Role of MAP Kinases in the Induction of Heme Oxygenase-1 by Arsenite: Studies in Chicken Hepatoma Cells: A Dissertation

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A Dissertation Presented

By

Kimberly Kirstin Elbirt

Submitted to the Faculty of the University of Massachusetts Graduate School of Biomedical Sciences, Worcester in partial fulfillment of the requirements for the degree of:

DOCTOR OF PHILOSOPHY

May 4, 1998

BIOCHEMISTRY AND MOLECULAR BIOLOGY
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ABSTRACT

The chicken hepatoma cell line, LMH, was evaluated with respect to its usefulness for studies of the regulation of heme metabolism. Levels of δ-aminolevulinate synthase mRNA and accumulation of porphyrins were used to evaluate the heme biosynthetic pathway. Regulation of heme oxygenase-1 by known inducers was used as a measure of heme degradation. The induction of heme oxygenase-1 by sodium arsenite was characterized. AP-1 transcription factor elements and MAP kinase signal transduction pathways that modulate expression of endogenous heme oxygenase-1 and transfected heme oxygenase-1 reporter gene constructs in response to arsenite were delineated.

In initial studies, the drug glutethimide was used alone or in combination with ferric nitrilotriacetate to induce δ-aminolevulinate synthase mRNA. Levels of porphyrins, intermediates in the heme biosynthetic pathway, and levels of δ-aminolevulinate synthase mRNA were increased by these treatments in a manner similar to those previously observed in the widely used model system, primary chick embryo liver cells. The iron chelator, deferoxamine, gave a characteristic shift in the glutethimide induced porphyrin accumulation in primary hepatocytes, but was found to have no effect on LMH cells. Heme mediated repression of δ-aminolevulinate synthase mRNA levels was similar among primary hepatocytes and LMH cells. Heme oxygenase-1 was regulated
by heme, metals, heat shock, and oxidative stress-inducing chemicals in LMH cells. Heat shock induction of heme oxygenase-1 mRNA levels was observed for the first time in primary chick embryo liver cells. These data supported the further use of LMH cells to elucidate mechanisms responsible for modulating heme oxygenase-1 gene expression in response to inducers.

The remainder of the studies focused on the role of heme oxygenase-1 as a stress response protein. The oxidative stress inducer, sodium arsenite was used to probe the cellular mechanisms that control the expression of heme oxygenase-1. A series of promoter-reporter constructs were used to search the heme oxygenase-1 promoter for arsenite responsive elements. Several activator protein-1 (AP-1) transcription factor binding elements were identified by computer sequence analysis. Three of these sites, located at -1578, -3656, and -4597 base pairs upstream of the transcription start site, were mutated. The arsenite responsiveness of the reporter constructs containing mutated AP-1 elements was less than that of the same constructs containing wild type AP-1 elements. At least part of the arsenite-mediated induction of heme oxygenase-1 required the activity of AP-1 transcriptional elements.

The MAP kinase signal transduction pathways and heme oxygenase-1 are activated by similar stimuli, including cellular stress. MAP kinases have been shown to exert control over gene expression through effects on the AP-1 family of transcription factors. The MAP kinases ERK, JNK, and p38 were activated by arsenite in LMH cells. Constitutively activated components of the
ERK and p38 pathways increased expression of heme oxygenase-1 promoter-luciferase reporter constructs. Arsenite-mediated induction of heme oxygenase-1 was blocked by dominant negative ERK or p38 pathway components, and by specific inhibitors of MEK (upstream ERK kinase) or p38. In contrast, reporter gene expression was unchanged in the presence of constitutively activated JNK pathway components. Dominant negative JNK pathway components had no effect on arsenite induced heme oxygenase-1 gene activity.

In summary, LMH cells were characterized as a new model system for the study of heme metabolism. This cell line was then used to delineate promoter elements and signaling pathways involved in the arsenite responsiveness of heme oxygenase-1 gene expression. Three AP-1 transcription factor binding sites in the heme oxygenase-1 promoter region were required for responsiveness to arsenite. The MAP kinases ERK and p38 were shown to play an integral role in arsenite-mediated induction of heme oxygenase-1. These studies elucidate one facet of heme oxygenase-1 regulation, and provide tools that will be useful in delineating additional regulatory mechanisms.
# TABLE OF CONTENTS

## CHAPTER I

INTRODUCTION AND OBJECTIVES ......................................................... 1

INTRODUCTION ....................................................................................... 1

Significance of heme and heme metabolism ........................................... 1

Biosynthesis of heme ............................................................................ 4

Regulation of heme biosynthesis in erythroid cells ................................. 7

Regulation of hepatic heme biosynthesis ............................................... 8

The regulatory heme pool .................................................................... 9

Diseases associated with defects in heme synthesis ............................... 9

THE DEGRADATION OF HEME ................................................................. 15

Catalytic heme degradation .................................................................. 15

Characterization of heme oxygenase .................................................... 15

MODEL SYSTEMS FOR THE STUDY OF HEME DEGRADATION ............ 19

Current model systems ...................................................................... 19

LMH hepatoma cell line ...................................................................... 19

REGULATION OF HEME OXYGENASE-1 EXPRESSION .......................... 21

Inducibility of heme oxygenase .......................................................... 21

Regulation of heme oxygenase-1 gene expression ............................... 22

The role of AP-1 in heme oxygenase-1 gene expression ....................... 23

THE MITOGEN-ACTIVATED PROTEIN (MAP) KINASES ....................... 25

Extracellular-signal regulated kinase .................................................. 26

C-jun N-terminal kinase ...................................................................... 28

p38 MAP kinase, homologue of HOG 1 .............................................. 31

Signal integration by MAP kinases .................................................... 31

Activation of MAP kinases by arsenite .............................................. 32
RESEARCH OBJECTIVES

Objective I: To establish whether LMH cells are a good model system for the study of heme metabolism ................................................................. 34

Objective II: To establish whether AP-1 transcription factor complex binding sites modulate sodium arsenite induction of HO-1 ............................................. 34

Objective III: To establish whether the mitogen-activated kinases modulate induction of HO-1 by arsenite ................................................................. 35

CHAPTER II

MATERIALS AND METHODS ................................................................. 36

MATERIALS ............................................................................................... 36

General materials ................................................................. 36

Cells and DNA .................................................................................. 37

METHODS ................................................................................................. 39

Cell culture and preparation of chemicals .................................................... 39

Porphyrins assays .................................................................................. 40

Fluorometric porphyrins assays .............................................................. 40

High performance liquid chromatography (HPLC) porphyrins assays .... 41

Quantitative iron assays ...................................................................... 42

Isolation of RNA .................................................................................. 43

Preparation of radiolabeled probes .......................................................... 44

Quantitation of messenger RNA ............................................................ 45

Northern blots ..................................................................................... 45

Dot blots ............................................................................................... 46

Heme oxygenase activity assays ............................................................ 48

Subcloning ............................................................................................. 50

Site-directed mutagenesis .................................................................... 52

Transfections ....................................................................................... 56

Assessment of reporter gene activity ...................................................... 57

Protein assays ...................................................................................... 58

Immune complex kinase assays ............................................................ 59

Statistical analysis of data .................................................................... 61
CHAPTER III

CHARACTERIZATION OF HEME BIOSYNTHETIC PATHWAYS IN THE CHICKEN HEPATOMA CELL LINE, LMH ........................................62

INTRODUCTION ..............................................................................62
RESULTS ..........................................................................................63
LMH cell culture and growth rate ..............................................63
Porphyrin accumulation in LMH cells versus primary CELCs ....63
Cellular iron accumulation .........................................................67
Upregulation of ALA synthase mRNA .......................................72
Downregulation of ALA synthase mRNA .................................72
Regulation of ALA synthase mRNA by metalloporphyrins in LMH cells .................................................................77
CONCLUSIONS .............................................................................83

CHAPTER IV

CHARACTERIZATION OF HEME OXYGENASE-1: .........................84

INTRODUCTION ..............................................................................84
RESULTS ..........................................................................................86
Initial detection of HO-1 mRNA in LMH cells .........................86
Gelatin-coated dishes enhance induction in LMH cells ............86
Dose response and time course of heme and cobalt induction of HO-1 mRNA .................................................................88
Synergistic induction of HO-1 mRNA by glutethimide and ferric
nitrilotriacetate (FeNTA) .................................................................98
Increased heme oxygenase activity levels correlate with induction of HO-1 mRNA ............................................................98
Effects of non-heme metalloporphyrins on HO-1 mRNA levels .................................................................102
HO-1 mRNA induction measured by both Northern blot and dot blot .........................................................105
Heat shock induction of HO-1 in CELCs and LMH cells .........109
Sodium arsenite induction of HO-1 mRNA in LMH cells ............113
CONCLUSIONS .............................................................................116
CHAPTER V

CLONING AND CHARACTERIZATION OF THE CHICKEN HEME OXYGENASE-1 PROMOTER ........................................ 118

INTRODUCTION.................................................................................................................. 118

RESULTS............................................................................................................................. 120

Construction of cHO-1 promoter-luciferase reporter plasmids ........................................ 120
Detection of basal and induced reporter plasmid luciferase activity .................................. 120
Responsiveness of pCHO7.1-Luc to cellular stressors ...................................................... 123
Optimization of arsenite-mediated induction of pCHO7.1-Luc ........................................... 127
Induction of transfected heme oxygenase-1 promoter luciferase reporter
constructs by sodium arsenite ....................................................................................... 128
Identification of putative transcriptional elements potentially involved in
modulating HO-1 gene expression ............................................................................. 128
Effects of arsenite on AP-1 control plasmid expression .................................................. 135
Role of AP-1 sites in arsenite induction of cHO-1 reporter plasmids ............................... 136

CONCLUSIONS..................................................................................................................... 147

CHAPTER VI

ROLE OF MAP KINASES IN SODIUM ARSENITE-MEDIATED
INDUCTION OF HEME OXYGENASE-1 ................................................................. 149

INTRODUCTION.................................................................................................................. 149

RESULTS............................................................................................................................. 152

Arsenite activates MAP kinases in LMH cells .................................................................. 152
Induction of pCHO7.1-Luc by components of MAP kinase signaling cascades ......... 152
Involvement of the ERK signaling cascade in arsenite induction of cHO-1 .............. 160
JNK MAP kinase is not implicated in arsenite induction of cHO-1 ......................... 163
Involvement of p38 MAP kinase in arsenite induction of the cHO-1 gene ................ 168

CONCLUSIONS..................................................................................................................... 172
CHAPTER VII

CONCLUSIONS ................................................................. 175
SUMMARY AND DISCUSSION ............................................. 175
FUTURE DIRECTIONS ...................................................... 181

BIBLIOGRAPHY ............................................................... 184

APPENDIX A: MEDIA AND BUFFERS .................................... 215
MEDIA ............................................................................ 215
BUFFERS ....................................................................... 218

APPENDIX B: PREPARATION OF CHEMICALS FOR CULTURE .... 221

APPENDIX C: LIST OF PLASMIDS ....................................... 222

APPENDIX D: STRUCTURES OF MAP KINASE INHIBITORS .... 224

APPENDIX E: SEQUENCE OF HO-1 PROMOTER ..................... 225
LIST OF TABLES

Table 1.1: Disease states related to deficiencies in heme biosynthetic enzymes................................................................. 14
Table 1.2: Characteristics of the three major MAP kinase families. .................. 27
Table 2.1: Templates and primers for site-directed mutagenesis of AP-1 elements............................................................................. 54
Table 2.2: Primers for site-directed mutagenesis. ................................................. 55
Table 4.1: Effects of heme or cobalt chloride on levels of HO-1 mRNA in LMH cells. ......................................................................... 87
Table 4.2: Comparative effects of selected chemicals on heme oxygenase activities in primary CELCs and LMH cells. ..................... 101
Table 4.3: Effects of selected chemicals on levels of HO-1 mRNA in LMH cells. .............................................................................. 106
Table 5.1: Induction of pCHO7.1-Luc, but not pCHO.TATA-Luc by inducers of endogenous HO-1. ..................................................... 126
LIST OF FIGURES

Figure 1.1: The structure of heme, ferrous protoporphyrin IX........................................... 2
Figure 1.2: Schematic diagram of the heme biosynthetic pathway................................. 5
Figure 1.3: Effects of the regulatory heme pool on hepatic heme metabolism................................................................. 10
Figure 1.4: The pathway for heme degradation........................................................................ 16
Figure 1.5: Comparison of the mammalian MAP kinase cascade components. .................................................. 29
Figure 2.1: Immune-Complex Kinase Activity Assays......................................................... 60
Figure 3.1: Porphyrin accumulation in LMH cells.............................................................. 64
Figure 3.2: HPLC determination of porphyrin accumulation..................................................... 68
Figure 3.3: Cellular iron content in CELCs and LMH cells................................................. 70
Figure 3.4: Effects of glutethimide, FeNTA, or both, on ALA synthase mRNA levels in LMH cells........................................... 73
Figure 3.5: Heme-dependent repression of ALA synthase mRNA levels in LMH cells. .................................................. 75
Figure 3.6: Comparison of heme-dependent repression of ALA synthase mRNA in CELCs and LMH cells........................................... 78
Figure 3.7: Effects of metalloporphyrins on ALA synthase mRNA levels in LMH cells. ........................................................................ 80
Figure 4.1: Effects of gelatin coating of culture dishes on induction of HO-1 mRNA in LMH cells.................................................. 89
Figure 4.2: Dose-response curves for induction of HO-1 mRNA by heme or cobalt chloride........................................................................ 91
Figure 4.3: Time course for induction of HO-1 mRNA by heme or cobalt chloride........................................................................ 94
Figure 4.4: Comparative efficacy of heme or cobalt chloride to increase
levels of HO-1 mRNA in CELCs and LMH cells..................................................96

Figure 4.5: Effects of glutethimide, FeNTA, or the combination of
glutethimide and FeNTA on levels of HO-1 mRNA in LMH cells.................99

Figure 4.6: Effects of selected metalloporphyrins on HO-1 mRNA levels
in LMH cells. ........................................................................................................103

Figure 4.7: Northern blot comparison of HO-1 mRNA induction by
selected treatments in CELCs and LMH cells.................................................107

Figure 4.8: Comparison of the effects of heat shock on HO-1 and
HSP70 mRNA levels in CELCs and LMH cells.................................................111

Figure 4.9: Sodium Arsenite (ARS) induction of endogenous HO-1
mRNA in LMH cells; and block by actinomycin D............................................114

Figure 5.1: HO-1 promoter-luciferase reporter constructs.............................121

Figure 5.2: Initial test for expression and induction of chicken HO-1
promoter luciferase reporter constructs in LMH cells....................................124

Figure 5.3: Dose- and time-dependence of induction of pCHO7.1-Luc
by sodium arsenite...............................................................................................129

Figure 5.4: Sodium arsenite induces cHO-1 promoter reporter constructs....131

Figure 5.5: Computer generated map of putative consensus transcription
elements in the proximal 7.1 Kb of the chicken HO-1 promoter.....................133

Figure 5.6: Arsenite induction of a luciferase reporter construct driven
by exogenous AP-1 elements................................................................................137

Figure 5.7: Involvement of an AP-1 element in sodium arsenite mediated
HO-1 expression..................................................................................................139

Figure 5.8: Mutation of AP-1 sites decreases responsiveness of
pCHO4.6-Luc to arsenite......................................................................................142

Figure 5.9: Mutation of AP-1 sites decreases responsiveness of
pCHO5.6-Luc to arsenite......................................................................................144

Figure 6.1: Effects of heme, sodium arsenite, cadmium chloride, or
heat shock on MAP kinase activity in LMH cells.............................................153
Figure 6.2: Time course of MAP kinase activation by sodium arsenite. ..........156
Figure 6.3: Effect of selected MAP kinase pathway components on
luciferase reporter gene activity in LMH cells co-transfected with
pCHO7.1-Luc..............................................................................................158
Figure 6.4: Effects of ERK signaling pathway components on reporter
gene activity in LMH cells co-transfected with pCHO7.1-Luc...............161
Figure 6.5: Effects of the MEK inhibitor, PD98059, on ERK activity and
arsenite mediated induction of HO-1. ......................................................164
Figure 6.6: Effects of JNK signaling pathway components on reporter
gene activity in LMH cells co-transfected with pCHO7.1-Luc...............166
Figure 6.7: Effects of inhibitors of MAP kinase pathways on HO-1 gene
expression in LMH cells. ........................................................................169
Figure 7.1: Possible mechanisms for induction of HO-1 by sodium arsenite..179
### ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Name</th>
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<tbody>
<tr>
<td>AIA</td>
<td>allylisopropylacetamide</td>
</tr>
<tr>
<td>AIP</td>
<td>acute intermittent porphyria</td>
</tr>
<tr>
<td>ALA</td>
<td>δ-Aminolevulinic acid</td>
</tr>
<tr>
<td>ALAD</td>
<td>δ-Aminolevulinic acid dehydratase</td>
</tr>
<tr>
<td>ALAS</td>
<td>δ-Aminolevulinic acid synthase</td>
</tr>
<tr>
<td>AP-1</td>
<td>Activator protein 1</td>
</tr>
<tr>
<td>ARS</td>
<td>Sodium arsenite</td>
</tr>
<tr>
<td>ATF</td>
<td>Activating transcription factor</td>
</tr>
<tr>
<td>ATP</td>
<td>Adenosine triphosphate</td>
</tr>
<tr>
<td>BSA</td>
<td>Bovine serum albumin</td>
</tr>
<tr>
<td>C/EBP</td>
<td>CCAAT-enhancer binding protein</td>
</tr>
<tr>
<td>CAT</td>
<td>Chloramphenicol acetyl transferase</td>
</tr>
<tr>
<td>cDNA</td>
<td>Complimentary DNA</td>
</tr>
<tr>
<td>CELCs</td>
<td>Chick embryo liver cells</td>
</tr>
<tr>
<td>CoA</td>
<td>Coenzyme A</td>
</tr>
<tr>
<td>CRE</td>
<td>Cyclic adenosine monophosphate responsive element</td>
</tr>
<tr>
<td>DDC</td>
<td>3,5-diethoxycarbonyl-1,4-dihydrocollidine</td>
</tr>
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<td>DFO</td>
<td>Deferrooxamine</td>
</tr>
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<td>DMSO</td>
<td>Dimethyl sulfoxide</td>
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<td>Dithiothreitol</td>
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<tr>
<td>EGF</td>
<td>Epidermal growth factor</td>
</tr>
<tr>
<td>ERK</td>
<td>Extracellular signal regulated kinase</td>
</tr>
<tr>
<td>FC</td>
<td>Ferrochelatase</td>
</tr>
<tr>
<td>FeNTA</td>
<td>Ferric nitritriacetate</td>
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<tr>
<td>GCK</td>
<td>Germinal Centre Kinase</td>
</tr>
<tr>
<td>GAPDH</td>
<td>Glyceraldehyde-3-phosphate dehydrogenase</td>
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<tr>
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<td>Glutethimide</td>
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<tr>
<td>GST</td>
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<td>HEPES</td>
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<td>Heme oxygenase</td>
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<td>HPLC</td>
<td>High performance liquid chromatography</td>
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<td>Heat shock protein</td>
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<td>c-Jun N-terminal kinase</td>
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<tr>
<td>LMH</td>
<td>White Leghorn strain M hepatoma</td>
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<tr>
<td>LPS</td>
<td>Lipopolysaccharide</td>
</tr>
<tr>
<td>Luc</td>
<td>Luciferase</td>
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<tr>
<td>MAPK</td>
<td>Mitogen activated protein kinase</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>MAPKAP-K2</td>
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<td>MAPK/ERK kinase</td>
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<td>Metalloporphyrin</td>
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<td>MKP</td>
<td>MAP kinase phosphatase</td>
</tr>
<tr>
<td>MLK</td>
<td>Mixed lineage kinase</td>
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<tr>
<td>mRNA</td>
<td>Messenger RNA</td>
</tr>
<tr>
<td>NADPH</td>
<td>Nicotinamide adenine dinucleotide phosphate, reduced</td>
</tr>
<tr>
<td>NO</td>
<td>Nitric oxide</td>
</tr>
<tr>
<td>PAGE</td>
<td>Polyacrylamide gel electrophoresis</td>
</tr>
<tr>
<td>PAK</td>
<td>p21 activated Ser/Thr kinase</td>
</tr>
<tr>
<td>PAR</td>
<td>4-(2-pyridylazo)resorcinol</td>
</tr>
<tr>
<td>PBGD</td>
<td>Porphobilinogen deaminase</td>
</tr>
<tr>
<td>PCA</td>
<td>Perchloric acid</td>
</tr>
<tr>
<td>PCR</td>
<td>Polymerase chain reaction</td>
</tr>
<tr>
<td>PDGF</td>
<td>Platelet-derived growth factor</td>
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<tr>
<td>PGK</td>
<td>Phospho glycerol kinase</td>
</tr>
<tr>
<td>Pro</td>
<td>Proline</td>
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<tr>
<td>RLU</td>
<td>Relative light units</td>
</tr>
<tr>
<td>RNA</td>
<td>Ribonucleic acid</td>
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<tr>
<td>SDS</td>
<td>Sodium dodecyl sulfate</td>
</tr>
<tr>
<td>SEM</td>
<td>Standard error of the mean</td>
</tr>
<tr>
<td>Ser</td>
<td>Serine</td>
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<td>SRE</td>
<td>Serum response element</td>
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<tr>
<td>β-gal</td>
<td>β-galactosidase</td>
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<tr>
<td>STAT</td>
<td>Signal transducers and activators of transcription</td>
</tr>
<tr>
<td>TCF</td>
<td>Ternary complex factor</td>
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<tr>
<td>TGF</td>
<td>Transforming growth factor</td>
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<tr>
<td>Thr</td>
<td>Threonine</td>
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<tr>
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<td>TPA-response element</td>
</tr>
<tr>
<td>Tyr</td>
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<tr>
<td>UROD</td>
<td>Uroporphyrinogen decarboxylase</td>
</tr>
<tr>
<td>UTR</td>
<td>Untranslated region</td>
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CHAPTER I
INTRODUCTION AND OBJECTIVES

