermistors placed at several locations within the CRIM (Figure 15 a,b,c,d thin line plots). Thermistor data indicated that MDAs 1, 2, and 3 operated below 23°C during the first four days and dropped back to 20°C for the remainder of the mission. MDA-4 maintained the set 37°C for the four day cell tests then dropped back to 20°C as planned.

The CMIX-2 payload demonstrated low-cost basic cell biology and bioprocessing research and potential for manufacturing in space using the generic multipurpose commercially-developed MDA hardware.
BIODYNAMIC CELL CULTURE SYSTEMS (ROTATORY CULTURE BIOREACTOR)

This project has both a ground-based component and a microgravity capability. In theory, the microgravity environment of space is expected to offer a unique advantage to the culture of anchorage dependent cells growing on microcarrier beads in that no agitation will be required to keep cells suspended. Gentle agitation can be carefully controlled to ensure that oxygen and nutrients are accessible to cells and metabolic products are removed from the micro-environment. Thus, microgravity can be exploited as a way to increase the aggregation of cells of similar or different types into tissue-density three-dimensional associations. In addition to growth of anchorage dependent cells, microgravity may offer a very unique advantage to suspension cultured cells by providing an environment in which selected cell types prosper and others do not differentiate and grow. The reduced response of T-lymphocytes to mitogens in microgravity is an
example. Because of this differential response of cells in microgravity, new ways to separate desirable cell types may be exploited. This project is maturing rapidly and hardware can be ready for flight by the first or second quarter of 1994.

The ground-based rotating culture devices used by this project produce a very low-shear culture environment and appear to simulate some aspects of microgravity in that they allow cells to remain evenly suspended in three dimensional configuration in a gentle culture environment similar to that expected in microgravity. Low shear culture is achieved and microgravity simulation is approached by randomizing the gravity vector. Rotating culture systems such as these are being used in the Bioreactor Laboratory at UAH for investigating the effect of altered gravity on both plant and animal cells.

THE APPARATUS (Available through Synthecon, Inc., Friendswood, TX)

The rotary cell culture bioreactor systems (RCCS) are simple, motor driven, non-perfused 100, 250 or 500 ml volume, horizontally oriented cylindrical vessels which rotate around the horizontal axis and operate in a standard CO₂ incubator. (Figure 16).

Figure 16. Two High Aspect Rotary Cell Culture Systems operating in the CO₂ incubator at UAH.

Rotation rate is adjustable from 0 to 75 rpm. Cells growing in the vessel are oxygenated by pumping 95% air-5% CO₂ through a central shaft covered with a gas exchange membrane or by passive air exchange over a larger membrane covering one end of the vessel. Vessel rotation at 8
to 20 rpm is sufficient to keep cells or cell-bead aggregates uniformly suspended during the early culture phase. As aggregates become larger as in the case of microcarrier cultures, the rotation rate is increased to maintain a uniform suspension. For cells growing on microcarrier beads, nutrients are replenished by allowing beads to settle to the bottom of the vessel, removing spent medium and replacing it with fresh medium. For suspension cells such as lymphocytes, the contents of the vessel are removed, cells are spun out, suspended in fresh medium and reloaded into the culture vessel. A transient disruption of the quiescent culture environment occurs during medium changes.

Flight model bioreactors will be ready to fly in the first or second quarter of 1994. The flight model will be an on-demand perfusion system in which a high aspect vessel is equipped with a chamber containing fresh culture medium. This medium chamber is separated from the cell culture chamber by a defined molecular weight cutoff membrane. High density cultures have been grown successfully on the ground in this device, the DHARV (Diffusion or Double High Aspect Rotating Vessel), a modification of the RCCS.

We have used this culture system to demonstrate that mouse 3T3 osteoblasts grow in three-dimensional aggregates and produce collagen in the matrix between the microcarrier beads (Reported at the 1991 ASGSB meeting in Louisville). Lymphocytes exposed to anti-OKT3 in the presence of IL2 differentiated and secreted cytokines into the medium. We are continuing to use the RCCS for three-dimensional modeling and mechanism research.