Introduction

**Significance of heme and heme metabolism.** Heme (ferrous protoporphyrin IX) plays a major role in the health and normal functioning of cells and organisms mainly by acting as the prosthetic group for hemoproteins. The tetrapyrrrole ring structure of heme (Figure 1.1) enables hemoproteins to perform reduction and oxidation reactions that are necessary for cell and tissue growth and maintenance. Hemoglobin and myoglobin are essential for respiration and gas exchange. The mitochondrial and microsomal cytochromes are the major hemoproteins that carry out steroid biosynthesis, detoxification and activation of xenobiotics, and energy generation. Hemoproteins also contribute to cellular defense mechanisms. Cellular protection is attributed to antioxidant proteins such as catalase, superoxide dismutase, and most recently, heme oxygenase, the rate-limiting enzyme of heme degradation. The balance of heme anabolism and catabolism in cells is essential to proper functioning. Lack of heme may result in the failure of cells to produce enough energy to sustain themselves, whereas excessive “free” or loosely-bound heme may lead to excessive oxidative stress, causing damage to lipids, proteins, and nucleic acids. Therefore, the biosynthesis and degradation of cellular heme are tightly controlled by several mechanisms.
Figure 1.1: The structure of heme, ferrous protoporphyrin IX. According to common reference, the pyrrole rings are labeled A through D, and the methenyl bridges between the rings are labeled α,β,γ, and δ. The substituents on the pyrrole rings are different for uroporphyrins (acetate and propionate), coproporphyrins (methyl and propionate), and protoporphyrins (methyl, propionate, and vinyl, as shown here). Mesoporphyrin derivatives have 1 methyl and 1 ethyl group on each of the A and B rings, and 1 methyl and 1 propionate group on each of the C and D rings. Protoporphyrin and mesoporphyrin may chelate other divalent cations (Mn, Co, Cu, Sn, Zn, etc.) to form metalloporphyrins.
Ferrous Protoporphyrin IX
(HEME)
Biosynthesis of heme. Heme biosynthesis is a multi-step process that has been well characterized. The major sites of heme synthesis are hepatocytes and developing erythrocytes, for which the overall steps in heme biosynthesis are similar. Heme synthesis begins and is completed in the mitochondria, with intermediate steps occurring in the cytosol (Figure 1.2). The first committed step of heme biosynthesis is the formation of δ-aminolevulinic acid (ALA), the precursor of porphyrins and chlorophylls, as well as the corrin ring of vitamin B_{12}. In the mitochondria, δ-aminolevulinic acid synthase (ALA synthase) [E.C. 2.3.1.37] catalyzes the condensation of succinyl CoA and glycine to form ALA. In the cytosol, ALA dehydratase (ALAD) [E.C. 4.2.1.24] links two molecules of ALA to form the monopyrrole, porphobilinogen (PBG). Porphobilinogen deaminase (PBGD) [E.C. 4.3.1.8] then converts four molecules of PBG into the linear tetrapyrrole, hydroxymethylbilane, which in the presence of uroporphyrinogen III cosynthase [E.C. 4.2.1.75], is subsequently converted to the asymmetric cyclic tetrapyrrole, uroporphyrinogen III, by inversion of pyrrole ring D (See Figure 1.1). In the absence of the cosynthase, hydroxymethylbilane undergoes spontaneous nonenzymatic cyclization to form uroporphyrinogen I. The formation of heme specifically requires the asymmetric isomer, uroporphyrinogen III. Through a series of four successive decarboxylations, uroporphyrinogen III is converted to coproporphyrinogen III by the next enzyme in the pathway, uroporphyrinogen decarboxylase (UROD) [E.C. 4.1.1.37]. UROD also catalyzes the formation of coproporphyrinogen I from
Figure 1.2: Schematic diagram of the heme biosynthetic pathway. Heme synthesis begins and ends in the mitochondria, with intermediate steps occurring in the cytoplasm of the cell. The substrates and products are indicated for each step. Enzymes are indicated in italics.
Glycine + Succinyl CoA
\[ \rightarrow \delta\text{-aminolevulinate synthase} \]

Mitochondria
\[ \delta\text{-aminolevulinate (ALA)} \]
\[ \rightarrow \delta\text{-aminolevulinate dehydratase} \]

Cytoplasm
porphobilinogen
\[ \rightarrow \text{porphobilinogen deaminase} \]
(hydroxymethylbilane)
uroporphyrinogen III
\[ \rightarrow \text{uroporphyrinogen III cosynthase} \]

(nonenzymatic)
uroporphyrinogen I
\[ \rightarrow \text{uroporphyrinogen III decarboxylase} \]
(UROD)
coproporphyrinogen I

Cytoplasm
coproporphyrinogen III
\[ \rightarrow \text{coproporphyrinogen oxidase} \]

Mitochondria
protoporphyrinogen IX
\[ \rightarrow \text{protoporphyrinogen oxidase} \]
protoporphyrin IX
\[ + \text{Fe}^{2+} \rightarrow \text{ferrochelatase} \]
ferrous protoporphyrin IX (heme)
uroporphyrinogen I. The next step is catalyzed by the mitochondrial enzyme, coproporphyrinogen oxidase [E.C. 1.3.3.3], which oxidatively decarboxylates the two propionic groups of the A and B rings of coproporphyrinogen III to vinyl groups, resulting in the formation of protoporphyrinogen IX.

Protoporphyrinogen oxidase [E.C. 1.3.3.4] then oxidizes the methylene groups which link the pyrrole rings of protoporphyrinogen IX, to methenyl groups to form protoporphyrin IX, the substrate for the final step of heme biosynthesis. Heme synthesis is completed by ferrochelatase (FC) [E.C. 4.99.1.1] through insertion of a ferrous iron atom into protoporphyrin IX to form heme (Ferrous protoporphyrin IX).

**Regulation of heme biosynthesis in erythroid cells.** During development, erythroid cells must maximize the production of the heme-containing oxygen transport protein, hemoglobin, to last for the lifetime of the erythrocyte. Two enzymes of heme biosynthesis have isoforms that are erythroid specific: ALA synthase, and porphobilinogen deaminase. ALA synthase is encoded as two separate genes: erythroid-specific (located on the X chromosome) and non-specific or housekeeping. The erythroid-specific and non-specific isozymes of porphobilinogen deaminase result from differential transcription and splicing of a single gene product. All of the other enzymes of heme biosynthesis are the same for developing erythrocytes and hepatocytes, and other cells. In developing erythrocytes, heme increases: 1) the transcription and translation of the erythroid form of ALAS; 2) the formation of the erythroid form of
porphobilinogen deaminase; and 3) the synthesis of many other proteins, including the other enzymes of heme biosynthesis and the globins. The overall rate of erythroid heme biosynthesis is dependent on the supply of iron for the final step, catalyzed by ferrochelatase\textsuperscript{7-11}.

**Regulation of hepatic heme biosynthesis.** Hepatic heme synthesis accounts for approximately 15% of the total heme produced in humans\textsuperscript{2,5}. In hepatocytes, heme is utilized primarily (65%) as the prosthetic group for microsomal cytochrome P450\textsuperscript{2,5}. Hepatic heme synthesis is controlled primarily by the rate of formation of ALA. As the first and rate-limiting enzyme, ALA synthase has been shown to be the major site of regulation of hepatic heme synthesis. Basal ALA synthesis is generally low, but is highly inducible (up to 100-fold) by many hormones (progesterone, estrogens, and testosterone). Chemicals or drugs can induce ALA synthase by several means: 1) by directly up-regulating ALA synthase transcription (e.g. barbiturates and hydantoins), 2) by increasing demand for heme through induction of cytochrome P450, 3) by rapidly destroying cytochrome P450 heme (e.g. chemicals such as allylisopropylacetamide (AIA) and 3,5-diethoxycarbonyl-1,4-dihydrocollidine (DDC)), and 4) by inhibiting other heme biosynthetic enzymes and causing a depletion of hepatic heme (e.g. succinylacetone, an inhibitor of ALA dehydratase, or iron chelators, which inhibit ferrochelatase). These chemicals and drugs are often used to induce or mimic porphyria in animals or cell culture models.
The regulatory heme pool. Hepatic ALA synthase is subject to negative feedback regulation by heme, the end-product of the pathway. It is generally accepted that a small, rapidly turning-over "regulatory" heme pool exists in hepatocytes \(^{12,13}\), and that the heme present in this pool is in dynamic equilibrium with the heme incorporated into hemoproteins and other cellular heme pools (Figure 1.3). The concentration of heme in the hepatic heme pool is maintained at concentrations estimated at \(10^{-7}\) to \(10^{-8}\) M by a balance between ALA synthase and heme oxygenase, the enzyme that controls heme degradation \(^{1,2,4,5,12}\). Both of these enzymes are regulated by heme. The regulatory heme pool controls heme biosynthesis by several mechanisms: 1) by decreasing the transcription of ALA synthase mRNA (although this has been shown in rodents only); 2) by decreasing the translation of ALA synthase mRNA into protein; and 3) by interfering with the processing of the ALA synthase precursor protein and uptake of the enzyme by mitochondria. Heme may also directly inhibit ALA synthase enzyme activity, but only at a much higher concentration of heme \((K_i = 2 \times 10^{-5} \text{ M})\) than that required for regulation of HO or ALA synthase gene expression \(^{2,4,12}\). Thus, depletion of regulatory heme generally increases ALA synthesis, whereas excess heme represses ALA synthesis.

Diseases associated with defects in heme synthesis. Deficiencies in heme biosynthetic enzymes may lead to various disease states, the most common being porphyria. Porphyrias were so named due to the characteristic
Figure 1.3: Effects of the regulatory heme pool on hepatic heme metabolism.

Heme exerts regulatory effects on both ALA synthase and heme oxygenase-1 to control both its synthesis and its degradation. Heme increases the transcription of HO-1, leading to increased production of HO-1 protein, which catalyzes heme degradation. Several steps in the production of functional mature ALA synthase protein may be inhibited by heme as indicated by minus signs, or by the plus sign indicating increased degradation of ALA synthase mRNA. Regulatory heme is incorporated into apo-hemoproteins as the prosthetic group to form functional holo-hemoproteins. Heme may also increase the transcription of apo-hemoproteins, especially the cytochrome P450 proteins.
accumulation and excretion of porphyrins in patients with these disorders. Because only porphyrinogens are substrates for all except the last step of the biosynthetic pathway, very little porphyrin normally accumulates in cells. Porphyrinogens are colorless and have no fluorescent properties. However, the porphyrinogens are very reactive, and are easily oxidized to their corresponding porphyrins. Oxidation can occur spontaneously in the presence of light and oxygen, or it can be catalyzed by cytochrome P450 mono-oxygenase mediated mechanisms upon activation by xenobiotics such as aromatic hydrocarbons. Porphyrins are stable, colored compounds (usually red to purple), that absorb light at about 400 nm (Soret band), and fluoresce when excited. The buildup of porphyrinogens and their oxidation to porphyrins cause the photosensitivity that is observed in most forms of porphyria. The properties of porphyrins have facilitated the detection and diagnosis of the various forms of porphyria. These colored, fluorescent compounds are excreted and can be quantitated by fluorescence spectroscopy or high performance liquid chromatography.

The erythroid form of ALA synthase is critical for erythrocyte development. A deficiency in erythroid ALA synthase leads to X-linked sideroblastic anemia. Deficiencies of the other enzymes in the heme biosynthetic pathway result in porphyrias. Porphyrias are categorized as erythroid or hepatic, depending on the site with the highest accumulation of porphyrin precursors. The hepatic porphyrias are characterized mainly by cutaneous photosensitivity,
neurological symptoms, buildup of porphyrin precursors in the blood and tissues, and excretion of porphyrins and/or their precursors in the urine and feces. The most common form of hepatic porphyria is porphyria cutanea tarda, which is characterized by photosensitivity and a high incidence of liver disease, e.g. cirrhosis. The most common form of acute hepatic porphyria is acute intermittent porphyria (AIP), for which the primary symptoms are abdominal pain accompanied by neurological symptoms. Hormones, drugs, and nutritional factors may induce or exacerbate porphyric attacks, which may include muscular paralysis, seizures, respiratory failure, and eventually death.\textsuperscript{2,3} Table 1.1 lists the disease states associated with deficiencies of the enzymes involved in heme biosynthesis.
Table 1.1: Disease states related to deficiencies in heme biosynthetic enzymes.

<table>
<thead>
<tr>
<th>Enzyme Deficiency</th>
<th>Disease and Inheritance Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ-aminolevulinic acid synthase erythroid</td>
<td>X-linked sideroblastic anemia</td>
</tr>
<tr>
<td>δ-aminolevulinic acid dehydratase hepatic</td>
<td>Nearly complete lack of activity, autosomal recessive: ALAD deficiency porphyria</td>
</tr>
<tr>
<td>Porphobilinogen deaminase hepatic</td>
<td>Heterozygous, autosomal dominant: acute intermittent porphyria</td>
</tr>
<tr>
<td>Uroporphyrinogen III cosynthase erythroid</td>
<td>Homozygous, autosomal recessive: congenital erythropoietic porphyria</td>
</tr>
<tr>
<td>Uroporphyrinogen decarboxylase hepatic</td>
<td>Heterozygous, variable: porphyria cutanea tarda; homozygous, autosomal recessive: hepatoerythropoietic porphyria</td>
</tr>
<tr>
<td>Coproporphyrinogen oxidase hepatic</td>
<td>Heterozygous, autosomal dominant: hereditary coproporphyria</td>
</tr>
<tr>
<td>Protoporphyrinogen oxidase hepatic</td>
<td>Heterozygous, autosomal dominant: variegate porphyria</td>
</tr>
<tr>
<td>Ferrochelatase erythroid</td>
<td>Heterozygous, autosomal dominant: erythropoietic protoporphyria</td>
</tr>
</tbody>
</table>
The Degradation of Heme

Catalytic heme degradation. The catalytic breakdown of heme to bilirubin was first described by Tenhunen et al. in 1968 \(^{16,17}\). Heme degradation is much less complicated than its biosynthesis (Figure 1.4). Heme oxygenase (HO) [E.C. 1.14.99.3] is the first and rate-limiting enzyme of heme catabolism. In association with NADPH ferrihemoprotein reductase (NADPH-cytochrome P450 reductase) [E.C. 1.6.2.4] and in the presence of NADPH or NADH, HO catalyzes the breakdown of heme into equimolar amounts of carbon monoxide, iron, and the linear tetrapyrrrole, biliverdin. The reductase-HO complex accepts electrons from NADPH or NADH to maintain the heme iron in the reduced state, which is required for the binding of molecular oxygen, and to oxidatively cleave the \(\alpha\)-methenyl bridge between pyrrole rings A and B of the heme molecule \(^{16,19}\). In most mammalian, but not avian species, biliverdin is subsequently reduced to bilirubin by biliverdin reductase (BVR) [E.C. 1.3.1.24]. The enzymatic activity of HO can be competitively inhibited by metalloporphyrins with the central iron atom replaced by tin, cobalt, zinc, or manganese \(^{19}\).

Characterization of heme oxygenase. Two isoforms of HO, HO-1 and HO-2, transcribed from separate genes have been characterized \(^{20-22}\). HO-1 has been detected in most vertebrate tissues, with the highest activities in the spleen, liver, and kidneys. Among other functions, HO-1 is thought to play a role in regulating the amount of heme (in the regulatory heme pool) available to
Figure 1.4: The pathway for heme degradation. The first and rate-limiting enzyme of heme degradation is heme oxygenase. The same reaction is carried out by both isoforms, HO-1 and HO-2. The oxidation of heme requires oxygen, NADPH ferrihemoprotein reductase, and NADPH or NADH as a source of reducing equivalents. The reaction requires a total of 3 oxygen molecules and 6 reducing equivalents per molecule of heme that is degraded. Enzymes are indicated in italics.
Ferrous Protoporphyrin IX (HEME)

\[
\begin{align*}
\text{NADPH} & \quad \xrightarrow{Heme\ Oxygenase} \\
\text{NADP} & \quad \xrightarrow{CO, \ Fe^{3+}} \\
\text{Biliverdin} & \quad \xrightarrow{\text{Biliverdin Reductase}} \\
\text{NADPH} & \quad \xrightarrow{\text{NADP}} \\
\text{Bilirubin} & \quad \xrightarrow{\text{NADP}}
\end{align*}
\]
form hemoproteins, such as the microsomal cytochromes P450, which play key roles in a vast array of reactions, including steroid biogenesis and phase I drug metabolism. The HO-1 genes from rodents, humans, and chicken have been cloned and characterized. The chicken HO-1 protein has 296 amino acids with a predicted molecular mass of 32 Kd. The length of the cDNA is 1258 bases, and shares 69% identity with rat HO-1 and 76% identity with human HO-1 cDNAs. The region from amino acids 128 - 136 and histidine-25 correspond to the heme binding and catalytic site, and are conserved among HO-1 proteins from rat, human, and chicken.

A very effective way to study the importance of a gene for cellular metabolism and survival is to obtain a gene knockout animal, or a knockout cell line. Recently, a strain of mice lacking the HO-1 gene has been described. Recent studies by Poss and Tonegawa in HO-1 deficient mice have highlighted the important metabolic and cytoprotective roles of this gene. The mice exhibited an incapacity to modulate body iron stores properly and were more sensitive to hepatic injury by iron, indicating that HO-1 plays an important role in iron utilization. After exposure to oxidative damage-causing agents, such as hemin, hydrogen peroxide, or cadmium, the mice were hypersensitive to cytotoxicity when given additional hemin or hydrogen peroxide. When subsequently challenged with endotoxin, HO-1 deficient mice were highly susceptible to hepatic necrosis or death.
Model Systems for the Study of Heme Degradation

Current model systems. The inducibility and regulation of HO-1 have been investigated using a number of model systems, including intact rodents, primary cultures of rat hepatocytes and chick embryo liver cells (CELCs)\(^{23,42-47}\), and various cell lines: Hepa, FEK\(_4\), L929, C6, HepG2, HeLa, etc.\(^{27,33,48-53}\). A widely-used model that closely approximates what occurs in vivo and in humans is that of primary cultures of chick embryo liver cells (CELCs). This system has been characterized and used successfully by many laboratories for investigations of numerous aspects of heme metabolism. Unlike rat hepatocytes\(^{50,54}\), CELCs retain normal inducibility of ALA synthase\(^{45,46,55-59}\). They also retain normal inducibility and levels of expression of other heme enzymes, such as the cytochromes P-450\(^{47,50,55-57,60,61}\) and HO-1\(^{18,23,45}\), making this a powerful system for the study of heme metabolism in vitro. However, there are some limitations to this primary culture system: the cells obtained are somewhat heterogeneous; the isolation must be repeated each week to obtain more cultures, resulting in weekly variations and limitations on the number of cultures that can be set up; and such primary cultures may only be used for experiments lasting up to 5-7 days, making stable transfections impossible.

LMH hepatoma cell line. Transient transfections of primary CELCs have provided valuable insights into the regulation of gene expression\(^{62,63}\).

However, recent work suggested differences in HO-1 expression between
transient and stable transfectants. Since long-term transient and stable transfections were not possible in primary cultures of CELCs, proliferating cell lines were investigated. LMH cells are the first chicken hepatoma cell line to be established. This cell line was derived from an hepatocellular carcinoma induced by feeding diethylnitrosamine to a male White Leghorn strain M chicken. As an immortal cell line, LMH cells provide some potential advantages over primary cultures: continuous long-term culture, cell type homogeneity, and a virtually endless supply. Using this cell line, Oddoux and Grininger have demonstrated normal responses and behavior with respect to plasma protein synthesis and hormonal regulation (with the exception of a defect in fibrinogen secretion), comparable to that observed in primary chicken hepatocytes. LMH cells have also been used successfully in transfection studies exploring regulation of the genes for chicken apolipoproteins AI and II, vitellogenin II, and in studies investigating insulin responsiveness.
Regulation of Heme Oxygenase-1 Expression

Inducibility of heme oxygenase. Many chemical and environmental stimuli are known to induce HO-1, including its substrate heme \(23,74,75\), other metalloporphyrins (MePNs) \(28,57,74,76\), transition metals \(23,77,78\), inflammatory cytokines \(79-82\), prostaglandins \(83,84\), ultraviolet light (UV) \(48,85,86\), phorbol esters \(87\), heat shock \(29,52,75\), and other chemical initiators of cellular stress responses, such as hydrogen peroxide \(85\), lipopolysaccharide (LPS) \(79,88\), and sodium arsenite (ARS) \(52,85,89,90\). In contrast, HO-2 is found mainly in the brain and testis, is unresponsive to any of the inducers of HO-1, and is essentially uninducible \(21,22,23\).