**CONCLUSIONS**

This funding supported, in part, experiments conducted on two Consort sounding rockets and five Shuttle flights. The achievements described in this report were the result of collaborative research among selected investigators brought into the collaboration for the purpose of gaining specific microgravity effect information. We (Hughes-Fulford, Gruener, Lewis) showed that the cytoskeleton is altered in low-g. Implications are that any cellular function, including signal transduction and secretory processes, which depend on the cytoskeleton may be affected during spaceflight. We intend to continue this research to fine tune the mechanisms of how microgravity influences molecular assembly. We (Principato, Lawless, Ochoa, Lewis) confirmed that the T cell receptor-mediated signal transduction pathway in T lymphocyte activation is not affected by low-gravity compared to non-TCR-mediated stimulation (Con-A) which classically does not promote proliferative response. This implies that microgravity may allow separation of proliferative signaling and secretory function in lymphocytes. To use microgravity in this way can permit us to specifically select mediators to put cells into either a proliferative or secretory state. Basic research and commercial production of selected cytokines are potential applications for this finding. The
demonstration of increased prostaglandin synthesis (Hughes-Fulford) during reduced bone cell growth, suggesting an effect of microgravity on prostaglandin-induced mitogenesis, can allow us to investigate the mechanisms controlling bone cell growth in low-g.

The funding contributed significantly to the scientific database in the areas described. We have three, and possibly four, Shuttle flights remaining in the CMDS CMIX Program extending through 1996 or 1997. We will also have about one sounding rocket launch per year. We hope to obtain funding from NASA Life Sciences to allow us to continue this extremely productive collaborative research and maximize our low-g access.

**PUBLICATIONS AND PRESENTATIONS**

1. Lewis, M.L. "Cellular Responses to Low-g". Invited seminar, Kansas State University, Manhattan, Kansas, Sept, 1991.


Abstracts submitted to the 1993 Annual Meeting of the American Society for Gravitational and Space Biology (ASGSB) based on results from CMIX-1 (STS-52) and CMIX-2 (STS-56).

1. M.L. Lewis, and J.M Cassanto. Automated, multiple-sample minilabs provide significant cell biology and space bioprocessing data for Shuttle middeck research.

2. M. Hughes-Fulford, K. Nelson, S. Blaug, C.G. Summer, B.D. Lukefahr and M.L. Lewis. MC3T3-E1 osteoblasts grown in microgravity on STS-56 have reduced cell growth, glucose utilization with altered actin cytoskeleton and increased prostaglandin synthesis.


**Local/State**

### UAH experiments aboard shuttle

**By MARTIN BURKEY**

**Times Science Writer**

Out of sight but not out of mind during the space shuttle mission this week is a package of experiments from the University of Alabama in Huntsville.

Containing vials of human, frog, and mouse cells, the experiments could offer clues to Earth-based ailments, UAH scientists said.

The Commercial MDA ITA experiment (CMIX 2) payload occupies one locker on the shuttle middeck. It consists of four brick-sized automated Material Dispersion Apparatuses. They are turned on by the crew and allowed to run until the end of the mission. This week, they are being used to conduct more than 30 experiments.

The devices were developed by Instrumentation Technology Associates Inc. of Exton, Pa.

Principal investigator and CMIX program manager Dr. Marian Llewellyn of UAH, said human, mouse, and frog cells will be used to learn how the human body responds to living in the weightless environment of space. The research may also give clues toward cures for certain diseases and conditions on Earth.

The research will focus on how cell structure and function are altered in microgravity and could contribute to remedies for some of the physiological problems of space adaptation experienced by astronauts, she said.

The research is sponsored by the UAH Consortium for Materials Development in Space CMDs. The UAH CMDs is one of 17 Centers for the Commercial Development of Space sponsored by NASA's Office of Advanced Concepts and Technology.

Scientists have learned that microgravity causes changes in the human body. During space travel, astronauts and cosmonauts have experienced bone demineralization, muscle atrophy, cardiovascular deconditioning, reduced immune cell response and even decreased in blood cell counts, Llewellyn said.

These space travel-induced conditions correspond to health problems on Earth such as osteoporosis, anemia, immune deficiencies and other types of immune cell dysfunctions. Lewis said the cell experiments flying on CMIX may give insights into cellular-level mechanisms and contribute to the understanding and treatment of these Earth-based conditions.

These live cell tests on bone cell development, lymphocyte function and muscle nerve cell responses will contribute information for potential development and testing of drugs to modify or eliminate some of the undesirable effects of space travel, said Lewis.