HO-1 has been characterized as a heat shock protein (HSP32), and growing evidence supports a role for HO-1 in protecting cells from oxidative stress \(48,85,89,91-96\). The protection afforded by HO-1 seems to be due to the production of biliverdin and bilirubin, which have been shown to be potent antioxidants \(92,97\). The degradation of heme also leads to production of CO, which is hypothesized to be a signaling molecule that may upregulate cGMP production in a manner similar to nitric oxide (NO) \(98,99\). Sodium arsenite causes oxidative stress, is a potent inducer of HO-1 in many cell types and systems, and has been described as a tumor promoting agent \(89,90,93,100\). HO-1 most recently has been suggested to play roles in protecting cells from oxidative stress produced during growth and development, and in tumors, with discrete
differences in expression observed between normal and cancerous cell types.

Previous studies have defined two general mechanisms for induction of HO-1. Heme, the heme precursor δ-aminolevulinate (ALA), and substances in the class of phenobarbital-like drugs (e.g., phenobarbital, glutethimide, or phenytoins) act via a heme-dependent mechanism; whereas transition metals act by a heme-independent mechanism. Heme and cobalt chloride, acting by two disparate mechanisms, are potent inducers of HO-1, and have been widely used for the characterization of HO-1 regulation. Distinctions between the mechanisms utilized by metals, heme, and heat shock to induce HO-1 have also been described. Despite these differences, the effects of diverse factors on HO-1 gene expression appear to be exerted chiefly at the transcriptional level, suggesting that multiple signal transduction pathways mediate induction of HO-1 gene transcription in response to a multitude of cellular stimuli.

Regulation of heme oxygenase-1 gene expression. Several cis-acting promoter elements involved in mediating HO-1 gene expression have been elucidated. In one study, stably transfected HO-1 reporter gene constructs were used to locate elements required for induction of the murine HO-1 gene by heme and heavy metals. Putative regulatory elements were identified between 3.5 Kb and 12.5 Kb upstream from the transcription start site. Evidence was presented for a basal level inducer and heme-responsive
element located as far as 10.5 Kb upstream of the transcription start site in the mouse HO-1 gene promoter. Several potential binding sites for known transcriptional regulators were identified in the human HO-1 promoter which may account for induction by a variety of inducers, including heme. Other work has located regions of the HO-1 promoter that mediate cadmium, heat shock, hypoxia, and LPS responsiveness.

The role of AP-1 in heme oxygenase-1 gene expression. Several recent studies have presented evidence supporting induction of HO-1 gene expression through the utilization of AP-1 elements present in the promoter regions of human, murine, and avian HO-1. (For a review of the AP-1 family of transcription factors, see Karin et al.). Glutathione depletion-mediated induction of rat HO-1 was shown to occur through AP-1 activation, and in human fibroblasts, depletion of glutathione induced the expression of HO-1 and c-Fos, an AP-1 transcription factor family member. Inamdar et al. identified a composite heme-responsive element that was derived from an extended AP-1 element. Studies by Alam et al. in murine hepatoma (Hepa) and fibroblast (L929) cells have identified and characterized enhancer sequences in the mouse HO-1 gene including AP-1 sites that bind c-Fos and c-Jun heterodimers and are responsive to phorbol ester, cadmium, heme, and several other inducers. The heme-, metal-, and arsenate responsive element identified by Alam et al. was termed a "core B" element, which includes the recognition sequence for the AP-1 family of transcription factors. Transcriptional activation
of HO-1 by LPS in mouse macrophages has also been attributed to a distal 5' AP-1 binding site located approximately 4 Kb upstream of the transcription start site \(^{68}\). Finally, Lu et al. have shown that arsenite and cobalt chloride treatments increase binding to an AP-1 consensus element in the chicken HO-1 promoter \(^{37,120}\). However, the signal transduction pathways and transcription factor complexes that target these elements have been largely unexplored.
The Mitogen-Activated Protein (MAP) Kinases

The mitogen-activated protein (MAP) kinases are components of signaling cascades which, in response to extracellular stimuli, target transcription factors, resulting in the modulation of gene expression. MAP kinases have two major distinguishing features: 1) they are activated by phosphorylation of threonine and tyrosine residues within protein kinase domain XIII, and 2) they are proline-directed serine/threonine protein kinases that require a minimum recognition sequence of Ser/Thr-Pro. The activation of MAP kinases is performed by upstream dual-specific kinases, called MAP kinase kinases (MAPKKs), which are in turn phosphorylated by MAP kinase kinase kinases (MAPKKKs). In addition, the MAP kinases can be regulated by MAP kinase phosphatases, such that the overall response to a signal is a complex balance between phosphorylation by upstream kinases and dephosphorylation by phosphatases.\textsuperscript{121,122}

MAP kinases are activated under conditions similar to those that induce HO-1 transcription, e.g., following exposure of cells to phorbol ester, cytokines, ultraviolet light, heat shock, LPS, ceramide, and inducers of oxidative stress, including arsenite.\textsuperscript{110,125-131} Three major MAP kinase subfamilies that mediate physiological responses have been described: Extracellular-signal regulated kinase (ERK), c-Jun N-terminal kinase (JNK), and p38 (a homologue of the yeast HOG1 kinase). A comparison of the characteristics of each MAP kinase
family and their major signaling cascade components are represented in Table 1.2. The complexity of these signaling cascades is further enriched by the occurrence of multiple isoforms for each family. In general, growth and proliferation signals are mediated primarily by ERK, and cellular stress signals are mediated mainly by JNK and p38. The specificity of signaling by these kinases, their targets, and the upstream components that mediate activation in response to cellular stimuli have been the subject of several reviews.¹²¹,¹²²,¹²⁶,¹³²,¹³⁸

In a recent review, Treistman presented a comparative analysis of MAP kinase pathway targets in *S. cerevisiae, D. melanogaster, C. elegans*, and mammals.¹³⁵ Physiological targets of the MAP kinases range from other cytosolic kinases or membrane-bound tyrosine kinase receptors (MAPKAP-K2, EGFR) to cytoskeletal components and nuclear transcription factors. In particular, the AP-1 family of transcription factors has been shown to be regulated in several ways by all three MAP kinase pathways.¹¹⁷,¹³⁹,¹⁴⁰

**Extracellular-signal regulated kinase.** The ERK pathway was the first of the MAP kinases to be cloned in mammals. Components of the ERK pathway were found to be homologous to protein kinases of the pheromone response pathway in *S. cerevisiae*.¹⁴¹ The regulatory motif for ERK activation is Thr-Glu-Tyr. Phosphorylation at both Thr and Tyr is required for full activation.¹⁴² Two isoforms that are similarly regulated are commonly referred to as p42/p44 MAPK or ERK1/2. ERK1/2 is activated mainly in response to mitogenic stimuli,
Table 1.2: Characteristics of the three major MAP kinase families. Below each of the families, the upstream cellular stimuli, phosphorylation sequences required for activation, and several downstream targets are indicated. The families are grouped by their characteristic phosphorylation motifs, which differ in the amino acid that is found between the Thr and Tyr that are phosphorylated for activation. Activating stimuli are more similar between JNK and p38, but the downstream targets are more similar between p38 and ERK. Some of the well-characterized targets (substrates) for each kinase are listed. Many other targets (not shown here) have been proposed for each kinase.

<table>
<thead>
<tr>
<th>MAP Kinase:</th>
<th>JNK/SAPK</th>
<th>p38/CSBP/RK</th>
<th>ERK</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Activators:</strong></td>
<td>Inflammatory cytokines</td>
<td>Inflammatory cytokines</td>
<td>Mito gens</td>
</tr>
<tr>
<td></td>
<td>UV radiation</td>
<td>UV radiation</td>
<td>EGF</td>
</tr>
<tr>
<td></td>
<td>Environmental stresses</td>
<td>Environmental &amp; osmotic stresses</td>
<td>Phorbol ester</td>
</tr>
<tr>
<td></td>
<td>Heat Shock</td>
<td>Heat Shock</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ischemia/reperfusion</td>
<td>Ischemia/reperfusion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceramide</td>
<td>LPS (endotoxin)</td>
<td></td>
</tr>
<tr>
<td><strong>Phosphorylated At:</strong></td>
<td>Thr-Pro-Tyr</td>
<td>Thr-Gly-Tyr</td>
<td>Thr-Glu-Tyr</td>
</tr>
<tr>
<td><strong>Substrates:</strong></td>
<td>c-Jun</td>
<td>ATF2</td>
<td>Elk-1</td>
</tr>
<tr>
<td></td>
<td>ATF2</td>
<td>Elk-1</td>
<td>ATF2</td>
</tr>
<tr>
<td></td>
<td>Elk-1</td>
<td>Max</td>
<td>c-Myc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SAP-1</td>
<td>STAT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GADD153/CHOP</td>
<td>EGFR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MAPKAP-K2</td>
<td>cPLA2</td>
</tr>
</tbody>
</table>
for which the activation pathway has been well-defined\textsuperscript{121,141}. Cell surface receptor tyrosine kinases such as the EGF and PDGF receptors activate a signaling cascade involving the G protein Ras, the MAPKKK Raf, the MAPKK MEK1/2, and ERK1/2, which then targets cytoskeletal proteins, other kinases, or transcription factors (Table 1.2 and Figure 1.5)\textsuperscript{121,132,134,140,141,143}. A specific inhibitor of MEK1/2, PD98059, has helped to more clearly delineate cellular targets of ERK\textsuperscript{144-147}. ERK effects changes in cellular morphology through phosphorylation of cytoskeletal proteins, including microtubule-associated proteins. Phospholipases that control arachidonic acid metabolism, and protein kinases (including p90\textsuperscript{RSK} (RSK), for which c-fos is a substrate) are cytosolic targets for ERK. ERK also regulates transcriptional activity through phosphorylation of several transcription factors, including Elk-1, c-Myc, ATF-2, C/EBPβ, and STAT proteins\textsuperscript{121,122,135}.

**C-jun N-terminal kinase.** The cloning of JNK helped to establish the current model of several parallel MAP kinase cascades in mammals that modulate physiological responses to diverse cellular stimuli. Several pathways have been identified in yeast, but there is no known yeast homologue for JNK. Activation of JNK occurs in response to environmental stress and inflammatory cytokines, and is therefore also referred to as stress-activated protein kinase (SAPK)\textsuperscript{129,148}. The phosphorylation site of the JNK family is a Thr-Pro-Tyr motif. There are several upstream activation mechanisms for JNK. Characterized mechanisms involve Rho family low molecular weight G-proteins (Cdc42 and
Figure 1.5: Comparison of the mammalian MAP kinase cascade components. Each MAP kinase is activated through a cascade of sequential phosphorylations of protein kinases. The cascades are grouped by level (MAP kinase, MAPK kinase, MAPKK kinase, etc.) to provide comparisons of the components between the MAP kinase families. MKK4 may activate both JNK and p38 (indicated by interrupted arrow), MKK7 is specific for JNK only. Downstream targets shown as transcription factors (Txn Factors) may also be cytosolic components or other kinases (see Table 1.2 and text). For clarity, the possible role of phosphatases in the modulation of MAP kinase activity is indicated for JNK only, but applies to all three MAP kinase pathways. Cooperative interaction or signal integration among the MAP kinase families may occur in the cytosol, via activation of a kinase, or in the nucleus, through dimerization of transcription factors activated by separate MAP kinases.
Rac1), p21 activated kinase (PAK), MEKK1, MUK, or MLK3 (mixed lineage kinase), MKK4 or MKK7, and JNK (Figure 1.5). JNK was discovered by and named for its primary function, regulation of the transcription factor c-Jun. Activation of JNK leads to the induction of apoptosis $^{127,149}$. Other transcription factor targets of JNK include ATF2 and Elk-1.

**p38 MAP kinase, homologue of HOG 1.** The third MAP kinase family to be described is p38, the homologue of the yeast high osmolarity glycerol regulated MAP kinase, HOG 1. In response to environmental stress or inflammatory cytokines, p38 is activated by phosphorylation at the Thr-Gly-Tyr motif. The pathway of activation involves Rho family G-proteins (Cdc42/Rac1), PAK, TAK (TGFβ-activated kinase) or MEKK1, MKK3 or MKK6, and p38 (Figure 1.5). Activation of p38 inhibits cell growth and promotes apoptosis. Recently, a class of pyridinyl imidazoles (the cytokine-suppressive anti-inflammatory drugs) were identified as specific inhibitors of the p38 family of MAP kinases $^{150-152}$. These inhibitors have facilitated elucidation of the cellular effects of p38. Primary targets for p38 are MAPKAP-K2, the Myc binding protein Max, and the transcription factor components Elk-1, SAP-1, ATF2, and GADD153.

**Signal integration by MAP kinases.** Recent studies have established mechanisms that allow integration of the ERK and p38 MAP kinase pathways. Novel protein kinases that are activated by both ERK and p38 MAP kinases have been described $^{153,154}$. These kinases, termed MNK1 and MNK2, are proposed to be a convergence point for co-operative action of the growth-factor
regulated ERK pathway and the stress-regulated p38 pathway\textsuperscript{153,154}. A second example is provided by Ets transcription factors that are phosphorylated and activated by both ERK and p38 MAP kinases\textsuperscript{155,156}. Investigation of MAP kinase involvement in the UV response of HeLa TK- and NIH3T3 cells revealed cooperative serum response element (SRE) and ternary complex factor (TCF) activation by ERK and p38 pathways\textsuperscript{156}. Both of these pathways were found to be required for induction of c-fos gene transcription by UV irradiation\textsuperscript{156}. Similar mechanisms may contribute to the integration of MAP kinase pathways at the HO-1 promoter.

**Activation of MAP kinases by arsenite.** Arsenite has been shown to activate MAP kinases\textsuperscript{110,123,157,158}, however, this arsenite-mediated activation has not been linked to a cellular gene response. Two recent studies have investigated the ability of sodium arsenite to activate MAP kinases. One study found that arsenite activated ERK, JNK, and p38 MAP kinases in PC12 cells\textsuperscript{131}. A separate study in HeLa cells found that JNK and p38 MAP kinases were activated by arsenite, however, no activation of ERK was observed\textsuperscript{159}. The discrepancy in MAP kinase activation by arsenite may be explained by the fact that these two studies were done in different cell types\textsuperscript{131,159}. It is generally acknowledged that MAP kinases can be differentially regulated by the same stimuli in diverse cell types.

It has also been proposed that arsenite affects gene expression by modulating the activities of transcription factor complexes bound to AP-1
elements in the promoter regions of several genes \(^{118,159,160}\). Putative AP-1 sites are present in the promoter regions of mammalian \(^{67,88,111,113}\) and chicken HO-1 \(^{37}\). Since the MAP kinase signaling cascades have been shown to target AP-1 elements, they are potential mediators of the arsenite induction of HO-1 \(^{117,139,140}\).
Research Objectives

Objective I: To establish whether LMH cells are a good model system for the study of heme metabolism. The aim of the work reported here was to study the expression and regulation of heme biosynthesis and degradation [4,8,16,17,26,27,40] in LMH cells, comparing results to those previously found in CELCs. Initially, growth maintenance and culture conditions were established for LMH cells. The comparative dose-responses and time courses of induction of HO-1 mRNA and heme oxygenase activities by heme and cobalt chloride were characterized. In addition, a measurable response to other treatments previously shown to increase HO-1 mRNA levels or heme oxygenase activities in normal CELCs was demonstrated for LMH cells. During these studies a small but significant heat shock induction of HO-1 mRNA in CELCs was detected, which had not been described previously.

Objective II: To establish whether AP-1 transcription factor complex binding sites modulate sodium arsenite induction of HO-1. The ability of arsenite to increase transcription of endogenous HO-1, and the activity of transfected luciferase reporter gene constructs under control of the HO-1 promoter were investigated. Transient transfection assays using reporter constructs containing successive deletions of the chO-1 promoter sequence were used to identify regions involved in modulating arsenite-mediated HO-1 gene expression. HO-1 reporter constructs containing mutated AP-1 elements
were constructed and tested for responsiveness to arsenite treatment. The results from these experiments suggest that AP-1 elements are involved in the sodium arsenite-mediated induction of HO-1 gene expression.

**Objective III: To establish whether the mitogen-activated kinases modulate induction of HO-1 by arsenite.** The mitogen activated protein (MAP) kinases were good candidates as signaling molecules for controlling HO-1 expression, since many of the activators of MAP kinases also induce HO-1. In LMH cells, the MAP kinases, ERK, JNK, and p38, were tested for activation by treatments that were known to induce HO-1. Sodium arsenite was a highly efficacious inducer of HO-1 and activator of all three MAP kinases. Arsenite-mediated activation of MAP kinases and induction of endogenous HO-1 mRNA expression were closely correlated. Therefore, arsenite was chosen to further investigate the involvement of MAP kinases in cHO-1 gene expression. Constitutively activated and dominant negative components of the MAP kinase signaling pathways were utilized to delineate the roles of ERK, JNK, and p38 in HO-1 gene expression as measured using HO-1 promoter-driven luciferase reporter gene constructs. Inhibitors of the ERK and p38 signaling pathways were also employed to further analyze the involvement of these kinases in arsenite-mediated induction of HO-1. Results from these experiments demonstrated roles for the ERK and p38 MAP kinase families in the sodium arsenite-mediated induction of cHO-1.
CHAPTER II
MATERIALS AND METHODS

Materials

General materials. Tissue culture dishes and 6 well plates were from Corning, Corning, NY; culture flasks were from Falcon, VWR Scientific, Bridgeport, NJ. Gelatin and fetal bovine serum were from Difco, Detroit, MI. Opti-MEM, Williams' E and Waymouth's MB 752/1 media, and LipoFECTAMINE™ Reagent were from Life Technologies, GIBCO/BRL, Grand Island, NY. Biliverdin and heme were from Porphyrin Products, Logan, UT. Oligo dT (12-18 bases) was from Pharmacia, Piscataway, NJ. Iron chloride for quantitative iron assays was from VWR Scientific, Bridgeport, NJ. Dexamethasone was from Gensia Pharmaceuticals, Irvine, CA. Chloroform, glycerol, isopropanol, potassium phosphate, and sodium vanadate were from Fisher, Pittsburgh, PA. Actinomycin D, adenosine triphosphate (ATP), bovine serum albumin (BSA), cadmium chloride, cobalt chloride, deferoxamine mesylate (DFO), dimethylsulfoxide, EDTA, EGTA, formaldehyde (37% v/v), formamide, glycyglycine, NADPH, O-nitrophenyl β-galactopyranoside (ONPG), penicillin, phenylmethyl sulfonylfluoride (PMSF), p-hydroxymercuribenzoic acid, piperacillin, sodium arsenite, sodium chloride, sodium citrate, sodium dodecyl sulfate (SDS), sodium hydroxide, streptomycin, 3,5,3'-triiodo-L-thyronine, triton...
X-100, Trizma base, and trypsin were from Sigma, St. Louis, MO. Dithiothreitol (DTT) and 4-(2-pyridylazo)resorcinol (PAR), mono sodium salt hydrate were from Aldrich Chemical Co., Inc., Milwaukee, WI. 3,5,5-Trimethylhexanoyl ferrocene (TMH-ferrocene) was provided as an orange powder by P. Nielsen, Universitätskrankenhaus, Eppendorf, Hamburg, Germany. Kinase inhibitors PD98059 and SB203580, were from CalBiochem, La Jolla, CA. Ultraspec RNAzol® was from Biotex, Houston, TX. Nitrocellulose (0.45 μm) was from Schleicher and Schuell, Keene, NH. All 32P -radionucleotides were from New England Nuclear, Boston, MA. All chemicals were of the highest purity available.