Two UAH students also have experiments in the CMIX 2 payload.

Phillip Nerren, a graduate student in biology, is flying an experiment with diatoms, single-celled microscopic plants. This study is crucial in evaluating whether diatoms could be used in a biological recycling system for air and water for long-term space missions.

The diatoms might help recycle carbon dioxide produced by humans.

Diatoms have a silicon cell wall instead of cellulose. This makes the cells more durable, Nerren said.

The diatoms were dehydrated before launch and rehydrated during the mission and their growth monitored.

Dan Baker, a graduate student in cellular biology, is studying how darkness affects the growth patterns of algae. Algae is ecologically important because it could serve as a food, fertilizer as well as suit industrial and pharmaceutical needs.

Several of those uses might be especially useful on a space station or a long space flight.

Other samples in the CMIX payload will study nerve cell communication, the body's mechanism for fighting infection, microencapsulation of drugs, AIDS, heart cells, and germination of mushroom spores and mustard and mustard spinach seeds.

### Discovery crew catches sunrises; pliers embarrass NASA

**By SUSAN HIGHTOWER**

The Associated Press

**SPACE CENTER, Houston —** Discovery's astronauts today twirled the shuttle to catch the dramatic sunrises and sunsets in space and began packing equipment for the trip home.

An embarrassed NASA, meanwhile, tightened rules on the use of tools on the launch pad and opened an investigation into how Discovery lifted off with a pair of pliers stuck on a rocket booster.

NASA said the pliers posed no danger during liftoff. But officials were amazed that the 8 to 10 inches long, remained wedged in a metal pocket on the outside of one of the twin boosters.

NASA spokeswoman Lisa Malone said a technician for booster maker Thiokol Corp. caused his pliers to be missing April 2, six days before Discovery blasted off.

The technician told his supervisor, but the supervisor never filed a report and consequently no search was conducted, officials said. Before launch, shuttle managers were unaware the pliers had been lost at the pad, Malone said.

In space, everything continued to go well for Discovery's five crew members on an atmospheric re-development mission. The astronauts, however, have been taking solar readings and measuring the shrinking ozone layer.

Pilot Stephen Oswald today alternately turned shuttle so its bay faced the glaring sun, then spun it toward deep space to cool instruments taking measurements of solar energy.

Oswald and astronaut Ellen Ochoa also turned off and put
MATERIALS DISPERSION AND BIODYNAMICS PROJECT

CMIX FLIGHT RESULTS
CELL BIOLOGY

BONE CELLS: Mouse osteoblasts grown on coverslips in the MDA.
Project collaborating scientist, Dr. Millie Hughes-Fulford, Univ. CASF

Flight result

- Cytoskeleton structure altered
- Glucose use less in microgravity
- Cellular growth rate retarded
- Increased prostaglandin synthesis

Significance

Cell function may be altered
Metabolism is altered
Bone replacement reduced
Bone mitogenesis control

Commercial Importance of this research

We have system to test drugs at the cellular level to prevent space osteoporosis. Benefits to ground-based treatment of osteoporosis possible.

Status: Ready to begin drug testing.
In negotiation with pharmaceutical industry
Mouse bone 3T3 cells grown on coverslips in the Materials Dispersion Apparatus wells on STS-56. The actin cytoskeleton was stained with rhodamine phalloidin. Cell growth was stimulated with fetal calf serum for four days, then fixed and evaluated by fluorescence microscopy after return of the CMIX-2 Payload.

Top: Actin cytoskeleton of ground control cells run concurrently with the flight experiment. Network of actin filaments are well defined and extend to periphery of the cell.

Bottom: Actin cytoskeleton of cells flown on STS-56. The actin filaments appear bunched and the cell shape is drastically different from the control. This data shows that the cytoskeleton in these cells is extremely gravity sensitive.
LYMPHOCYTES (Immune System Cells)

**Flight result**

- Response to growth mediators variable
- Glucose use is less in microgravity
- Cellular growth rate retarded
- T cell receptor is not affected
- Non-T-cell receptor response reduced
- Human B cells response not impaired

**Significance**

- Cell signaling altered
- Metabolism is altered
- Other functions may be active
- Immune system function OK
- Research tool (mechanisms)
- Immune system function OK

*Commercial Importance of this research*

Results indicate that some cellular products (cytokines) may be produced at higher levels in microgravity. These can be target biopharmaceuticals for low-g production.

*Status:* Ready to begin communications with pharmaceutical and biotechnology industries interested in immune cell products.
MATERIALS DISPERSION AND BIODYNAMICS PROJECT

CMIX FLIGHT RESULTS
CELL BIOLOGY

LYMPHOCYTES (Immune System Cells)

IL6

IL-1 Beta

GMCSF

Gamma IFN

Figure 20. Viability of human T lymphocytes in the Bioprocessing Modules on STS-56.

Figure 21. Cell counts of human T lymphocytes flown in the BPMs on STS-56. Ground control cell counts were significantly higher the flown counts after four days.
AUTOMATED, MULTIPLE-SAMPLE MINILABS PROVIDE SIGNIFICANT CELL BIOLOGY AND SPACE BIOPROCESSING DATA FOR SHUTTLE MIDDECK RESEARCH. M.L. Lewis¹ and J.M. Cassanto². Consortium for Materials Development in Space, University of Alabama, Huntsville, Alabama¹ and Instrumentation Technology Associates, Inc., Exton, PA²

CMIX-2, the second of five Commercial MDA ITA Experiments, was launched on STS-56 on 4/8/93. The payload, returned after a nominal 9-day mission, consisted of 35 separate experiments (approximately 400 data points) in four Materials Dispersion Apparatus (MDA) Minilabs. Objectives of experiments on mouse, human, amphibian and algal cell cultures, collagen assembly, seed germination, micro-encapsulation, fluid dynamics, and protein crystal growth were to expand knowledge of low-g response and to identify potential processes/products which can benefit from space bioprocessing. One MDA was adapted for cells on coverslips, 37° incubation and triple containment. Three MDA's operated at 20° for plant and amphibian cells and other bioprocessing experiments. Significant information was obtained on mechanisms of bone and immune cell growth and function. Altered cytoskeletal morphology in both mammalian and amphibian cells confirmed cytoskeletal sensitivity to gravity. The CMIX-2 payload demonstrated low-cost basic cell biology research and potential for manufacturing in space using generic multipurpose commercially-developed hardware for space bioprocessing.
MC3T3-E1 OSTEOBLASTS GROWN IN MICROGRAVITY ON STS-58 HAVE REDUCED CELL GROWTH, GLUCOSE UTILIZATION WITH ALTERED ACTIN CYTOSKELETON AND INCREASED PROSTAGLANDIN SYNTHESIS. M. Hughes-Fulford, K. Nelson, S. Bleua, C.G. Summer, B.D. Lukens, AND M.L. Lewis, VA Medical Center and UCSF Medical Center San Francisco, CA 94121 and Consortium for Materials Development in Space and The University of Alabama in Huntsville, Huntsville, AL 35899

Spaceflight is an environmental condition where long term space inhabitants have lost up to 16% of weight bearing bone during flight. Since PGE2 is postulated to be one of the key regulators of local bone formation, it is possible that a dysfunction of its synthesis or action might play a role in reduced osteoblast growth seen in spaceflight. In this study, we investigated whether bone growth was inhibited in spaceflight in the absence of hormonal changes or by changes in PGE2 synthesis or its action. The osteoblasts were launched on STS-58 in a quiescent state, fetal calf sera (FCS) was added after 16 hours of microgravity exposure. After four days of growth in space we fixed the cells before return to Earth's gravity. Ground controls were treated in the same manner. Upon landing, we examined cell number, cell cytoskeleton, glucose utilization and prostaglandin synthesis. Using microscopic methods, we found that osteoblasts grew more slowly in spaceflight, with the number of cells grown in microgravity being roughly 2/3 of those on the ground. Secondly, we found the cytoskeleton of the flown osteoblast to have altered actin structure, unlike any actin architecture we have seen before. The flown cells used less glucose than their ground controls. Finally, with reduced glucose utilization and cell number, the flown cells had a significant 1.69 fold increase in prostaglandin synthesis when compared to ground controls. Taken together, these data suggest that microgravity directly affects the growth of osteoblasts resulting in reduced glucose utilization. The surprising increase in prostaglandin synthesis during reduced growth of the osteoblasts may be the result of an uncoupling of the prostaglandin stimulatory pathway of bone mitogenesis in microgravity.