**Cells and DNA.** Fertilized Barred Rock chicken eggs were from Carousel Farms, Holliston, MA. LMH cells and the pGAD-28 plasmid were generous gifts from D. L. Williams, Dept. of Pharmacological Sciences, SUNY-Stony Brook, Stony Brook, NY. The rat HO-1 cDNA was a gift from S. Shibahara, Tohoku University School of Medicine, JAPAN. The pALX plasmid containing the cDNA of the housekeeping form of chicken ALA synthase was a gift from D. Engel, Northwestern University, Evanston, IL. The lambda FIX II clone containing genomic chicken heme oxygenase-1 promoter sequence, and pCHO3.6-CAT were provided by T. H. Lu, Division of Digestive Disease and Nutrition, University of Massachusetts Medical Center, Worcester, MA. The pGL3 Basic and pGL3 Control plasmids were gifts from G. Gil, Division of Digestive Disease and Nutrition, University of Massachusetts Medical Center, Worcester, MA. The
pPGK-βgal plasmid was a gift from P. Dobner, Department of Molecular Genetics and Microbiology, University of Massachusetts Medical Center, Worcester, MA. Expression vectors for signaling pathway components and MAP kinases have been described: ERK2 \textsuperscript{155}, MEK1 \textsuperscript{161}, MEKK1 \textsuperscript{162,163}, JNK1 \textsuperscript{164}, MLK3 \textsuperscript{165}, MKK6 \textsuperscript{166}; Ras and Raf \textsuperscript{167}, as has the expression vector for dominant negative c-Jun (TAM67) \textsuperscript{168}. Luciferase Assay Reagent, Wizard\textsuperscript{TM} plasmid DNA preparation kits, and the primers GLprimer2 and RVprimer3 were purchased from Promega, Madison, WI. The QuickChange\textsuperscript{TM} Site-Directed Mutagenesis Kit and Quickhyb\textsuperscript{®} hybridization solution were from Stratagene, La Jolla, CA. DNA sequencing was performed by Dana Farber Cancer Institute, Boston, MA, and by the Nucleic Acids Facility, University of Massachusetts Medical Center, Worcester, MA.
Methods

Cell culture and preparation of chemicals. Cultures of primary chick embryo liver cells (CELCs) were freshly prepared each week by Otto Gildemeister and Joyce Pepe as described \(^{23,44-46,56,57,169}\). LMH cells were maintained in Waymouth's MB 752/1 complete medium (Appendix A); and routinely passaged twice a week \(^{64}\). Complete and serum-free Williams' E and Waymouth's media contained penicillin/streptomycin. In some experiments, 1µg/mL piperacillin was added to the culture medium. In experiments involving both CELCs and LMH cells, cells were plated on Corning dishes 6 cm in diameter. CELCs were prepared and plated on uncoated dishes in 5 mL Williams' E complete medium (Appendix A). LMH cells were resuspended and plated at 80% confluence in 5 mL Williams' E complete medium on dishes coated with 0.1% (w/v) gelatin. On the day of treatment, the cells were washed once with 5 mL of Williams' E complete medium. Preparation of and treatment with chemicals were exactly as described for primary CELCs \(^{23,44-46,56,57,169}\). Sodium arsenite, cadmium chloride, cobalt chloride, and heme were prepared as described \(^{23,44-46,56,57,64,169}\). All other chemicals were freshly prepared on the day of treatment and added directly to the culture medium (Appendix B).
Porphyins assays

Fluorometric porphyins assays. LMH cells or CELCs were prepared and seeded into 3-cm wells in 6-well plates. On the morning of treatment, medium was changed to Williams' E complete. Cells were typically exposed to treatments for 18 hours. From the time of treatment, all steps were carried out in subdued lighting. The medium was removed to 12 x 75 mm culture tubes and assayed separately. The plates were washed once with 1X PBS, and harvested in 2 mL PBS by scraping with a rubber spatula. Cells and media were disrupted by sonicating for 6 seconds with a sonicator (Bronson model 450, VWR Scientific, Bridgeport, NJ) equipped with a microtip (output: 2, duty cycle: 30). Sonicates were centrifuged at 1,000 x g for 10 minutes and aliquoted into tubes for protein determination (50 µL each) and four-side-clear 4 mL cuvettes (200 µL each) for porphyrin determinations. To extract porphyrins and porphyrinogens and oxidize porphyrinogens to porphyrins, 1.8 mL of perchloric acid (PCA)/methanol/water (5/50/50, v/v/v) was added to the cuvettes. Known amounts (50 µg/L) of uroporphyrin and coproporphyrin were assayed as controls for standardization. A Perkin-Elmer LS 50B spectrophotometer-fluorometer fitted with an R928 (red wavelength sensitive) photomultiplier was used to measure the fluorescence at each of three wavelength excitation/emission pairs (400 nm/595 nm, 405 nm/595 nm, and 410 nm/605 nm); excitations were measured at a slit width of 5 nm, emissions at a slit width of 20 nm. Data were input into a Microsoft Excel worksheet that automatically
calculated the levels of uroporphyrin, coproporphyrin, and protoporphyrin in each sample based on the results of porphyrin standards and Grandchamp equations \(^{170}\). The amount of protein in each sample was determined by the BCA method (See Protein assays).

*High performance liquid chromatography (HPLC) porphyrins assays.*

HPLC porphyrin determinations were performed on a Waters Baseline 810 HPLC System, equipped with a Shimadzu RF-551 Fluorometer with a R-928 (red sensitive) photomultiplier tube, essentially as described \(^{171}\). Cells were seeded and harvested as described for fluorometric assays. All steps were performed under subdued lighting. Porphyrins and porphyrinogens were extracted and oxidized from 500 \(\mu\)L of each sonicate with 10 \(\mu\)L of 10 N hydrochloric acid. The tubes were centrifuged at 1,000 \(x\) g for 10 minutes to remove cellular debris, and 250 \(\mu\)L of supernatant was injected using a WISP autoinjector apparatus. Porphyrins were separated on a C\(_{18}\) reverse-phase micropalpaku column, with a gradient consisting of two solvents: A, 1:1 (v:v) 0.1 M ammonium phosphate, pH 4.5, and methanol; B, 100% HPLC-grade methanol. A linear gradient from 70% A, 30% B to 100% B was run over 7 minutes with a flow rate of 1.5 mL/minute, followed by 100% B for another 11 minutes at the same flow rate. Porphyrin standards were run every three samples.
**Quantitative iron assays.** On the day of treatment, cells were washed and the medium changed to Williams’ E complete. Treatments were for 18 hours, except for TMH-ferrocene which was for 4 hours. Cells were washed once with 1X PBS and harvested in 1 mL of PBS. A scintillation vial was weighed before and after adding cells to obtain a wet weight for the cellular material. The vials were placed in an 80°C oven overnight to dry. After drying, the cellular material was split into three samples and transferred to 30 mL Kjeldahl tubes, which were weighed before and after addition of cellular material to obtain dry weights for each triplicate. Cells were digested by heating for 3 minutes in 1:1 (v:v) sulfuric acid and nitric acid. Samples were transferred to 16 x 100 mm tubes, and allowed to cool. Standards containing known quantities of iron were prepared and assayed with the samples. Each tube received 2 mL of 0.5 M potassium phosphate buffer, 1.75 mL of 6 M ammonium hydroxide, 100 μL of 10% hydroxylamine, 5.3 mL of Milli-Q water, and 500 μL of 0.1% 4-(2-pyridylazo)resorcinol (PAR), mono sodium salt hydrate. Tubes were inverted gently to mix and allowed to stand at room temperature overnight. The next morning, the absorbance of the iron-PAR adduct was read at 500 nm on a spectrophotometer. Suitable standards were run simultaneously to generate a linear standard curve. The iron concentrations were calculated as μg iron/mg of dry weight using the equation from the best-fit linear regression standard curve and the known dry weights of the samples.
Isolation of RNA. Total RNA was isolated using Ultraspec RNAzol®, following the manufacturer's protocol. The cells from one 6 cm culture dish or from one 3 cm well of a 6 well plate were harvested directly into 0.5 mL of Ultraspec RNAzol® and total RNA isolated as described. Cells were harvested by scraping with a rubber spatula. The lysate was transferred into 1.5 mL microcentrifuge tubes, and 100 μL of chloroform was added. The tubes were vortexed briefly and incubated on ice for at least 15 minutes. Following centrifugation (14,000 x g at 4°C for 15 minutes), the top phase was transferred to a new tube. An equal volume (300 - 400 μL) of isopropanol was added to precipitate the RNA. The tubes were vortexed and incubated at -20°C for at least 1 hour. Following centrifugation (14,000 x g for 15 minutes), the supernatant was removed, and the pellet was washed with 0.5 mL of 75% ethanol/DEPC-treated water. Pellets were dried in a vacuum apparatus, and resuspended in 50 μL of DEPC-treated water for dot blots or 0.5% SDS for Northern blots. Samples were stored at -20°C or incubated at 65°C for 45 minutes to dissolve the RNA. Nucleic acid purity was assessed by determining the absorbance ratio at 260 nm/280 nm (1.80 or higher was required). RNA concentrations were estimated from the absorbance at 260 nm (1 AU = 40 μg/mL RNA).
Preparation of radiolabeled probes. Radiolabeled probes for detection of mRNA for the housekeeping form of ALA synthase, chicken HO-1, and chicken glyceraldehyde phosphate dehydrogenase (GAPDH) were synthesized by random priming and incorporation of $\alpha^{32}$P-dCTP using the DECAprime II™ DNA Labeling Kit from Ambion Inc., Austin, TX or the Ready-To-Go™ DNA Labeling Beads from Pharmacia Biotech, Piscataway, NJ. The ALA synthase probe template was a 1.7 Kb Eco RI fragment of the pALX plasmid containing the ALA synthase cDNA. The cHO-1 probe template was a 1.3 Kb polymerase chain reaction (PCR) product obtained using T7 and T3 primers, with the cHO-1 cDNA as the PCR template. The GAPDH probe template was a 530 base pair (bp) PCR product obtained using the linearized pGAD-28 plasmid as template and the primers GAP1: 5'-GAAAGTCGGA GTCAACGGAT TTG -3' and GAP2: 5'-TGGCATGGAC AGTGGTCATA AGAC -3'. The PCR program for HO-1 and GAPDH probes was as follows: delay, 94°C for 3 min.; 30 cycles of: segment 1, denaturation (94°C for 1 min. 30 sec.), segment 2, renaturation (54°C for 2 min.), segment 3, elongation (72°C for 2 min.); delay, 72°C for 10 min.; soak at 4°C. Poly-A and chicken heat shock protein 70 (HSP 70) probes were end-labeled with $\alpha^{32}$P-dCTP using the DECAprime II™ DNA Labeling Kit from Ambion Inc., Austin, TX. The Poly-A probe template was a 12 - 18 base polythymidylate oligonucleotide from Pharmacia. HSP 70 was detected using an oligonucleotide probe complementary to the plus strand of the cDNA from base pairs 2518 to 2542 (5'— AGAGACAAAC ATCCAGAATA CAAGG —3').
Quantitation of messenger RNA.

Northern blots After isolation, RNA was dissolved in 0.5% SDS, and incubated at 65°C for 45 minutes. The volume of RNA required for 10 μg per sample was calculated from the absorbance measured at 260 nm, and samples were prepared by diluting in DEPC-treated water. HEPES buffer (Appendix A) was added, and the samples were heated to 85°C for 15 minutes. Sample loading dye (2 μL of 0.02% bromophenol blue) was added to each tube. The samples were spun briefly, and 20 μL of sample or marker was loaded into each well of a 1.2% agarose/formaldehyde gel containing ethidium bromide. The gel was run at 80 Volts for 2 hours using 1X HEPES running buffer. The gel was washed in DEPC-treated water 3 times for 20 minutes to remove excess ethidium and formaldehyde, and photographed on a transilluminator. The RNA was transferred to a nitrocellulose filter by capillary action overnight using 20X SSC. Following transfer, the RNA was immobilized by ultraviolet (UV) light crosslinking. The blot was prehybridized in Quickhyb® for 30 minutes at 65°C. The blot was hybridized for 1 hour in Quickhyb® containing a radiolabeled HO-1 probe that specifically recognized the ~1.3 Kb chicken HO-1 mRNA (see Preparation of radiolabeled probes), and washed with 0.1X SSC three or four times for a total of 1 to 2 hours at 65°C to remove nonspecific binding. The amount of specific RNA was visualized by autoradiography, and quantitated using a PhosphorImager and Image Quant software (Molecular Dynamics, Sunnyvale, CA). For normalization, the blot was stripped by
washing in boiling hot DEPC-treated water 3 times, allowing the water to come to room temperature between each cycle. Blots were rehybridized with a radiolabeled GAPDH probe that specifically recognized the ~1.3 Kb chicken GAPDH mRNA (see Preparation of radiolabeled probes), and GAPDH mRNA was quantitated in the same manner as cHO-1 mRNA. The levels of HO-1 message in each lane were normalized to the levels of GAPDH message.

Dot blots. Dot blots were performed essentially as described \(^{57}\). After isolation, total RNA was resuspended in 50 \(\mu\)L of DEPC-treated water. Samples were prepared for loading as follows, for three duplicate blots: 20 \(\mu\)L of DEPC-treated water, 36 \(\mu\)L of 20X SSC, and 24 \(\mu\)L of 37% formaldehyde were added to 40 \(\mu\)L of RNA and incubated at 65°C for 15 minutes. For each duplicate blot, 200 \(\mu\)L of 10X SSC was added to the samples. The dot blot apparatus was set up with two pieces of prewet Whatman 3M paper and one sheet of prewet nitrocellulose. The wells were washed once with 10X SSC, 200 \(\mu\)L of each sample was loaded per dot, followed by a second wash with 10X SSC. The nitrocellulose was removed from the apparatus and the RNA was UV-crosslinked to the membrane using a Stratalinker. Blots were prehybridized with Quickhyb\(^\circledR\) at 65°C for 30 minutes. Each blot was hybridized at 65°C for 1 hour in Quickhyb\(^\circledR\) containing a radiolabeled probe (see Preparation of radiolabeled probes) previously shown by Northern blot to bind only the mRNA of interest. After hybridization, the blots were washed with 0.1X SSC three or four times for a total of 1 to 2 hours at 65°C to remove nonspecific
binding. Quantitation of specific binding was performed using a PhosphorImager and Image Quant software. The amount of specific mRNA was normalized to total poly-A mRNA, measured on a duplicate blot probed with a radiolabeled poly-T probe as described\textsuperscript{57} (see Preparation of radiolabeled probes), or to GAPDH mRNA, measured on a duplicate blot probed with a radiolabeled GAPDH probe, as described\textsuperscript{57}. 
Heme oxygenase activity assays. Heme oxygenase activity was measured by a modification of the method of Tenhunen *et al.* [17], as described previously [23,46,107,169]. This assay measures the conversion of heme to biliverdin by a two-step reaction. In the first step heme is converted to biliverdin by heme oxygenase (HO). In the second step, biliverdin is converted to bilirubin by biliverdin reductase (BVR). All mammals express endogenous BVR; however, chickens do not express this enzyme. Exogenous BVR was obtained as a 105,000 x g supernatant of a 20% homogenate of perfused rat liver as described [174]. Under the assay conditions, the amount of BVR added to reactions was capable of reducing 1.5 nmoles of biliverdin/minute in a total volume of 1 mL, enough to ensure complete conversion of all of the biliverdin formed by HO to bilirubin.

LMH cells or CELCs were plated in 6 cm dishes as described above. The dishes were washed twice with 1X PBS, and harvested in 0.6 mL of Harvest Buffer (Appendix A) by scraping with a rubber spatula. Each cell suspension was sonicated for 3 seconds using a sonicator (Bronson model 450, VWR Scientific, Bridgeport, NJ) equipped with a microtip (output: 2, duty cycle: 30). A 50 μL aliquot of the lysate was used for protein determinations.

Two sets of 16 x 100 mm culture tubes per sample were set up, one for control and one as test. Each reaction contained 200 μL of cell sonicate (0.6-0.8 mg of homogenate protein from CELCs or 0.4-0.6 mg of homogenate protein from LMH cells), 70 mM potassium phosphate, pH 7.4, 5 mM deferoxamine mesylate
(Appendix B), BVR (20 μL of rat liver 105,000 x g supernatant), and 4 mM NADPH (3.96 mg/mL in 0.1 potassium phosphate) to make a final volume of 1 mL. The tubes were incubated in a 37°C shaking water bath for 5 min. The remainder of the assay was performed in subdued lighting. Test reactions were started by adding heme-albumin (40 μM final concentration, Appendix B) to the test set of tubes, the control tubes received heme-albumin after the reaction was stopped. After 10 minutes at 37°C, the tubes were placed in an ice bath. To stop the reactions, 20 μL of 50 mM p-hydroxymercuribenzoic acid was added to each tube. The tubes were mixed by vortexing. Using a spectrophotometer (Aminco DW 2000), a split beam wavelength scan from 450 to 550 nm was done for each sample. The rate of bilirubin formation was calculated from the difference in absorbance at 470 nm and 540 nm. The following equation was used to calculate the amount of biliverdin formed, as described \(^{17,23,107}\): \[ \Delta A_{470-540\text{ nm}} = 66 \text{ mM}^{-1} \text{ cm}^{-1} \] 

\[
\text{OD}(470-540) \times 1.010 \text{ mL final volume} \times 1000 \text{ pmole}  
= 0.066 \text{ OD/nmole bilirubin/mL} \times 0.2 \text{ mL init. vol.} \times 10 \text{ min.} \times \text{ mg prot/mL} \times 1 \text{ nmole}
\]

= pmoles bilirubin/minute x mg protein
Subcloning. The pCHO3.6-Luc reporter plasmid was constructed by subcloning 3728 base pairs of the chicken HO-1 proximal promoter from a CAT construct (pCHO3.6-CAT, provided by T. H. Lu) into the pGL3 Basic plasmid vector, upstream of the luciferase reporter gene. The ligation junctions were verified by sequencing.

Deletion constructs were produced by first cloning a 7.1 Kb fragment of the genomic chicken HO-1 promoter into the pGL3 basic luciferase reporter vector, followed by restriction enzyme digestion and self-ligation of the backbone to excise the deleted region. A lambda FIX® II vector containing approximately 12 Kilobases (Kb) of genomic chicken heme oxygenase-1 (cHO-1) sequence, including some coding sequence and ~10.5 Kb of promoter sequence, was digested with the restriction enzymes Xba I and Xho I. The 7.1 Kb fragment (sequence reported in Appendix E) was ligated into a pGL3 Basic luciferase reporter vector that had been digested with the restriction enzymes Nhe I and Xho I. The ligation mix was transformed into DH5α cells plated on Luria Broth agar plates supplemented with 100 μg/mL of ampicillin, and incubated overnight at 37°C. DNA minipreps for several colonies were tested for insertion of the 7.1 Kb fragment by restriction enzyme digests. Colonies that were positive for pCHO7.1-Luc were verified by sequencing the ligation junctions using the commercial primers GLprimer2 and RVprimer3 (Promega). Deletion constructs were made by digesting pCHO7.1-Luc with Mlu I and the respective enzyme for each construct (see Figure 5.1). Restriction enzyme cut
sites were blunted prior to ligation: for a 3' overhang, the DNA was treated with T4 Polymerase; for a 5' overhang, the DNA was treated with Klenow fragment. Following ethanol precipitation, blunt-end ligation was performed. The Xho I sites were ligated proximal to the start of the luciferase gene. The distal restriction enzyme site corresponding to each deletion was ligated with the Mlu I site at -7085 bp (this numbering is relative to the 7.1 Kb fragment). Positive colonies were identified by DNA minipreps followed by a diagnostic Xba I and Xho I restriction enzyme digest. The ligation junctions of each deletion construct were verified by sequencing.
Site-directed mutagenesis. AP-1 elements located at -1578 bp, -3656 bp, and -4597 bp upstream of the cHO-1 transcription start site were mutated, as shown in Figures 5.7 - 5.9. For each AP-1 site, two of the seven bases that comprise the consensus AP-1 element were mutated. The two changes were made in base pairs that disrupt the wild type palidromic structure, and would therefore be likely to be important for transcription factor binding \(^{117}\). The bases chosen for mutagenesis have also been reported to interfere with transcription factor binding \(^{27,37,49,87,111,160}\). AP-1 mutants were constructed with the QuickChange™ Site-Directed Mutagenesis Kit using templates and PCR primers as listed in Table 2.1. Table 2.2 lists the primer sequences. The pCHO2.5-Luc mutants have two base-pair mutations in the AP-1 element at -1578 bp. The pCHO4.6-Luc mutants have two base-pair mutations in the AP-1 element at -3656 bp, at -1578 bp, or at both sites. The pCHO5.6-Luc series are single, double, or triple mutants containing two base-pair mutations in the AP-1 elements at -4597 bp, -3656 bp, -1578 bp, at two of these sites, or at all three sites. The PCR reactions were set up with 5 μL of 10X reaction buffer, 30 ng of DNA template, 125 ng of each oligonucleotide primer, and 1μL of dNTP mix in a final volume of 50 μL. Just before starting thermocycling program, 2.5 U of Pfu DNA Polymerase was added to each reaction and 30 μL of mineral oil were used to overlay the liquid in each tube. The PCR thermocycling program was performed as suggested in the manufacturer's protocol: segment 1, soak for 30 seconds at 95°C; segment 2, 14 cycles of: denaturation for 30 seconds at 95°C;
renaturation for 1 minute at 55°C, and synthesis for 2 min./Kb of plasmid length (16 minutes for mutations of pCHO2.5-Luc; 20 minutes for mutations of pCHO4.6-Luc; 23 minutes for mutations of pCHO5.6-Luc) at 68°C; segment 3, soak at 4°C. The wild type DNA was then digested with 10 U of Dpn I for 1 hour at 37°C. 1 - 3 μL of mutant DNA was transformed into 50 μL of supercompetent E. coli cells as described.
Table 2.1: Templates and Primers for Site-Directed Mutagenesis of AP-1 Elements. The cHO-1 AP-1 mutants were constructed using the listed templates and primers. Four sets of primers were used in combination with wild type or confirmed mutant constructs, as shown, to obtain all of the listed mutants (see Figures 5.7-5.9). F = forward primer, R = reverse primer. See Table 2.2 for primer sequences.

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<th>Mutant construct:</th>
<th>PCR Template:</th>
<th>PCR Primers Used:</th>
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<td>2.5mut F1  2.5mut R1</td>
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<td>pCHO4.6mut36-Luc</td>
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</tr>
<tr>
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<td>2.5mut F2  2.5mut R2</td>
</tr>
<tr>
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<td>pCHO5.6-Luc</td>
<td>4.6mut F  4.6mut R</td>
</tr>
<tr>
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<td>pCHO5.6-Luc</td>
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</tr>
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<td>4.6mut F  4.6mut R</td>
</tr>
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<td>pCHO5.6mut4-Luc</td>
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</tr>
<tr>
<td>pCHO5.6mut134-Luc</td>
<td>pCHO5.6mut14-Luc</td>
<td>4.6mut F  4.6mut R</td>
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</tbody>
</table>
Table 2.2: Primers for Site-Directed Mutagenesis. The PCR primers used for site-directed mutagenesis are grouped in pairs. The AP-1 elements are underlined, with the mutated bases in bold lettering. The wild type AP-1 sequence is: 5'-TGAGTC-3'. The templates used with each primer pair are listed in Table 2.1.