Significant morphological and functional changes take place in primary cultures of Xenopus myocytes and neurons after rotation in the slow clinostat (i,ii). To test if these cells are sensitive to the actual microgravity of space, we flew primary cultures of myocytes in the presence of polylysine-coated polystyrene beads which, like neuron, induce acetylcholine receptor [AChR] clustering. Cell cultures were mounted in the MDA hardware (ITA technologies; John Cassanto, President), in collaboration with Dr. Marian Lewis (University of Alabama) on STS-52 and -56 flights. Cells were exposed to beads within 24 hrs of orbit entry and were fixed prior to re-entry (exposure to microgravity, before fixation, was 9d for both flights). Data analysis revealed: decreased cell and nuclear surface areas, decreased actin filament linearity, and increased actin filament "cabling". AChR aggregation was decreased in response to bead contact, and in fluorescent bungarotoxin binding area present in bead-associated clusters. Data from these flight experiments show better than 80% (by parameters assayed) concordance with results from the slow clinostat. We interpret these results to provide further evidence for 1) cellular changes in altered gravity, 2) possible involvement of the cytoskeleton in gravi-sensing, and 3) usefulness of the clinostat as an earth-bound simulation paradigm.


Supported by a NASA contract (RG) and a Res. Associate (RaR).
EFFECTS OF MICROGRAVITY ON LEUKOCYTE GROWTH CONTROL AND FUNCTION. (M.L. Lewis, M.A. Principato, B.D. Lawless, D.R. Morrison, W.C. Kapp, S.L. Strobl and A.C. Ochoa) Department of Biology, University of Alabama, Huntsville, AL 35899, Immunology Branch, Food and Drug Administration, Laurel, MD 20708, Department of Cellular Immunology, Rockefeller University, NY, NY 10021, NASA Johnson Space Center, Houston, TX 77058 and Program Resources Inc./DynCorp, Frederick MD 21702.

Spaceflight results in significant reduction in mitogenic activation of human T lymphocytes. Causal mechanisms are not understood though cell contact and macrophage function are implicated. We evaluated microgravity effect on lymphocyte responsiveness, cytokine secretion and signaling through the T cell receptor (TCR) complex. Human or murine T lymphocytes were exposed to: non-TCR binding Con A, an efficient activator of resting T cells in unit gravity but not in microgravity; anti-CD3 plus IL2; and superantigen Staphylococcal Enterotoxin B (SEB) in the presence of Class II presenting feeder layers in unit-gravity and on Space Shuttle flights STS-50, 52, 54, and 56. Cells were exposed to mediators for two to 94 hours followed by fixation of flown cells in microgravity. The human peripheral blood mononuclear cells (hPBMC), exposed to Con-A remained primarily in G1 during spaceflight while ground controls progressed through the replicative cycle. Glucose utilization, significantly lowered in spaceflight, confirmed reduced metabolic activity of Con-A treated cells. However, stimulation of normal hPBMC in flight with anti-CD3+IL2 resulted in activation and appreciable cytokine production (gamma-IFN, GM-CSF, IL-1beta, and IL-6) confirming previous flight results indicating significant changes in cytokine secretion. Stimulation of purified murine splenic T cells through direct engagement of the T cell receptor with the SEB superantigen or via the TCR-associated CD3 molecule using anti-CD3+IL2 was also achieved in microgravity. In both instances, the murine T cell populations transitioned into DNA synthesis (S phase) and mitotic division (G2+M), indicative of cellular proliferation. We conclude that T cell activation via the TCR-mediated pathway is unaffected by microgravity while non-TCR-mediated activation, confirmed by poor proliferative response to Con A, does not promote cell division in microgravity. Our results suggest that microgravity may permit separation of proliferative signaling and T cell responsiveness and thus provide an unparalleled opportunity to investigate basic cellular mechanisms controlling growth and function.