<table>
<thead>
<tr>
<th>Primer name</th>
<th>Primer Sequence</th>
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<tr>
<td>2.5 mut F1</td>
<td>5' - GCAGAGCAAAG ACAGGAAAAG CATGGCTTCG TCAGGCTGGG AGCGCTGAG -3'</td>
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<tr>
<td>2.5 mut R1</td>
<td>5' - CTCAGCGCTC CCAGCCTGAC GAGCCATGC TTTTCCTGTC TTGCTCTGC -3'</td>
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<td>2.5 mut F2</td>
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<td>2.5 mut R2</td>
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<tr>
<td>4.6 mut F</td>
<td>5' - GCAAGATCTG GTTGCCTGAG AAGCCCCCCT CCCAGGGCAGG C -3'</td>
</tr>
<tr>
<td>4.6 mut R</td>
<td>5' - GCCTGGCTGG GAGGGGGCT TCC TCAGCAA CCAGATCTTG C -3'</td>
</tr>
<tr>
<td>5.6 mut F</td>
<td>5' - GCAAGGGGCG CCTTACCTGC TGAGGAA CAG CAGAGGGCC ACCTGAGG -3'</td>
</tr>
<tr>
<td>5.6 mut R</td>
<td>5' - CCTCACGTTG CCTCTCTGCT GTCTCAGC AAATAGGGGC CCCTTTCG -3'</td>
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</table>
**Transfections.** LMH cells were plated in gelatin coated 6-well plates at a density of $3.2 \times 10^5$ cells/well. For transfections, each well received 0.5 µg of pSV-βgal or pPGK-βgal, and 0.5 - 1.0 µg of cHO-1 promoter/reporter and/or MAP kinase plasmid DNA using LipoFECTAMINE™ (0.25µg DNA/µL of reagent), according to the manufacturer's protocol. Total DNA transfected was kept constant by adding pBLUESCRIPT KS II+ plasmid DNA. Cells were incubated at 37°C, 3% CO₂ for 5 hours, after which 2 mL of Waymouth's complete medium was added. Incubation was continued overnight at 37°C, 5% CO₂ for a total of 20 - 24 hours. Cells were incubated with serum-free Waymouth's for at least 20 hours prior to treatment with selected chemicals or harvest for assays.
Assessment of reporter gene activity. Reporter gene expression was assessed by quantitation of luciferase activity, normalized to β-galactosidase activity, and protein content. Some experiments, in which dominant negative ERK kinase components were transfected, were normalized to protein content only, because the β-galactosidase values were outside the linear range (0.2 to 2.0 absorbance units). For luciferase activities, transfected cells were washed twice with 1X PBS, and harvested by scraping in 250 μL of glycylglycine harvest buffer (Appendix A). Cells were lysed by three cycles of freeze-thaw (3 minutes in liquid nitrogen followed by 3 minutes at 37°C), followed by a 10 minute centrifugation at 14,000 x g at 4°C. The supernatant was retained, and 15 μL aliquots of cell lysate were used for each assay. For luciferase activity measurements, luminometer tubes containing lysates were placed into a Monolight 2010® Luminometer (Analytical Luminescence Labs, Ann Arbor, MI), and 100 μL of Luciferase Assay Reagent was automatically injected. Relative light units produced in 10 seconds were recorded and normalized with β-galactosidase activities and protein content. For β-galactosidase activities, 15 μL of cell lysate was added to 200 μL of Z Buffer (Appendix A) and 100 μL of 5 mg/mL O-nitrophenyl galactoside (ONPG) dissolved in 0.1 M potassium phosphate, pH 7.0. The samples were mixed and incubated at 37°C for 1.5 - 2 hours. The absorbance at 420 nm was measured and used for normalization of luciferase activities\textsuperscript{173}. 
**Protein assays.** Protein concentrations were measured by the bicinchoninic acid method on a Spectronic GENESYS 2 spectrophotometer, using BSA as standard \(^{175}\). Protein content of cell lysates was calculated from the BSA standard curve and used for calculation of heme oxygenase activity or for normalization of luciferase activity.
Immune complex kinase assays. Immune complex kinase activity assays were performed as described. Cells were harvested by scraping into 1.0 mL of 1X Triton lysis buffer (TLB, Appendix A). Lysates were centrifuged at 14,000 x g at 4°C for 15 minutes. Anti-ERK2, anti-JNK1 (Santa Cruz Biotechnology, Inc.) or anti-p38 antibodies were bound to Protein G Sepharose beads (10 μL per assay) for at least 30 minutes and washed twice with 1X TLB prior to adding cell lysates. Pre-bound antibodies were incubated with 300 μL of cell extract in a final volume of 500 μL with 1X TLB. After mixing at 4°C for at least 3 hours, the immunoprecipitates were washed three times with 1X TLB, and once with 1X kinase assay buffer (Appendix A). After aspiration, the kinase assay was set up with 10 μL Protein G Sepharose beads/antibody/kinase complex, 26 μL kinase assay buffer, 2 μL of kinase substrate (2 μg of GST-Elk1 for ERK, GST-ATF2 for p38, and GST-cJun for JNK), 1 μL 1 mM ATP, 1 μL carrier-free [γ-32P] ATP (approximately 10 μCi/μL) for a final volume of 40 μL. Samples were incubated at room temperature for 30-45 minutes. The reactions were stopped with 3X SDS loading buffer, and 15-20μL were run on SDS-PAGE. This method is schematically represented in Figure 2.1. Results were visualized by autoradiography and quantitated using a PhosphorImager and Image Quant software (Molecular Dynamics, Sunnyvale, CA).
Figure 2.1: Immune-Complex Kinase Activity Assays.

1. Treat Cells w/inducer
2. Harvest + Spin
3. Add supt. to beads
4. Wash
   - Add substrate and *ATP*
   - Incubate @ Rm. Temp.
5. + SDS Loading Buffer
6. Run on SDS-PAGE
7. Dry Gel
8. DATA
   - Expose on film or PhosphorImager
Statistical analysis of data. Experiments were repeated two to four times; except for immune complex kinase assays and Northern blots, every experiment included at least triplicate samples for each treatment group. Representative results from single experiments are presented. Statistical analyses were performed with JMP 3.0.2 software (SAS Institute, Cary, NC). Differences in mean values were assessed by ANOVA, with the Tukey-Kramer correction for multiple pair-wise comparisons, or Dunnett's test versus a control. For experiments with non-normally distributed data, the Wilcoxon/Kruskal-Wallis (Rank Sums) test was used. P values <0.05 were considered significant.
CHAPTER III

CHARACTERIZATION OF HEME BIOSYNTHETIC PATHWAYS IN
THE CHICKEN HEPATOMA CELL LINE, LMH

Introduction

The purpose of the studies in this chapter was to characterize porphyrin and heme biosynthesis in a potential model cell system, LMH cells. The accumulation of porphyrins (the constituents of the heme biosynthetic pathway) and expression and regulation of ALA synthase (normally the rate-limiting enzyme of heme biosynthesis) were studied.

A widely used model system for studies of the regulation of heme metabolism is primary cultures of chick embryo liver cells (CELCs). Primary CELCs retain all of the characteristics of normal hepatic function and mimic human metabolism more closely than mammalian systems, such as rat. LMH cells were derived from a liver tumor dissected from a male White Leghorn chicken that had been treated with intraperitoneal injections of diethylnitrosamine. Preliminary experiments were performed to investigate the heme biosynthetic pathway in these cells, since this is a transformed cell line in which heme metabolism had not been characterized previously. The purpose of these studies was to ensure that the pathways of heme biosynthesis in LMH cells were intact as compared to CELCs, and to determine if LMH cells would be an appropriate model system for the study of heme biosynthesis.
Results

LMH cell culture and growth rate. LMH cells were routinely passaged 1:4 or 1:6 approximately twice a week. Cells were cultured in 25 mL flasks coated with 0.1% gelatin. It was later discovered that the cells attach and grow normally even in the absence of gelatin. After routine culture conditions for LMH cells had been established, their growth rate was measured by trypan blue staining. The number of cells per plate was counted at the time of plating (0 hours), and again at 12, 24, 48, and 72 hours. The average doubling time was calculated to be 21 hours.

Porphyrin accumulation in LMH cells versus primary CELCs. Defects in the biosynthetic enzymes lead to accumulation of certain types of porphyrins. Chemicals that increase the production of porphyrins, either alone or in combination with chemicals that block steps in heme biosynthesis, were used to analyze the response of LMH cells as compared to primary CELCs. Primary CELCs have shown increased production of porphyrins in response to δ-aminolevulinic acid (ALA), glutethimide (Glut), and the combination of glutethimide and ferric nitrilotriacetate (FeNTA). In Figure 3.1, LMH cells were given exogenous ALA to increase porphyrin production. When treated with ALA alone or in combination with the ferrochelatase inhibitor, deferoxamine (DFO), LMH cells accumulated mainly copro- and protoporphyrins. At the concentration tested (250 μM), DFO had little effect on porphyrin accumulation.
Figure 3.1: Porphyrin accumulation in LMH cells. LMH cells were treated with 35 μM δ-aminolevulinate (ALA) alone or in combination with 250 μM deferoxamine (DFO), 50 μM glutethimide (Glut) alone or in combination with 250 μM deferoxamine or 50 μM FeNTA for 18 hours prior to harvest. Harvest and assays were performed as described in Methods. Data represent mean ± SEM, n=3. *Significantly greater than No Treatment, P < 0.001. †Significantly greater than glutethimide alone, P < 0.001. §Significantly less than glutethimide alone, P < 0.001.
Addition of iron to CELCs by treatment with FeNTA is thought to synergize porphyrin accumulation either by increasing cytochrome P-450 dependent oxidation of porphyrinogen to porphyrin or by inducing HO-1 activity, thereby reducing the size of the regulatory heme pool (See Figure 1.3)\textsuperscript{12,13}. When treated with glutethimide alone, LMH cells accumulated large quantities of uroporphyrin, and some copro- and protoporphyrin. The combination of Glut and FeNTA produced a shift in porphyrin levels as compared to glutethimide alone with a decrease in protoporphyrin and an increase in uroporphyrin. FeNTA alone did not cause porphyrin accumulation (data not shown). Surprisingly, when DFO was given in combination with glutethimide, there was no change in porphyrin accumulation. Unlike CELCs, LMH cells did not exhibit a shift from mostly uroporphyrin, with some copro- and protoporphyrin to mostly protoporphyrin in the presence of DFO. When given in combination with either ALA or Glut, 250 μM DFO had no effect on porphyrin accumulation in LMH cells.

Chelation of intracellular iron should remove iron from the heme biosynthetic pathway resulting in inhibition of iron incorporation into protoporphyrin to form heme by the final enzyme of heme biosynthesis, ferrochelatase. This should result in an increase in protoporphyrin, with a corresponding decrease in uro- and coproporphyrins. The lack of effect of DFO in LMH cells was further investigated by inducing porphyrin production with glutethimide, and then treating with increasing doses of DFO. To investigate possible differences in iron metabolism between the two cell types, the more
accurate method of high performance liquid chromatography was used to quantitate porphyrins. Figure 3.2 shows the lack of effect of DFO in LMH cells versus primary CELCs. Changes in porphyrin levels (increased protoporphyrin, decreased uro-, 7-carboxyl-, and coproporphyrins) were observed for CELCs, while up to 625 μM DFO caused no change in LMH cells. This lack of effect may be due to differences in iron transporters, the presence of cellular proteins with higher affinity for iron than DFO, or lack of uptake of DFO in LMH cells, so that it is unable to chelate cellular iron and inhibit ferrochelatase activity.

**Cellular iron accumulation.** Since LMH cells exhibited a noticeable difference in porphyrin accumulation when treated with DFO, cellular iron accumulation was studied. Cellular iron was quantitated in LMH cells or CELCs that had been treated with DFO, or with exogenous sources of iron, either FeNTA or TMH-ferrocene (Figure 3.3). In untreated cells, iron contents were similar. When treated with DFO, CELCs showed no significant change in iron content, LMH cells had no detectable cellular iron, suggesting that LMH cells may not be permeable to DFO, but that it may remove iron from the cells. DFO probably penetrates into CELCs to chelate intracellular iron and remains within the cells, resulting in iron levels similar to control values. There were slight differences in the type of exogenous iron preferred by the two cell types, LMH cells took up FeNTA to a greater degree than TMH-ferrocene, whereas CELCs absorbed more TMH-ferrocene than FeNTA (Figure 3.3). These results are consistent with the hypothesis of a difference in uptake or metabolism of iron.
Figure 3.2: HPLC determination of porphyrin accumulation. Porphyrin accumulation was measured in primary CELCs (A) and LMH cells (B) in the presence of 50 μM glutethimide and increasing concentrations of deferoxamine. Primary CELCs or LMH cells were treated with 50 μM glutethimide and increasing doses of deferoxamine: 0, 125, 250, 375, 500, or 625 μM for 18 hours. Harvest and assays were as described in Methods. Di-carboxyl porphyrin represents protoporphyrin levels, 7-carboxyl porphyrins represent intermediates between uroporphyrin and coproporphyrin. All sample groups represented were treated with 50 μM glutethimide to induce porphyrin synthesis. The rising concentrations of DFO did not significantly alter the values for total porphyrins/mg protein, data was transformed to show percent of total porphyrins/mg protein. Data represent mean ± SEM, n=3. (A) CELCs; For uro- and 7-carboxyl porphyrins, all data points are significantly lower than glutethimide only (0 μM), P < 0.01; for di-carboxyl (proto) porphyrins, all data points are significantly higher than glutethimide only (0 μM), P < 0.001. (B) LMH cells; no deferoxamine treated group was significantly different from the glutethimide only (0 μM) group.
Figure 3.3: Cellular iron content in CELCs and LMH cells. The effects of an iron chelator and exogenous iron sources on cellular iron content were tested in primary CELCs and LMH cells. Primary CELCs and LMH cells were treated with 250 μM deferoxamine or 50 μM FeNTA for 18 hours, or 5 μM TMH-ferrocene for 4 hours prior to harvest. Harvest and assays were as described in Methods. Data represent mean ± SEM, n=3. *Significantly greater than all other treatments, P < 0.01. †Significantly different between CELCs and LMH cells by paired t-test, P < 0.001.
between the two cell types. The differences in porphyrin and iron metabolism were not investigated further.

**Upregulation of ALA synthase mRNA.** ALA synthase is the enzyme that catalyzes the rate-limiting step in heme biosynthesis. In primary CELCs, phenobarbital-like drugs (e.g. glutethimide) caused increased ALA synthase activity and mRNA levels. Synergistic induction of ALA synthase mRNA was observed in response to the combination of glutethimide and FeNTA $^{45,107}$.

Since ALA synthase is the key enzyme controlling production of heme, ALA synthase mRNA levels were measured in LMH cells in response to treatments that upregulate or downregulate ALA synthase expression. ALA synthase mRNA was quantitated in LMH cells treated with increasing doses of glutethimide, FeNTA, or both (Figure 3.4). Glutethimide alone produced a modest increase in ALA synthase mRNA, while FeNTA alone had no effect. Synergism was observed in LMH cells given the combined treatment, however higher doses than those in CELCs were required to reach maximal induction.

**Downregulation of ALA synthase mRNA.** Increased cellular heme leads to decreased ALA synthase expression through several mechanisms: decreased translocation of precursor protein into mitochondria, decreased mRNA translation, and in rat, decreased transcription $^{1-5}$. A time course was performed in LMH cells to test for decreased ALA synthase mRNA in the presence of heme. Figure 3.5 shows that heme decreased the levels of ALA synthase mRNA as early as 2 hours after administration in LMH cells. This
Figure 3.4: Effects of glutethimide, FeNTA, or both, on ALA synthase mRNA levels in LMH cells. LMH cells were exposed to increasing concentrations (0, 25, 50, 100, or 200 µM) of glutethimide, FeNTA, or the combination of glutethimide and FeNTA for 18 hours prior to harvest. Harvest, RNA isolation, and quantitation were performed as described in Methods. Data represent mean ± SEM, n=3. *Significantly greater than No treatment and glutethimide alone, P < 0.001. **Significantly greater than No treatment or FeNTA alone, P < 0.05. †Significantly greater than No treatment and glutethimide alone, P < 0.01.
Figure 3.5: Heme-dependent repression of ALA synthase mRNA levels in LMH cells. LMH cells were exposed to 20 μM heme for 2, 4, 6, 8, 10, or 12 hours prior to harvest. Harvest, isolation, and quantitation of RNA were performed as described in Methods. Data represent mean ± SEM, n=3. *Significantly different from No Treatment (0 hours), P < 0.001.
Aminolevulinate synthase mRNA
(ALA synthase mRNA/Poly-A RNA)
repression was maintained throughout the 12 hour duration of the experiment.

Since the heme-dependent regulation of ALA synthase mRNA is a major component of the normal regulation of heme biosynthesis, a side-by-side comparison of ALA synthase mRNA levels in LMH cells versus CELCs was performed (Figure 3.6). Heme-dependent repression of ALA synthase mRNA was observed for both cell types. In the presence of heme, ALA synthase mRNA levels were 28% of control in CELCs, and 64% of control in LMH cells. The comparison indicated that both the basal and heme-repressed levels of ALA synthase mRNA were higher in LMH cells than in CELCs. This may be due to the differing natures of these two cell types: LMH cells are rapidly metabolizing and have a high growth rate, whereas primary CELCs quickly become dormant, eventually dying within 7 - 10 days.

**Regulation of ALA synthase mRNA by metalloporphyrins in LMH cells.** Finally, metalloporphyrins other than heme have regulatory effects on ALA synthase activity and mRNA levels. Tin mesoporphyrin and zinc mesoporphyrin repressed ALA synthase activity and mRNA in primary CELCs that had been induced with glutethimide and FeNTA. Copper protoporphyrin caused a slight increase in induced activity and manganese protoporphyrin was not tested. Manganese protoporphyrin, copper protoporphyrin, tin mesoporphyrin, zinc mesoporphyrin, and iron protoporphyrin (heme) were tested for the ability to regulate ALA synthase mRNA levels in LMH cells (Figure 3.7). Both concentrations of heme tested reduced ALA synthase
Figure 3.6: Comparison of heme-dependent repression of ALA synthase mRNA in CELCs and LMH cells. Cells were either left untreated or treated with 20 µM heme for 6 hours prior to harvest. Harvest, isolation, and quantitation of RNA were performed as described in Methods. Data represent mean + SEM, n=4. *Significantly different from all others, P < 0.001. †Significantly different from untreated LMH cells, and from Heme-treated CELCs, P < 0.01. §Significantly different from untreated CELCs, P < 0.01.
Figure 3.7: Effects of metalloporphyrins on ALA synthase mRNA levels in LMH cells. Cells were treated with 10 μM or 20 μM heme, or 10 μM of the other metalloporphyrins: manganese protoporphyrin, copper protoporphyrin, tin mesoporphyrin, or zinc mesoporphyrin, for 6 hours prior to harvest. The metalloporphyrins were dissolved in DMSO, therefore, a DMSO solvent (1 μL per mL of culture medium) control was also included. Harvest, isolation, and quantitation of RNA were performed as described in Methods. Data represent mean + SEM, n=3. *Significantly less than DMSO control, P < 0.0055.
mRNA levels in LMH cells. Manganese protoporphyrin and zinc mesoporphyrin also decreased levels of ALA synthase mRNA. Repression by tin mesoporphyrin was not statistically significant. No repression was observed for copper protoporphyrin and the DMSO solvent control.
Conclusions

LMH cells exhibited porphyrin and heme metabolism similar to that of primary CELCs. Unlike primary rat hepatocyte cultures, LMH cells more closely exhibit characteristics observed in primary CELCs, porphyrin accumulations are inducible and regulation of ALA synthase seems normal.

The major difference between primary CELCs and LMH cells was in the type of porphyrin that accumulated, especially in the presence of deferroxamine. There may be differences in cellular iron metabolism. In all other aspects of heme biosynthesis tested, LMH cells were similar to primary CELCs, supporting the use of this cell line for studies of heme metabolism and its regulation.
CHAPTER IV
CHARACTERIZATION OF HEME OXYGENASE-1:
COMPARISON OF LMH CELLS TO PRIMARY CULTURES OF CHICK
EMBRYO LIVER CELLS

Introduction

Heme oxygenase catalyzes the degradation of heme into biliverdin, carbon monoxide, and iron. Two forms of this enzyme, heme oxygenase-1 and -2, have been identified; only heme oxygenase-1 (HO-1) is subject to induction by heme, metal ions, and other chemical and physical perturbations (e.g. drugs, oxidants, and heat shock). Primary chick embryo liver cells (CELCs) are widely used for the study of heme metabolism because of their ease of preparation, low cost, and high degree of similarity to human heme metabolism. Nonetheless, this system has some limitations: new cultures must be prepared every week; the resulting cell populations are somewhat heterogeneous; and cells are short-lived, limiting the feasible duration of time course and transfection studies. LMH cells are the first chicken hepatoma cell line to be established.

The aim of the work summarized in this chapter was to characterize the regulation of heme oxygenase-1 in LMH cells, and to compare this regulation to that previously described in primary CELCs. Initially, culture
conditions which provided optimal induction of HO-1 were established. The induction of HO-1 was then assessed by measuring changes in mRNA levels or enzyme activities in response to several treatments, including heme, metals, sodium arsenite, and heat shock, which have been shown to increase the expression of heme oxygenase \(^{23,29,32,51,52,74,85,89-91,100,178}\). The comparative dose-responses and time courses of induction of HO-1 mRNA and heme oxygenase activities by heme and cobalt chloride were characterized. In addition, LMH cells exhibited a measurable response to other treatments previously shown to increase HO-1 mRNA levels or heme oxygenase activities in normal CELCs. Similarities were observed with respect to regulation of HO-1 expression in primary hepatocytes and LMH cells. During these studies, a small but significant heat shock induction of HO-1 mRNA in CELCs was detected. This was the first reported measurable heat shock response of HO-1 in CELCs or LMH cells. These experiments support the use of LMH cells as a model for the study of HO-1 regulation.
Results

Initial detection of HO-1 mRNA in LMH cells. For the initial characterization of heme degradation in the LMH cell line, HO-1 mRNA levels were measured in response to treatments previously shown to increase these levels in primary CELCs. To detect a response, LMH cells were treated with heme or cobalt at concentrations and for exposure times formerly shown to produce robust inductions in CELCs, namely, 10 μM heme for 5 hours or 75 μM cobalt chloride for 18 hours. Heme caused a 5.8-fold increase and cobalt chloride caused a 3.8-fold increase in HO-1 mRNA levels in LMH cells (Table 4.1).

Gelatin-coated dishes enhance induction in LMH cells. In previous work, others have found that LMH cells required gelatin coating of culture vessels to achieve monolayer growth. In contrast, CELCs are routinely cultured directly on plastic dishes. After initial studies with heme and cobalt chloride had confirmed demonstrable increases in HO-1 mRNA levels in LMH cells, culture conditions were analyzed to optimize the similarities between CELCs and LMH cells and to maximize the inducible response of LMH cells to selected chemicals. Effects of the medium or other factors relating to the conditions of cell cultures were tested. Although gelatin was not necessary for growth of LMH cells, gelatin coating of dishes enhanced the responsiveness of
Table 4.1: Effects of heme or cobalt chloride on levels of HO-1 mRNA in LMH cells. LMH cells were treated with 10 μM heme for 5 hours or 75 μM cobalt chloride for 18 hours prior to harvest. Harvest, isolation, and quantitation of RNA were as described in Methods. For each sample, HO-1 mRNA was quantitated by dot blot and normalized to total poly-A RNA measured on a duplicate blot. Data represent mean + SEM, n=3. *Significantly greater than No Treatment control (P < 0.0001).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Levels of HO-1 mRNA (Arbitrary Units)</th>
<th>Fold Induction</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Treatment</td>
<td>17.6 ±3.40</td>
<td>-</td>
</tr>
<tr>
<td>Heme</td>
<td>102.0 ±12.0*</td>
<td>5.8</td>
</tr>
<tr>
<td>Cobalt Chloride</td>
<td>67.5 ±16.2*</td>
<td>3.8</td>
</tr>
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</table>
LMH cells to treatments (Figure 4.1). Accordingly, subsequent experiments were conducted with LMH cells grown on gelatin-coated dishes.

Dose response and time course of heme and cobalt induction of HO-1 mRNA. Next, dose-response and time course relationships for heme or cobalt chloride treatment on HO-1 mRNA levels were investigated. LMH cells were treated with increasing doses of heme for 7.5 hours (Figure 4.2A) or cobalt chloride for 18 hours (Figure 4.2B), and HO-1 mRNA levels were measured. The data from both treatments describe typical saturation curves. The dose of cobalt chloride required to reach maximal response in LMH cells was found to be slightly higher than that observed for maximal HO activity, and induction of HO-1 mRNA or HO-1 CAT reporter constructs in CELCs

Concentrations of ≥20 μM heme, or ≥150 μM cobalt chloride, led to maximal increases in the amount of HO-1 mRNA in LMH cells. Differences in concentrations required for maximal induction (e.g., for cobalt chloride) cannot be attributed to differences in the medium, which was identical for primary CELCs and LMH cells; the only difference in extracellular environment was the presence of gelatin-coating for LMH cells. It is possible that gelatin may bind some chemicals such as cobalt, making them less available to the cells.

In other systems, regulation of HO-1 expression has been shown to occur principally at the level of transcription, unless heme oxygenase activity has been inhibited. Most previous studies in CELCs quantitated heme
Figure 4.1: Effects of gelatin coating of culture dishes on induction of HO-1 mRNA in LMH cells. Cells were plated on uncoated culture dishes (shaded bars) or on dishes coated with 0.1% gelatin (hatched bars), and treated with 10 μM heme for 5 hours or with 75 μM cobalt chloride for 18 hours. Harvest, isolation, and quantitation of RNA were performed as described in Methods. Data represent mean + SEM, n=3. *Significantly greater than control, (P < 0.0005). †Significantly greater than the same treatment without gelatin coating, (P < 0.05).
Figure 4.2: Dose-response curves for induction of HO-1 mRNA by heme or cobalt chloride. LMH cells were treated with the indicated concentrations of (A) heme for 7.5 hours or (B) cobalt chloride for 18 hours. Harvest, isolation, and quantitation of RNA were performed as described in Methods. Data represent means ± SEM, n=3.
oxygenase activities, because the increase in activities occurred as a consequence of increased mRNA levels. In CELCs, heme treatment produces a rapid initial increase in levels of heme oxygenase activities and HO-1 mRNA levels followed by a decrease back to control levels by 12 hours \(^{18,23,46,57,178}\). In contrast, following addition of cobalt chloride, an initial lag phase of about 12 hours is observed, followed by a steady increase in activities and mRNA levels throughout the duration of the experiment \(^{18,57,77,78,109}\). To delineate the temporal response of LMH cells to treatment with heme or cobalt chloride, the induction of HO-1 mRNA levels was studied over 24 hours. As shown in Figure 4.3A, maximal induction was observed 6-8 hours after treatment with 20 μM heme; HO-1 mRNA levels then decreased, reaching control levels by 24 hours. After an initial lag phase of 8-12 hours, 200 μM cobalt chloride caused a steady increase in HO-1 mRNA levels throughout the duration of the experiment (Figure 4.3B). The temporal relationship between treatment and the rise in HO-1 mRNA in LMH cells correlated well with that previously observed in CELCs. For direct comparison, the effects of heme or cobalt chloride on HO-1 mRNA in primary cultures of CELCs versus LMH cells were examined in the same experiment. As shown in Figure 4.4, the fold of maximal induction for each treatment was similar in CELCs and LMH cells; i.e., the efficacy is similar in the two cell types. The potency of heme is also similar among CELCs and LMH cells, but cobalt chloride is more potent in primary CELCs.
Figure 4.3: Time course for induction of HO-1 mRNA by heme or cobalt chloride. Prior to harvest, LMH cells, plated on gelatin-coated dishes, were exposed to either (A) 20 μM heme or (B) 200 μM cobalt chloride for the indicated times. Harvest, isolation, and quantitation of RNA were performed as described in Methods. Data represent means + SEM, n=3. * No treatment control (24h). †This point is also a 24 hour control.
Figure 4.4: Comparative efficacy of heme or cobalt chloride to increase levels of HO-1 mRNA in CELCs and LMH cells. In a single experiment, both CELCs and LMH cells were simultaneously treated with the appropriate doses of heme or cobalt chloride required for maximal induction for each cell type (heme, 20 \( \mu \)M for both cell types; cobalt chloride, 75 \( \mu \)M for primary CELCs and 200 \( \mu \)M for LMH cells). Cells were treated with heme for 7.5 hours or with cobalt chloride for 18 hours prior to harvest. Harvest, isolation, and quantitation of RNA were performed as described in Methods. Data represent means + SEM, n=4. There were no significant differences in the induction between primary CELCs and LMH cells.
Synergistic induction of HO-1 mRNA by glutethimide and ferric nitriotriacetate (FeNTA). The combination of glutethimide and FeNTA produces a synergistic induction of HO-1 mRNA in CELCs. This induction has been shown to be due to the interdependence of ALA synthase and HO-1 on the levels of cellular heme\textsuperscript{45,107}. In Figure 4.5, the ability of glutethimide + FeNTA to produce synergistic increases in HO-1 mRNA was examined in LMH cells. Treatment with glutethimide or the combination of glutethimide + FeNTA increased HO-1 mRNA levels, with the highest induction at 50 \(\mu\text{M}\) concentrations of each chemical. FeNTA alone had no significant effect on HO-1 mRNA levels. In addition, synergistic induction of HO-1 mRNA was observed at 50 \(\mu\text{M}\) glutethimide + 50 \(\mu\text{M}\) FeNTA (Figure 4.5). These data agree with previously observed results for HO activity in CELCs\textsuperscript{45,107}.

Increased heme oxygenase activity levels correlate with induction of HO-1 mRNA. Similarities in HO-1 regulation for CELCs and LMH cells also were observed when heme oxygenase activities were investigated. To confirm that activities of HO-1 also were increased in LMH cells, both cell types were treated with heme, cobalt chloride, or glutethimide + FeNTA. All treatments increased heme oxygenase activities in a fashion similar to that observed for HO-1 mRNA (Table 4.2). In fact, in this experiment, the heme-mediated induction of activity was greater in LMH cells than CELCs. Glutethimide alone caused no significant increase in heme oxygenase activity in LMH cells (117±6 pmol bilirubin/mg protein). In CELCs, induction of HO-1 mRNA has been correlated
Figure 4.5: Effects of glutethimide, FeNTA, or the combination of glutethimide and FeNTA on levels of HO-1 mRNA in LMH cells. LMH cells were treated with increasing concentrations of glutethimide, ferric nitrilotriacetate, or both, for 18 hours prior to harvest. Harvest, isolation, and quantitation of RNA were performed as described in Methods. Data represent mean + SEM, n=3.

*Significantly greater than no treatment control (0 μM), P<0.05; †Significantly greater than no treatment control, P<0.01; §Significantly greater than glutethimide alone, P<0.05.
Table 4.2: Comparative effects of selected chemicals on heme oxygenase activities in primary CELCs and LMH cells. Incubation times were: heme - 10 h; cobalt chloride, and the combination of glutethimide and FeNTA - 20 h.

Concentrations were: 20 μM heme, 50 μM glutethimide + 50 μM FeNTA for both cell types; 75 μM cobalt chloride for CELCs, and 200 μM cobalt chloride for LMH cells. Cells were harvested and heme oxygenase activity assays were performed as described in Methods. Data represent mean ± SEM, n=4.

*Significantly greater than control (P < 0.0005). †Significantly greater than control (P < 0.0001). §Significantly greater than in CELCs (P < 0.01).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Heme Oxygenase Activity (pmol bilirubin/mg prot./min)</th>
<th>Fold Induction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary CELCs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Treatment</td>
<td>55 ±6</td>
<td>1.0</td>
</tr>
<tr>
<td>Heme</td>
<td>273 ±14*</td>
<td>5.0</td>
</tr>
<tr>
<td>Cobalt Chloride</td>
<td>382 ±14†</td>
<td>7.0</td>
</tr>
<tr>
<td>Glut + FeNTA</td>
<td>199 ±9*</td>
<td>3.6</td>
</tr>
<tr>
<td><strong>LMH Cells</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Treatment</td>
<td>77 ±4</td>
<td>1.0</td>
</tr>
<tr>
<td>Heme</td>
<td>557 ±14†§</td>
<td>7.2</td>
</tr>
<tr>
<td>Cobalt Chloride</td>
<td>429 ±64†</td>
<td>5.6</td>
</tr>
<tr>
<td>Glut + FeNTA</td>
<td>292 ±25*</td>
<td>3.8</td>
</tr>
</tbody>
</table>
with subsequent increases in HO-1 protein and enzyme activity\textsuperscript{178}. For both cell 
types, increases in HO-1 mRNA in response to heme or cobalt chloride, and 
synergy in response to glutethimide + FeNTA also correlated with observed 
increases in enzyme activity levels. These data are consistent with 
transcriptional regulation of HO-1 expression in both cell types. Although 
apolipoprotein II expression was reported to be decreased in LMH cells\textsuperscript{69}, the 
expression of several other proteins, including HO-1, was comparable in LMH 
cells and CELCs\textsuperscript{65,66}. The levels of HO-1 protein expression in LMH cells were 
reported to be similar to those in CELCs, supporting the notion that LMH cells 
are a useful model not only for assessing regulation of HO-1 mRNA expression, 
but also HO-1 protein and activity levels.

**Effects of non-heme metalloporphyrins on HO-1 mRNA levels.** Unlike 
heme, some other metalloporphyrins have been shown to repress ALA 
synthase activity and to inhibit heme oxygenase in a competitive manner\textsuperscript{44,57,177}. 
Zinc mesoporphyrin has been shown to inhibit heme oxygenase in several 
model systems for porphyria, including primary CELCs and in rats and mice 
\textsuperscript{44,46,57,177,179-181}. Tin protoporphyrin has been used in humans with acute 
porphyria, in combination with intravenous heme, in an attempt to inhibit heme 
oxygenase and thereby prolong the duration of heme-mediated inhibition of 
ALA synthase\textsuperscript{182-184}. Inhibition of HO-1 mRNA by several metalloporphyrins was 
tested in LMH cells (Figure 4.6). Both concentrations of heme tested
**Figure 4.6**: Effects of selected metalloporphyrins on HO-1 mRNA levels in LMH cells. Cells were treated with 10 μM or 20 μM heme; or with 10 μM non-heme metalloporphyrin dissolved in DMSO for 6 hours prior to harvest (MP = mesoporphyrins, PP = protoporphyrins). DMSO was added at not more than 1 μL per mL of medium as a solvent control. Harvest, isolation, and quantitation of RNA was performed as described in Methods. Data represent mean + SEM, n=3. *Significantly less than DMSO solvent control, P < 0.05. †Significantly greater than DMSO control, P < 0.05.
significantly increased HO-1 mRNA levels. No effect on HO-1 mRNA was observed for manganese protoporphyrin (MnPP), while zinc and tin mesoporphyrins (ZnMP and SnMP) resulted in HO-1 mRNA levels lower than DMSO solvent control levels.

**HO-1 mRNA induction measured by both Northern blot and dot blot.** To further characterize HO-1 regulation in LMH cells, additional chemicals and stimuli were tested, which previously have been shown to elevate HO-1 mRNA levels and enzyme activities in primary CELCs and other cell culture systems. Heme, cobalt chloride, cadmium chloride, sodium arsenite, and 3,5,5-trimethylhexanoylferrocene (TMH-ferrocene) were each tested for their abilities to increase the levels of HO-1 mRNA. Dot blot data are presented in Table 4.3. LMH cells were treated with chemicals at concentrations and times used routinely in CELCs. All treatments caused significant increases in HO-1 mRNA levels, with the highest degree of induction by arsenite. Additionally, heme, arsenite, cobalt, cadmium, and heat shock were tested by Northern blot (Figure 4.7) for their ability to induce HO-1 mRNA in CELCs and LMH cells. All treatments gave similar fold inductions for both cell types. Although there have been no previous reports of a heat shock response in primary CELCs, heat shock significantly increased HO-1 mRNA levels in both CELCs and LMH cells. For both cell types, increases in HO-1 mRNA measured by Northern blot were more pronounced than that observed by dot blot for all treatments except for
**Table 4.3:** Effect of selected chemicals on levels of HO-1 mRNA in LMH cells.

Cells were treated with selected chemicals for the indicated times prior to harvest. Concentrations of chemicals and incubation times were: heme, 20 μM for 6 h; cobalt chloride, 200 μM for 18 h; cadmium chloride, 1.5 μM for 18 h; sodium arsenite, 25 μM for 18h; and TMH-ferrocene, 5 μM for 4h. Harvest, isolation, and quantitation of RNA were performed as described in Methods. Relative amounts of mRNA were normalized to total Poly-A RNA. Data represent mean ± SEM, n=4. *Significantly greater than control (P < 0.0001). †Significantly greater than other treatments (P < 0.0005).

<table>
<thead>
<tr>
<th>TREATMENT</th>
<th>Levels of HO-1 mRNA (Arbitrary Units)</th>
<th>Fold Induction</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Treatment</td>
<td>29.6±2.7</td>
<td>-</td>
</tr>
<tr>
<td>Heme</td>
<td>106±16 *</td>
<td>3.6</td>
</tr>
<tr>
<td>Cobalt Chloride</td>
<td>135±3.6 *</td>
<td>4.5</td>
</tr>
<tr>
<td>Cadmium Chloride</td>
<td>123±13 *</td>
<td>4.2</td>
</tr>
<tr>
<td>Sodium Arsenite</td>
<td>177±4.2 *†</td>
<td>6.0</td>
</tr>
<tr>
<td>TMH-ferrocene</td>
<td>89.3±4.4 *</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Figure 4.7: Northern blot comparison of HO-1 mRNA induction by selected treatments in CELCs and LMH cells. Prior to harvest, cells were left untreated or exposed to 10 μM heme for 6 h, 75 μM sodium arsenite for 4 h, 200 μM cobalt chloride for 18 h, 1.5 μM cadmium chloride for 18 h, or heat shock at 43°C for 2 h. Harvest, isolation, and quantitation of RNA was performed as described in Methods. A single band located at 1.3 Kb was detected with the probe specific for chicken HO-1. The blot was stripped and rehybridized with a probe specific for chicken GAPDH. HO-1 mRNA was normalized to GAPDH mRNA levels for each lane. Fold inductions in CELCs and LMH cells are presented.
### Fold Induction of HO-1/GAPDH mRNA

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Primary CELCs</th>
<th>LMH Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>10 μM heme</td>
<td>10.8</td>
<td>5.2</td>
</tr>
<tr>
<td>75 μM ARS</td>
<td>47.9</td>
<td>35.9</td>
</tr>
<tr>
<td>200 μM CoCl₂</td>
<td>29.2</td>
<td>5.5</td>
</tr>
<tr>
<td>1.5 μM CdCl₂</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Ht Shk (43°C)</td>
<td>3.2</td>
<td>9.8</td>
</tr>
</tbody>
</table>
cadmium chloride, which showed no significant induction. For dot blots, less
HO-1 mRNA may have remained bound to the membrane after washing,
resulting in decreased binding of radiolabelled probe. This may account for the
observed differences between Northern and dot blot results.

Studies in intact rats, or with other liver-derived cell lines have indicated
variation in the response of HO-1 mRNA to cobalt vs. cadmium. Recently, Alam
\(^{27}\) showed that HO-1 mRNA in the cell lines Hepa and L929 was not induced by
cobalt, but was markedly induced by cadmium. In LMH cells, the induction by
cobalt is not only measurable, but is at least comparable to that observed for
cadmium or heme in other systems \(^{23,77,109}\). Northern analysis indicated little to
no induction by cadmium, but a significant induction by cobalt was observed.
Differences in minimal doses required for maximal induction may be due to cell-
specific changes in uptake or metabolism of the chemicals used, or to
differences in cell surface-to-volume ratios, as LMH cells are morphologically
different from primary CELCs. Despite the requirement for greater
concentrations of cobalt chloride in LMH cells, the pattern of induction seems to
be generally similar to that observed for CELCs when analyzed by either
Northern or dot blots.

**Heat shock induction of HO-1 in CELCs and LMH cells.** Although heat
shock has produced a response in rat, mouse, and some human cell lines
(Hep3B) \(^{185}\), heat shock-mediated induction of HO-1 mRNA has not been
detected in other human cell lines (HepG2, HeLa), macrophages, or primary
CELCs previous to the work presented here\textsuperscript{89,185,186}. Since a heat shock response was observed by Northern blot (Figure 4.7), the ability of CELCs and LMH cells to mount a heat shock response was further investigated by following induction of HO-1 and HSP70 mRNA levels through a 5 hour time course of incubation at 43°C (Figure 4.8). The time courses of the heat shock response in CELCs and LMH cells were similar. Both CELCs and LMH cells were found to respond to heat shock with an increase in HO-1 mRNA, although the fold increase in message levels was considerably greater in LMH cells than in CELCs. As shown in Figure 4.8A, the results for CELCs show a slight but significant increase in HO-1 and HSP70 mRNA levels (2.9-fold and 4.7-fold versus no treatment (0 hour) control, respectively). Peak induction of HO-1 mRNA in CELCs occurred at 2 hours and returned to basal levels by 5 hours. Earlier results in CELCs involved only a 5 hour time point, at which time the slight increase in HO-1 mRNA was already past. The heat shock mediated induction in LMH cells was 9.1-fold for HO-1 mRNA and 26.7-fold for HSP70 mRNA levels (Figure 4.8B). These results with LMH cells indicate that HO-1 mRNA induction follows the same pattern as the HSP70 mRNA, with maximal increase observed after 2 hours of incubation at 43°C. A similar response was seen for HO-1 mRNA in CELCs, but for HSP70, peak mRNA levels were observed slightly earlier, at 1 hour. Heat shock mediated induction was observed in both CELCs and LMH cells despite the notable absence of a putative or functional heat shock element in the chicken HO-1 promoter.
Figure 4.8: Comparison of the effects of heat shock on HO-1 and heat shock protein 70 (HSP70) mRNA levels in CELCs and LMH cells. (A) CELCs or (B) LMH cells were incubated at 43°C for the indicated times prior to harvest. Harvest, isolation, and quantitation of RNA were performed as described in Methods. Data represent mean ± SEM, n=3. *Significantly greater than control (P<0.05). †Significantly greater than control (P<0.01). §Significantly greater than control (P<0.005). ․Significantly greater than control (P<0.0005).
Sodium arsenite induction of HO-1 mRNA in LMH cells. Regulation of HO-1 gene expression has been shown to occur at the transcriptional level for many inducers: heme, the transition metals cobalt and cadmium, and the cellular stressor LPS. A time course was done to examine the level of regulation by the most potent inducer of HO-1 mRNA, sodium arsenite. LMH cells were treated with 75 µM arsenite in the presence or absence of actinomycin D, which was used to inhibit the synthesis of nascent mRNA. HO-1 mRNA levels were quantitated and normalized to GAPDH mRNA, as measured by both Northern and dot blots, with similar results. Data from dot blots are illustrated in Figure 4.9. Peak induction of HO-1 mRNA by arsenite occurred at 4 hours, consistent with previous results. No arsenite-mediated induction of HO-1 mRNA was observed when LMH cells were pretreated for 4 hours with actinomycin D. This data is consistent with transcriptional regulation of HO-1 by arsenite.
Figure 4.9: Sodium Arsenite (ARS) induction of endogenous HO-1 mRNA in LMH cells; and block by actinomycin D. Cells were treated with 75 μM ARS for the indicated times prior to harvest. Some plates received 1 μM Actinomycin D, 4 hours prior to treatment with sodium arsenite. At $t=0$, 75 μM ARS was added directly to the medium. Plates were incubated at 37°C until harvest. Total RNA was prepared and levels of HO-1 and GAPDH mRNAs measured as described in Methods. Data represent mean ± SEM, n=3. *Significantly greater than control, P<0.01.
Conclusions

The results presented in this chapter support the use of LMH cells as a model system for the study of HO-1 expression. LMH cells have detectable and inducible heme oxygenase-1. Culture conditions that support robust induction were defined. Results from all treatments tested support normal HO-1 regulation and expression in LMH cells, and provide evidence that heme metabolism in LMH cells parallels that previously characterized in primary CELCs. The potencies of some chemical inducers (e.g., cobalt chloride) were lower in LMH cells. However, the efficacies and time courses were very similar to those observed in primary CELCs. Similar increases in heme oxygenase activities were also observed. The effects of non-heme metalloporphyrins on HO-1 mRNA levels in LMH cells also correlated well with previous results in CELCs \(^{44,57,177}\). Both zinc and tin mesoporphyrins caused slight decreases in HO-1 mRNA levels in LMH cells. These data lend additional support that control of HO-1 expression in LMH cells is similar to that observed in normal liver cells in vivo, and in primary cultures. In addition, induction of HO-1 in response to heat shock in primary CELCs was identified for the first time.