Submitted to the 1993 Annual Meeting of the American Society for Cell Biology
A potentially debilitating effect of spaceflight is the demineralization and abnormal deposition of bone ECM. Most of the data on mineralizing tissue in microgravity are from adult bone. Less is known about growing bones with active growth plates, and even less is known about microgravity effects on formation and initial calcification of the growth plate. We have flown an explant organ culture system, using the pre-metatarsals from embryonic mice, in experiments on two shuttle flights. In ground based culture, pre-metatarsal mesenchyme is removed from day 13 embryos. By culture day 3, the cells have differentiated into chondrocytes and organized into cartilage rods. With further culture, some cells terminally differentiate into hypertrophied chondrocytes. The matrix surrounding the hypertrophied cells calcifies, documented in our cultures by alizarin red staining, establishing the initial site for osteoblasts to begin bone deposition. For microgravity experimentation, we modified the culture system for use in available flight hardware. On STS-54, in the CGBA payload, we did our culture experiments in Bioserve FPAs. Pre-metatarsals were placed on the membranes of Millicell units, covered with Matrigel, and cultured in medium-filled FPA chambers. At 8 hours MET, some cultures were fixed and some were given additional medium. At MET 5 days 2 hours, all cultures were fixed. Histology shows differentiation during flight into cartilaginous rods. No conspicuous differences were noted between flight tissues and ground controls. A second flight opportunity was on STS-56, where we flew older pre-metatarsals in the CMIX payload. Little evident growth occurred in flight or in ground controls, but the tissue remained healthy for the 4 day experiment.

We tested the hypothesis that human splenic B lymphocytes are resistant to in vitro activation in microgravity (μg) by stimulation and fixation aboard STS-56. Methods: Normal human splenocytes derived from living organ donors were prepared by density gradient centrifugation and kept frozen until use. The cells were thawed and loaded into the wells of a Materia Dispersion Apparatus (MDA, ITA) at L-30 hr and maintained at 20°. The cells were activated in flight at 37° with one of; medium, lipopolysaccharide (LPS), S. aureus cowan (SAC), α-CD3 or CD40 ligand at L+16 hr then fixed at L+5 days in modified PLP. Simultaneous ground-based controls were performed. Staining and cell cycle analysis were performed post-flight using propidium iodide staining and FACS. Data: Substantial activation of human B cells was evident with soluble (LPS), membrane bound (SAC, CD40 ligand) and cell-contact (α-CD3) reagents. The magnetic beads used for mixing the cultures exhibited the ability to activate the cultures, increasing "background" activation. As shown below, no significant difference in the fraction of cells entering cell cycle in flight (μg) vs. ground-based controls was evident.

<table>
<thead>
<tr>
<th>Activating Agent</th>
<th>Ground-Based</th>
<th>Flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>46.5</td>
<td>51.4</td>
</tr>
<tr>
<td>LPS</td>
<td>81.8</td>
<td>75.4</td>
</tr>
<tr>
<td>SAC</td>
<td>84.6</td>
<td>81.4</td>
</tr>
<tr>
<td>α-CD3</td>
<td>94.4</td>
<td>99.8</td>
</tr>
<tr>
<td>CD40 Ligand</td>
<td>88.8</td>
<td>88.8</td>
</tr>
</tbody>
</table>

Conclusion: Under these experimental conditions, in vitro activation of human splenic B cells was not impaired by μg. Supported by NASA 18433
Superantigen-mediated T cell Receptor Stimulation in Zero Gravity.
M.A. Principato*, B.D. Lawless**, M. Lewis 0.
*Immunobiology Branch, CFSAN, Food and Drug Administration, Laurel, MD. **Rockefeller University, New York. 0 Univ. of Alabama, Huntsville, AL.

We examined the responses of purified murine T cells following potent in vitro stimulation of the T cell receptor complex (TcR) during the STS-56 mission of April 1993. Murine splenic T cells were stimulated by engagement of the TcR associated-CD3 molecule using an anti-CD3 monoclonal or by direct stimulation of VB8 and VB6 T cell subpopulations with a superantigen, Staphylococcal Enterotoxin (SEB). Proliferative responses were assayed by measurement of accumulated DNA content via flow cytometry as an indicator of progression through the mitotic cell cycle.

The results demonstrate that direct stimulation of the CD3-TcR complex by the 2C11 monoclonal or engagement of the appropriate VB families by SEB resulted in proliferation in matched ground controls and cultures activated in orbit. These data indicate that zero gravity does not preclude primary activation of T lymphocytes via direct engagement of the TcR complex, and that the stoichiometry between SEB, class II molecules, and the appropriate T cell receptor is maintained in zero gravity.