In conclusion, LMH cells exhibit levels of heme oxygenase-1, and mechanisms of its regulation similar to those observed in primary chicken hepatocytes. Minor differences were observed in the efficacies of some treatments. Although no heat shock response had previously been reported for
chicken HO-1, induction of HO-1 mRNA was observed in response to heat shock in LMH cells, and for the first time, in CELCs. Actinomycin D blocked arsenite-mediated induction of HO-1 mRNA in LMH cells. This is consistent with a transcriptional regulation mechanism for this chemical. Other facets of regulation of heme metabolism may be elucidated through long-term studies and stable transfections, which are now possible using this cell line.
CHAPTER V

CLONING AND CHARACTERIZATION OF THE CHICKEN HEME OXYGENASE-1 PROMOTER

Introduction

As previously described, studies in which the level of HO-1 induction has been investigated have shown that HO-1 expression is transcriptionally regulated. Several cis-acting promoter elements involved in mediating HO-1 gene expression have been elucidated $^{33,111-113}$. In one study $^{28}$, stably transfected HO-1 reporter gene constructs were used to locate elements required for induction of the murine HO-1 gene by heme and heavy metals. Putative regulatory elements were identified between 3.5 Kb and 12.5 Kb upstream from the transcription start site. Recently, evidence for a basal level inducer and heme-responsive element located as far as 10.5 Kb upstream of the transcription start site in the mouse HO-1 gene promoter was presented $^{87}$. Other work has located regions of the HO-1 promoter that mediate cadmium, heat shock, hypoxia, and lipopolysaccharide (LPS) responsiveness in rat, mouse, and human HO-1 genes $^{27,29,87,88,113,115,116}$. However, the transcription factor complexes that target these elements have been largely unexplored.

Work summarized in this chapter focused on the induction of chicken HO-1 by the tumor promoter arsenite, which produced the greatest increases in
levels of HO-1 mRNA and activities in LMH cells, as shown in Chapter IV. The ability of arsenite to increase transcription of endogenous HO-1, and the activity of transfected luciferase reporter gene constructs under control of the HO-1 promoter, was investigated using LMH cells. Regions of the cHO-1 promoter were subcloned into a luciferase reporter vector, and tested for responsiveness to HO-1 inducers. Transient transfection assays were used to investigate the modulation of HO-1 transcription by arsenite. In other systems, arsenite has been proposed to affect gene expression by modulating the activities of transcription factor complexes bound to AP-1 elements in the promoter regions of several genes\(^{118,159,160}\). Putative AP-1 binding sites are present in the promoter regions of mammalian\(^{67,88,111,113}\) and chicken HO-1\(^{37}\). The roles of three putative AP-1 transcription factor complex binding sites (located at -1578, -3656, and -4597 base pairs, upstream of the transcription start site) in arsenite-mediated induction of HO-1 gene expression were studied.
Results

Construction of cHO-1 promoter-luciferase reporter plasmids.

Transcriptional regulation is mediated by the binding of transcription factors to specific sequences in the promoter regions of genes. The recent cloning and characterization of the genomic chicken HO-1 gene\textsuperscript{37} has aided the development of tools to elucidate the mechanisms involved in modulating HO-1 gene expression. To facilitate the search for promoter elements involved in arsenite induction of HO-1, a series of cHO-1 promoter-luciferase reporter plasmids were constructed using convenient restriction enzyme recognition sites (Figure 5.1, see Methods for details of cloning). The largest plasmid contained a 7132 bp Xba I - Xho I fragment of cHO-1 promoter sequence (including the transcription start site and some 5'-UTR) cloned upstream of the firefly luciferase reporter gene cassette in the commercially available reporter vector, pGL3 basic. Each successive deletion plasmid contained approximately 1 Kb less of the 5' promoter sequence than the corresponding next largest plasmid. Appendix E contains the sequence of the 7132 bp fragment that was cloned into pGL3 basic, and the restriction sites used to create the deletions.

Detection of basal and induced reporter plasmid luciferase activity. A test transfection was performed using the smallest, pCHO.TATA-Luc, and largest, pCHO7.1-Luc, constructs to detect basal level reporter gene expression, and heme-induced or arsenite-induced reporter gene expression. Controls were:
Figure 5.1: HO-1 promoter-luciferase reporter constructs. Restriction enzyme sites used for creating reporter constructs are shown in relation to the chick heme oxygenase-1 TATA box (3' end = -26 base pairs), cHO-1 txn = transcription start site (+1), and the Xho I cloning site (+54). Abbreviated restriction enzyme recognition sites are designated as follows: Pfi MI (F), Pml I (P), Nhe I (N), Bgl II (B), Eco RI (E), Tth 111 I (T). The restriction enzyme and sequence location used to create each construct are identified beside each representation. Sequence of the proximal promoter region has been deposited with GenBank (Accession number U95209). For the entire 7132 bp chicken HO-1 promoter sequence, see Appendix E. The pCHO3.6-Luc construct was subcloned into pGL3 by ligation of a fragment taken from a chloramphenicol acetyltransferase (CAT) reporter construct. See Methods for details of creation of constructs. See Appendix C for a comprehensive list of plasmid constructs.
nontransfected cells; cells that were subjected to transfection conditions, including the transfection reagent, but received no plasmid DNA; cells that received the pGL3 control plasmid, which contains the luciferase gene under control of an SV40 enhancer and promoter; and cells that received the promoterless and enhancerless vector control plasmid, pGL3 basic. Cells transfected with pGL3 basic were left untreated or treated with heme or arsenite.

As shown in Figure 5.2, the highest normalized luciferase reporter gene activity was observed for the positive control vector plasmid, pGL3 control. The negative control vector, pGL3 basic, had a low basal expression which was unaffected by heme or arsenite treatment. Activity of the minimal promoter construct, pCHO.TATA-Luc, was not increased by treatment with heme or arsenite. Basal expression of pCHO7.1-Luc was much greater than pCHO.TATA-Luc or pGL3 basic. No induction over basal was observed by heme for pCHO7.1-Luc, however, arsenite produced a robust (8.3-fold) increase in reporter gene activity from pCHO7.1-Luc.

**Responsiveness of pCHO7.1-Luc to cellular stressors.** To characterize further the usefulness of this construct as a tool for studying HO-1 gene expression under conditions of cellular stress, the effects of several chemicals implicated in stimulating cellular stress responses were tested. The minimal promoter construct, pCHO.TATA-Luc served as a negative control. The effects of arsenite, cadmium, cobalt, hydrogen peroxide, and LPS were tested on both pCHO.TATA-Luc and the largest construct, pCHO7.1-Luc (Table 5.1). There
Figure 5.2: Initial test for expression and induction of chicken HO-1 promoter luciferase reporter constructs in LMH cells. Cells were transfected with no DNA, or pGL3 control, pGL3 basic, pCHO.TATA-Luc, or pCHO7.1-Luc plasmid DNA approximately 48 hours prior to treatment. Treatments were: 20 μM heme for 8 h or 25 μM sodium arsenite for 8 h. All transfections that received DNA also received pPGK-βgal plasmid DNA for normalization of luciferase activity. Harvest and assays were performed as described in Methods. Data represent mean ± SEM, n=3. * Significantly greater than pCHO7.1-Luc, no treatment, P < 0.001.
Table 5.1: Induction of pCHO7.1-Luc, but not pCHO.TATA-Luc by inducers of endogenous HO-1. LMH cells were transfected with either pCHO.TATA-Luc or pCHO7.1-Luc approximately 48 hours prior to treatments. Cells were treated as follows: 75 μM sodium arsenite for 6 h; 1.5 μM cadmium chloride for 20 h; 200 μM cobalt chloride for 20 h; 0.5 mM hydrogen peroxide for 6 h; and 1.5 μg/mL LPS for 20 h. Harvest and assays were performed as described in Methods. Data represent mean ± SEM. * Significantly greater than no treatment control, \( P < 0.001 \). † Significantly greater than all other treatments, \( P < 0.01 \).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Normalized RLU ± SEM</th>
<th>Fold Induction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>pCHO.TATA-Luc</strong></td>
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<td></td>
</tr>
<tr>
<td>None</td>
<td>2410 ± 88</td>
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<td>Sodium arsenite</td>
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<td>Cadmium chloride</td>
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<td>Hydrogen Peroxide</td>
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<td><strong>pCHO7.1-Luc</strong></td>
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<td>Lipopolysaccharide</td>
<td>3550 ± 264</td>
<td>1.1 ± 0.1</td>
</tr>
</tbody>
</table>
was no significant increase in activity of pCHO.TATA-Luc in response to any
treatment tested. Sodium arsenite had the greatest effect on pCHO7.1-Luc
reporter gene expression, with a 4.3-fold increase in normalized luciferase
activity (Table 5.1). Lesser degrees of induction were observed with this
construct after exposure to hydrogen peroxide (1.6-fold) and cadmium chloride
(2.3-fold). LPS and cobalt chloride have been shown to induce HO-1 in some
experimental systems; however, no induction was observed for LPS or cobalt
chloride with pCHO7.1-Luc in LMH cells under these conditions.

The lack of a response to LPS may be explained by a cell-type specific
difference; e.g., it is not known whether LMH cells have LPS receptors, which
would confer responsiveness to this chemical. In liver, the major effects of LPS
are thought to be on Kupffer cells which release cytokines that exert effects on
the other cell types \(^{187, 188}\). Since LMH cells are derived from hepatocytes, they
may indeed lack the pathway that directly responds to LPS. Alternatively, the
promoter elements required for responsiveness to cobalt chloride and LPS may
not be present in the pCHO7.1-Luc construct, or a silencer element may be
preventing reporter gene expression.

Optimization of arsenite-mediated induction of pCHO7.1-Luc. Arsenite
potently induced both endogenous HO-1 and transiently transfected HO-1
reporter constructs in LMH cells, making this a good system for studying the
arsenite-mediated cellular stress response. Further analysis was performed on
the arsenite-induced increase in reporter gene expression in cells transfected
with pCHO7.1-Luc. Dose response and time course experiments established that the most effective dose for arsenite induction of reporter constructs was 75 μM and peak induction occurred at 6 hours (Figure 5.3). Therefore, these conditions were used to further investigate the mechanism of sodium arsenite induction of HO-1 gene transcription.

**Induction of transfected heme oxygenase-1 promoter luciferase reporter constructs by sodium arsenite.** Sodium arsenite is a potent inducer of HO-1 mRNA in CELCs. In LMH cells, 75 μM sodium arsenite gave a peak induction of HO-1 mRNA (3.9-fold) at 4 hours (Figure 4.9). The highly reproducible, robust induction of HO-1 mRNA expression by arsenite provides a reliable system to study the promoter elements and signaling mechanisms involved. The HO-1 promoter-luciferase reporter constructs were tested for responsiveness to sodium arsenite to define regions of the promoter that may be responsible for the induction effects. Although arsenite induced several constructs, the highest folds of induction were observed for pCHO5.6-Luc and pCHO7.1-Luc (Figure 5.4).

**Identification of putative transcriptional elements potentially involved in modulating HO-1 gene expression.** The MacVector® analysis program was used to identify putative transcription factor binding site sequences within the cHO-1 promoter region. Many putative transcriptional elements are present in the proximal 7.1 Kb promoter region of the chicken HO-1 gene that was subcloned into pGL3 basic. Figure 5.5 diagrams several potential candidates...
Figure 5.3: Dose- and time-dependence of induction of pCHO7.1-Luc by sodium arsenite. LMH cells were transfected with pCHO7.1-Luc plasmid DNA approximately 48 h prior to treatment. Cells were treated with increasing concentrations of arsenite for 8 hours (A), or with 75 μM arsenite for increasing lengths of time (B). Harvest and assays were performed as described in Methods. Luciferase activity (relative light units, RLU) was normalized to β-galactosidase activity and protein content. Data represent mean + SEM, n=3. *Significantly greater than control (No treatment), P<0.001.
Figure 5.4: Sodium arsenite induces cHO-1 promoter reporter constructs.
LMH cells were transfected with deletion construct and pPGK-βgal plasmids approximately 48 hours prior to treatment. Cells that received treatment were exposed to 75 μM sodium arsenite for 6 hours prior to harvest. Harvest and assays were performed as described in Methods. Data represent mean ± SEM, n=3. *Significantly greater than no treatment and other constructs containing less than 3.6 Kb of HO-1 promoter, P < 0.001. †Significantly less induction than 5.6 and 7.1 Kb constructs.
Normalized Activity (Fold of untreated control)

- No Treatment
- + 75 μM ARS
Figure 5.5: Computer generated map of putative consensus transcription elements in the proximal 7.1 Kb of the chicken HO-1 promoter. The MacVector® software package was utilized to search for several putative transcription factor binding sites in the 7132 bp cHO-1 promoter sequence. The program was set up to search previously identified nucleic acid subsequences that were likely to be utilized by stimuli known to modulate HO-1 gene expression. Among the elements identified were: metal responsive element (MRE), activator protein 1 (AP-1), core B heme responsive/AP-1 element (coreB/AP-1) \(^{87}\), oncogene c-myc/max heterodimer binding site (Myc/Max), antioxidant response element (ARE), purine rich binding site (Pu box), cyclic AMP responsive element binding site (CREB), an octamer site (Octamer), and a GC box binding site (Sp1). Each element and its corresponding symbol, except for Sp1, are represented on the right side of the figure. The Sp1 site is labeled above the promoter representation. The deletion constructs are aligned with the element map to allow comparison of the elements present in each construct.
for elements that may modulate cHO-1 gene expression in response to treatments that lead to increased transcription of HO-1 mRNA.

Some evidence has suggested that gene induction by sodium arsenite is mediated through an AP-1 element. Guyton et al. found that arsenite treatment increased nuclear extract binding to an AP-1 element in the GADD153 (CHOP) gene promoter. In LMH cells transfected with cHO-1 deletion constructs, increased induction by arsenite correlated with the presence of putative AP-1 consensus sites in the distal promoter (Figure 5.4).

Several putative consensus AP-1 elements were identified in the 7135 bp sequence of cHO-1 promoter region by the subsequence search function of the MacVector® software program. The role of the three most proximal AP-1 sites (located at -1578, -3656, and -4597 bp) as transcriptional elements that modulate HO-1 gene expression in response to arsenite was investigated by: 1) testing the effects of arsenite on both negative and positive control plasmids, and 2) by introducing specific base pair mutations in these sites in the context of selected reporter gene constructs.

**Effects of arsenite on AP-1 control plasmid expression.** Two control plasmids were obtained to investigate transcriptional modulation by AP-1 elements in LMH cells. The negative control plasmid was GAL4-Luc, a construct containing the luciferase gene cassette under control of the yeast GAL4 promoter. The positive control plasmid was 4xTRE-Luc, a construct containing the luciferase gene cassette under control of 4 consecutive TPA-
responsive AP-1 elements. Each construct was transfected into LMH cells that were left untreated or treated with arsenite or the phorbol ester, TPA, and luciferase activity was measured (Figure 5.6). Since these constructs were tested for activation in a chicken hepatoma cell line, the yeast GAL4 promoter was unable to promote treatment-induced expression of the luciferase gene (Figure 5.6). In contrast, the 4xTRE-Luc construct was activated by both treatments, with a 6.2 fold induction by arsenite and an 8.4 fold induction by TPA (Figure 5.6).

Role of AP-1 sites in arsenite induction of cHO-1 reporter plasmids. The role of an AP-1 site as a transcriptional element that may modulate HO-1 gene expression in response to arsenite was investigated. For initial studies, the reporter construct pCHO2.5-Luc, which contains a single consensus AP-1 element located at -1578 base pairs, upstream of the transcription start site was used. The role of this AP-1 site in transcriptional activation was studied by making site-directed mutations in 2 out of 7 base pairs, as illustrated in Figure 5.7A. Two separate mutants were made and tested for their ability to be induced by treatment with arsenite (Figure 5.7B). Both mutant 1 and mutant 2 were incapable of being induced by arsenite treatment. Common transcription factor dimer pairs that bind to AP-1 elements are Jun/Jun, Fos/Jun, or ATF/Jun. The role of these dimer pairs in arsenite induction of HO-1 was studied by co-transfecting a dominant negative c-Jun with the wild type pCHO2.5-Luc. The
Figure 5.6: Arsenite induction of a luciferase reporter construct driven by exogenous AP-1 elements. LMH cells were transfected with GAL4-Luc or 4xTRE-Luc plasmid DNA for approximately 48 hours prior to treatment. Cells were left untreated or treated with 0.1 \( \mu \text{M} \) TPA for 6 hours or 75 \( \mu \text{M} \) sodium arsenite for 6 hours prior to harvest. Harvest and assays were performed as described in Methods. Data represent mean \( \pm \) SEM, \( n=3 \). *Significantly greater than no treatment control, \( P < 0.01 \).
**Figure 5.7:** Involvement of an AP-1 element in sodium arsenite-mediated HO-1 expression. (A), The pCHO2.5-Luc HO-1 promoter-luciferase reporter construct (created with the Tth 111 I site at -2519 bp of the HO-1 promoter) contains an AP-1 site at -1578 base pairs. Site directed mutants 1 and 2 contain different two-base changes, indicated in **bold** and **underlining**. Abbreviated recognition sites are designated as follows: Tth 111 I (T), Nhe I (N), Pml I (P), Eco RI (E). The diagram at the bottom of the figure represents the wild type or mutant AP-1 constructs by: solid bar for wild type, or for mutants, a 1 or 2 on the bar indicating the mutation made at that location. (B), LMH cells were transfected with wild type pCHO2.5-Luc, either alone, or in combination with TAM67 (dominant negative c-Jun), or with mutant 1 or mutant 2, and pPGK-βgal. Following transfection, cells were left untreated or treated with 75 μM ARS for 6 hours. Luciferase activities were normalized to β-galactosidase activities and protein content. Data are presented as mean fold induction versus untreated control + SEM, n=3. *Significantly greater than wild type, P < 0.05.*
A

TGAGTCA
TTCGCTCA
GAGGTCG

wild type
mutant 1
mutant 2

TATA Box (-26)
cHO-1 txn (+1)

Xho I (+54)

Tth 111 I
(-2519)
pCHO2.5-Luc
pCHO2.5mut1-Luc
pCHO2.5mut2-Luc

B

No Treatment
+ 75μM ARS

Normalized Activity
Fold of untreated control

Wild type
Mutant 1
Mutant 2
Wild type +dom. neg. c-Jun
dominant negative c-Jun blocked the arsenite induction of luciferase reporter
gene activity.

To further investigate possible cooperativity among the three putative
consensus AP-1 elements, two additional reporter plasmids were mutated. The
deletion constructs, pCHO4.6-Luc, which encompasses two of the AP-1 sites
(Figure 5.8), and pCHO5.6-Luc, containing all three proximal AP-1 sites (Figure
5.9), were used as templates for single, double, or triple AP-1 mutants. The
mutations made at -1578 bp are the same as those represented in Figure 5.7A
for the pCHO2.5-Luc mutants. The two bases that were mutated in the AP-1
elements at -3656 and at -4597 bp were the same and are shown for the -3656
bp site at the top of Figure 5.8.

The pCHO4.6-Luc series of AP-1 mutants, and the resulting fold
induction of luciferase activity of each mutant in response to arsenite treatment
are shown in Figure 5.8. Additionally, the pCHO4.6-Luc wild type construct was
also co-transfected with a dominant negative c-Jun. The pCHO5.6-Luc series of
mutants, and resulting fold inductions by arsenite are shown in Figure 5.9.
When LMH cells were transfected with the mutant constructs and tested for
arsenite induction of luciferase activity, all mutants except for pCHO5.6mut13-
Luc had lowered activities as compared to the wild type construct (Figures 5.8
and 5.9). Some single mutations decreased arsenite reporter gene activity to a
similar extent as double mutations or the triple mutation. All three AP-1
elements were necessary for the full response to arsenite. No single AP-1
Figure 5.8: Mutation of AP-1 sites decreases responsiveness of pCHO4.6-Luc to arsenite. The pCHO4.6-Luc promoter reporter plasmid (created with the Pml I site at -4575 bp of the HO-1 promoter) was used as a template for site-directed mutagenesis of AP-1 sites located at -3656, or -1578 bp upstream of the transcription start site. Mutation of the AP-1 site was done by mutating two base pairs out of seven, as indicated at the top of the figure. The mutated bases are shown in **bold** and *underlining*. Double mutants were made by using pCHO4.6mut3-Luc as template for mutations at -1578, which were the same as for mutations of pCHO2.5-Luc, shown in Figure 5.7A. The bars represent the wild type or mutant AP-1 constructs by: solid bar for wild type, or for mutants, a 1 or 2 on the bar at -1578, indicating which mutation was made at that location, and a 1 at the -3656 site for constructs containing the mutation listed at the top of the figure. The primers and template for each mutant plasmid are listed in Table 2.1 in Methods. LMH cells were transfected with wild type or mutant plasmids approximately 48 hours prior to treatment. Additionally, one set of transfections included wild type pCHO4.6-Luc and a dominant negative c-Jun plasmid, TAM67. Cells were left untreated, or treated with 75 μM sodium arsenite for 6 h. Harvest and assays were performed as described in Methods. Fold inductions (arsenite treated versus untreated) are presented beside the bar representing each construct. Data represent mean ± SEM, n=3.

*Significantly less than wild type, P < 0.01. †Significantly less than wild type, P < 0.05.
TGAGTCA
TGAGGAA

wild type
mutant 3

-3656

-1578

TATA (-26)
cHO-1
txn (+1)

Xho I (+54)

P
N
B
E
T
N
T
EP

Fold Induction by 75 μM Arsenite

pCHO4.6-Luc 3.34 ± 0.43
pCHO4.6 mut1-Luc 1.78 ± 0.12 *
pCHO4.6 mut2-Luc 2.04 ± 0.16 *
pCHO4.6 mut3-Luc 1.09 ± 0.10 *
pCHO4.6 mut1 3-Luc 1.15 ± 0.09 *
pCHO4.6 mut2 3-Luc 1.39 ± 0.15 *
pCHO4.6-Luc + dom. neg. c-Jun 1.29 ± 0.22 *
Figure 5.9: Mutation of AP-1 sites decreases responsiveness of pCHO5.6-Luc to arsenite. The pCHO5.6-Luc promoter reporter plasmid (created with the Pfl MI site at -5605 bp of the HO-1 promoter) was used as a template for site-directed mutagenesis of AP-1 sites located at -1578 (mutants 1 and 2), -3656 (mutant 3), or -4597 (mutant 4) bp upstream of the transcription start site. Mutation of each AP-1 site was done by mutating two base pairs out of the seven consensus bases, as indicated at the top of Figure 5.9 for the site at -3656 bp. Mutations at -1578 bp were the same as those of pCHO2.5-Luc, as shown in Figure 5.7A. The bars represent the wild type or mutant AP-1 constructs by: solid bar for wild type, or for mutants, a 1 or 2 on the bar at -1578, indicating which mutation was made at that location, a 1 at the -3656 site in constructs containing the mutation listed at the top of Figure 5.8, and a 1 at the -4597 site in constructs containing a mutated AP-1 at this site. The primers and template for each single, double, or triple mutant plasmid are listed in Table 2.1 in Methods. LMH cells were transfected with wild type or mutant plasmids approximately 48 hours prior to treatment. After transfection, cells were left untreated, or treated with 75 μM sodium arsenite for 6 h. Harvest and assays were performed as described in Methods. Fold inductions (arsenite treated versus untreated) are presented beside the representation for each plasmid. Data represent mean ± SEM, n=3. *Significantly less than wild type, P < 0.05. †Significantly less than wild type, P < 0.01. ‡Significantly less than wild type, P < 0.001.
mutation completely blocked induction by arsenite, and different combinations of double mutations displayed similar abilities to block arsenite induction. These data are consistent with some level of cooperativity in the response to arsenite among the AP-1 elements that were tested. When one or two AP-1 elements were mutated, the remaining wild type AP-1 element(s) continued to modulate at least a partial response to arsenite. However, since some activation was still observed even when all three AP-1 sites were mutated, either there was still some binding causing activation at these sites, or other transcriptional elements may also be involved in producing the full response to arsenite. Arsenite induction of both pCHO2.5-Luc and pCHO4.6-Luc was significantly lowered when co-transfected with dominant negative c-Jun. These experiments implicate a role for at least one AP-1 element in the sodium arsenite-mediated induction of HO-1 gene expression.
Conclusions

In summary, arsenite induces both endogenous HO-1 mRNA and transfected HO-1 promoter-driven luciferase gene expression. A series of promoter reporter plasmids with selected deletions in the promoter region was used to explore the region of control. The results of studies using control AP-1 plasmids supported the hypothesis that AP-1 elements were involved in arsenite-mediated regulation of HO-1 expression. Experiments in which cHO-1 reporter constructs containing mutated AP-1 elements were shown to be less responsive to arsenite treatment provided further evidence that arsenite modulates HO-1 gene expression by activating AP-1 transcription factor complexes. Together, these data implicate AP-1 as one of the transcription factors that contribute to the majority of the arsenite-mediated induction of HO-1 gene expression.

The data presented in this chapter present a reliable model system that was used to investigate the transcriptional control of cHO-1 gene expression by the cellular oxidant and tumor promoter, sodium arsenite. The major findings of this study are: sodium arsenite is a potent inducer of both endogenous HO-1 and transfected HO-1 promoter-reporter constructs, and AP-1 elements are involved in transcriptional activation of HO-1 by arsenite. However, given the complexity of the HO-1 promoter, and the residual activity of AP-1 mutant constructs, it is likely that other transcription factor elements are also involved in
the modulation of HO-1 gene transcription. Two more AP-1 elements located further upstream were not tested by mutational analysis. These elements, as well as other transcription factor binding sites located further upstream (beyond the sequence of the reporter constructs tested here), may account for the lower induction of reporter constructs as compared to endogenous HO-1 mRNA in LMH cells. The deletion reporter constructs and subsequent mutations described here provide useful tools for further investigations into the transcriptional regulation of cHO-1 by many chemicals or other perturbations.
CHAPTER VI
ROLE OF MAP KINASES IN SODIUM ARSENITE-MEDIATED
INDUCTION OF HEME OXYGENASE-1

Introduction

As previously described, HO-1 is an inducible enzyme that catalyzes
heme degradation and has been proposed to play a role in protecting cells
against oxidative stress-related injury. The induction of HO-1 by the tumor
promoter sodium arsenite was investigated in the chicken hepatoma cell line,
LMH. In the previous chapter, a cHO-1 promoter driven luciferase reporter
construct that was reproducibly induced to high levels (at least 4-fold) in
response to sodium arsenite treatment was identified. This construct, pCHO7.1-
Luc was used to investigate the role of mitogen-activated protein (MAP) kinases
in arsenite-mediated HO-1 gene expression.

The effects of diverse factors on HO-1 gene expression appear to be
regulated at the transcriptional level, suggesting that multiple signal
transduction pathways mediate induction of HO-1 gene transcription in
response to a multitude of cellular stimuli. The MAP kinases are
serine/threonine protein kinases that have been shown to be activated under
conditions similar to those that induce HO-1 transcription, e.g., following
exposure of cells to phorbol ester, cytokines, ultraviolet light, heat shock, LPS,
ceramide, and inducers of oxidative stress \textsuperscript{110,123-130}. MAP kinases are components of signaling cascades which, in response to extracellular stimuli, target transcription factors, resulting in the modulation of gene expression. Three major MAP kinase subfamilies that mediate physiological responses were investigated: Extracellular signal regulated kinase (ERK), c-Jun N-terminal kinase (JNK), and p38 (a homologue of the yeast HOG1 kinase).

Arsenite-mediated activation of MAP kinases \textsuperscript{110,123,131,157-159} has been demonstrated, however, a cellular gene response to this activation has not been described. Both arsenite \textsuperscript{37,118,159,160} and the MAP kinase signaling cascades \textsuperscript{139,140} have been shown to target AP-1 elements. Data presented in Chapter V (Figures 5.7 - 5.9) support the involvement of AP-1 in the arsenite-mediated induction of HO-1.

In this study, transient co-transfection assays were used to investigate the mechanism of arsenite-mediated HO-1 gene expression. In LMH cells, sodium arsenite, cadmium and heat shock, but not heme, induced activity of the MAP kinases extracellular-regulated kinase (ERK), c-Jun N-terminal kinase (JNK), and p38. To examine whether these MAP kinases were involved in mediating HO-1 gene expression, constitutively activated and dominant negative components of the ERK, JNK, and p38 MAP kinase signaling pathways were utilized. Activated components of the ERK and p38 MAP kinase signaling pathways increased gene expression from an HO-1 promoter-driven luciferase reporter gene construct. A p38 inhibitor, a MEK inhibitor, and dominant
negative components of the ERK and p38 MAP kinase pathways were able to block nearly all of the arsenite-mediated induction of HO-1. In contrast, for the JNK pathway, activated components were unable to induce HO-1 gene expression, and dominant negative components were unable to block arsenite induction. These experiments demonstrate a role for the ERK and p38 MAP kinase families in the sodium arsenite-mediated induction of HO-1 gene expression.
Results

Arsenite activates MAP kinases in LMH cells. The ability of heme, sodium arsenite, cadmium chloride, and heat shock to activate ERK, JNK, and p38 was assessed in LMH cells. Cells were treated with 20 μM heme, a known inducer of endogenous HO-1; 75 μM sodium arsenite, a potent inducer of both endogenous HO-1 and HO-1 reporter gene constructs; 1.5 μM cadmium chloride, a known metal inducer of HO-1; or exposed to heat shock (at 43°C) for 0, 30, or 60 minutes. Immune complex kinase assays were performed to detect changes in MAP kinase activity (Figure 6.1). Treatment with sodium arsenite increased the activity of all three MAP kinases. In contrast, cadmium and heat shock caused only slight increases in ERK and p38 activities, and heme had no effect on any of the MAP kinases in LMH cells. To further characterize the arsenite-mediated activation of the MAP kinases, a more detailed time course was performed (Figure 6.2). The peak activation times observed for arsenite exposure were 10 minutes for ERK, 20 minutes for p38, and 45 minutes for JNK.

Induction of pCHO7.1-Luc by components of MAP kinase signaling cascades. To link activation of MAP kinases with the induction of HO-1 gene expression, several expression constructs encoding constitutively activated or dominant negative components of the MAP kinase signaling pathways were co-transfected with the pCHO7.1-Luc reporter construct (Figure 6.3). The constitutively activated MAP kinase components would be expected to increase
Figure 6.1: Effects of heme, sodium arsenite, cadmium chloride, or heat shock on MAP kinase activity in LMH cells. Cells were treated with 20 μM heme, 75 μM sodium arsenite, 1.5 μM cadmium chloride, or exposed at 43°C (heat shock) for 0, 30, or 60 minutes prior to harvest. (A), Immune complex kinase assays were performed for ERK (top), JNK (middle), and p38 (bottom). Bands indicate phosphorylated substrates: GST-Elk1 for ERK, GST-cJun for JNK, and GST-ATF2 for p38. Lane 14 was left empty, Lane 15 was a positive control (EGF treated LMH cell lysate for ERK, and UV-treated LMH cell lysates for JNK and p38). (B-D), Data from immune complex kinase assays were quantitated with the aid of a PhosphorImager and plotted as time courses of ERK, JNK, or p38 MAP kinase activation.
<table>
<thead>
<tr>
<th>Time (Minutes)</th>
<th>Lane</th>
<th>MW Marker</th>
<th>20 μM Heme</th>
<th>75 μM Arsenite</th>
<th>1.5 μM Cadmium</th>
<th>43°C Heat Shock</th>
<th>+ control</th>
</tr>
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<tbody>
<tr>
<td></td>
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<td>4</td>
<td>5</td>
<td>6</td>
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ERK (Elk-1)

JNK (c-Jun)

p38 (ATF2)
Figure 6.2: Time course of MAP kinase activation by sodium arsenite. LMH cells were treated with 75μM ARS for the indicated times. Cell lysates were harvested and immune complex kinase assays specific for ERK, JNK, and p38 MAP kinases were performed. Data are plotted as fold induction relative to untreated control values.
Figure 6.3: Effect of selected MAP kinase pathway components on luciferase reporter gene activity in LMH cells co-transfected with pCHO7.1-Luc.

Constitutive activators of ERK MAP kinase (MEK1S218E-S222D and MEK1ΔN3-S218E-S222D), JNK MAP kinase (MEKK1), and p38 MAP kinase (MKK6S207E-T211E) were tested for their ability to induce reporter gene activity. Dominant negatives of the ERK pathway (MEK1K97A), JNK pathway (MEKK1K432A), and p38 pathway (M KK6S207A-T211A) were also tested. LMH cells were co-transfected with pCHO7.1-Luc, pPGK-βgal, and the indicated MAP kinase construct using LipoFECTAMINE®. Luciferase activities were normalized to β-galactosidase activities and protein content. Data represent mean + SEM, n=3. *Significantly greater than control (pCHO7.1-Luc only), P < 0.005.
reporter gene activity if the downstream MAP kinases are involved in transducing cellular signals that control HO-1 gene expression. Constitutively activated forms of MEK1 (the kinase immediately upstream of ERK), MEKK1 (a kinase proposed to act upstream of JNK), and M KK6 (a kinase upstream of p38) were tested for their abilities to induce luciferase gene expression from pCHO7.1-Luc. Activated MEK1 and M KK6 were able to induce reporter gene expression, while no induction was observed for MEKK1 (Figure 6.3). As expected, all dominant negative components failed to affect basal levels of luciferase expression from pCHO7.1-Luc.

Involvement of the ERK signaling cascade in arsenite induction of HO-1.

To investigate the role of ERK in arsenite induction of HO-1, several ERK pathway components (Ras activated and dominant negative, Raf wild type and activated, MEK1 activated and dominant negative, and wild type ERK2) were co-transfected with pCHO7.1-Luc, then left untreated or treated with arsenite. If the ERK pathway was important for arsenite signaling, an activated component of the pathway would be expected to increase luciferase gene activity in the absence of arsenite, whereas the dominant negative construct would be expected to block the ability of arsenite to induce luciferase activity from the reporter gene. As shown in Figure 6.4, the activated Ras, Raf, and MEK1 components all increased luciferase gene activity, indicating each component led to induction of HO-1 gene expression. Dominant negative Ras and MEK1
Figure 6.4: Effects of ERK signaling pathway components on reporter gene activity in LMH cells co-transfected with pCHO7.1-Luc. Wild type Raf, ERK2, or constitutive activators of Ras (Ras 61L), Raf (Raf-BXB), and the ERK pathway (MEK1S218E-S222D) were tested for their ability to induce reporter gene activity. Dominant negatives of Ras (Ras 17N), and the ERK pathway (MEK1K97A) were tested for their ability to block arsenite induction of the reporter gene. LMH cells were co-transfected with pCHO7.1-Luc, pPGK-βgal, and the indicated MAP kinase construct using LipoFECTAMINE®. Luciferase activities were normalized to protein content. Data represent mean ± SEM, n=3. *Significantly greater than untreated, P < 0.01. †Significantly greater than untreated control (pCHO7.1-Luc only), P < 0.01. §Significantly greater than arsenite treated control, P < 0.005.
also decreased induction by arsenite treatment. The wild type ERK2 and wild
type Raf gave results similar to the pCHO7.1-Luc only control.

A role for ERK in arsenite-mediated HO-1 expression was supported by
another experiment in which ERK activity was blocked using an inhibitor
(PD98059) specific for MEK1, the kinase immediately upstream of ERK. This
inhibitor (See Appendix D for structure) has been shown to be highly specific
(IC_{50} of 2-7 \mu M) and noncompetitive with respect to the ATP binding site of
MEK1^{144-147}. Immunoprecipitated ERK2 from cells treated with PD98059 for 30
minutes prior to receiving arsenite was incapable of phosphorylating the
substrate Elk-1. Dose response analysis of the effects of the MEK inhibitor on
ERK activity demonstrated inhibition of arsenite activation of ERK (Figure 6.5A).
The role of ERK in arsenite induction of pCHO7.1-Luc was then probed using
PD98059. As shown in Figure 6.5B, at 30 \mu M the inhibitor blocked
approximately 60\% of the arsenite induction of the HO-1 reporter gene.

**JNK MAP kinase is not implicated in arsenite induction of chO-1.**

Possible involvement of JNK in HO-1 induction by arsenite was studied by co-
transfecting components of the JNK pathway with pCHO7.1-Luc. If JNK was an
important intermediate in the pathway to HO-1 induction, wild type constructs
would be expected either to increase luciferase reporter activity or to give
results similar to control, while dominant negative components would block the
arsenite increase in reporter gene activity. Figure 6.6 shows that wild type JNK,
MEKK1, or MLK3 resulted in luciferase gene activity levels similar to control.
Figure 6.5: Effects of the MEK inhibitor, PD98059, on ERK activity and arsenite-mediated induction of HO-1. LMH cells were left untreated or treated with the indicated concentrations of MEK inhibitor. Some samples received 75μM ARS 30 minutes after addition of inhibitor. (A), Cells were harvested 10 minutes after addition of ARS (40 minutes after inhibitor) and ERK activity was measured by immune complex kinase assays. Data was quantitated with a PhosphorImager and plotted as a dose response curve. [Insert: PhosphorImager scan of the kinase assay gel; M - SDS-PAGE low molecular weight protein standard, Lane 1: No treatment, Lane 2: 75 μM ARS only, Lane 3: 10 μM PD only, Lanes 4 - 8: 75 μM ARS plus increasing concentrations of PD (1, 5, 10, 20, 30 μM), Lane C: EGF treated LMH cell lysates as positive control]. (B), Prior to treatment, cells were transfected with pCHO7.1-Luc, and pPGK-βgal. Cells were harvested 6 hours after addition of ARS (6.5 hours after inhibitor). Luciferase activities were normalized to β-galactosidase activities and protein content. Data represent mean + SEM, n=3. **Significantly less than ARS only control, P < 0.005. *Significantly less than ARS only control, P < 0.001.
A

ERK Activity (Phosphoimager Units)

PD98059 (µM)

O Inhibitor alone
- PD98059 + 75µM ARS

B

Normalized RLU (RLU/µg prot.)

PD98059 (µM)

O Inhibitor Alone
- PD98059 + 75µM ARS
Figure 6.6: Effects of JNK signaling pathway components on reporter gene activity in LMH cells co-transfected with pCHO7.1-Luc. Wild type JNK, and activators of the JNK kinase pathway (MEKK1 and MLK3) were tested for their ability to induce reporter gene expression. Dominant negative JNK MAP kinase pathway components (MEKK1 K432A and MLK3 K144R) were tested for their ability to block arsenite induction of the reporter gene. LMH cells were co-transfected with pCHO7.1-Luc, pPGK-βgal, and the indicated MAP kinase construct using LipoFECTAMINE®. Luciferase activities were normalized to β-galactosidase activities and protein content. Data represent mean + SEM, n=3.

* Significantly greater than untreated control, P < 0.05.
However, in contrast to the results for ERK components, arsenite treatment continued to increase luciferase gene activity in the presence of co-transfected dominant negative MEKK1 or MLK3.

**Involvement of p38 MAP kinase in arsenite induction of the cHO-1 gene.**

In Figure 6.3, an ERK component (MEK), or a p38 component (M KK6), demonstrated the ability to induce luciferase reporter activity. To further delineate a role for p38 in arsenite signaling, a p38 kinase specific inhibitor (SB203580) was tested for the ability to block arsenite induction of HO-1 gene expression. SB203580 is a pyridinyl imidazole (See Appendix D for structure) that specifically binds to p38 kinase with a 1:1 stoichiometry, and competitively inhibits the binding of ATP with a $K_i$ of 21 nM and an $IC_{50}$ of 42 nM$^{150-152}$. Figure 6.7A shows the effects of SB203580 on arsenite induced HO-1 mRNA levels in LMH cells. When cells were pretreated with inhibitor at 20 μM for 30 minutes prior to arsenite treatment, the ability of arsenite to increase HO-1 mRNA levels was decreased to only 47% of the control (no inhibitor). The inhibitor alone caused no significant change in HO-1 mRNA levels.

Since both kinase inhibitors (PD98059 for MEK in Figure 6.5B and SB203580 for p38 in Figure 6.7A), blunted arsenite-mediated induction of HO-1, the combined action of both the MEK and p38 inhibitors on expression of the pCHO7.1-Luc reporter gene was further investigated (Figure 6.7B). Cells were treated with MEK inhibitor, p38 inhibitor, or both, either alone or 30 minutes prior to arsenite treatment. The MEK inhibitor blocked 48%, and the p38
**Figure 6.7:** Effects of inhibitors of MAP kinase pathways on HO-1 gene expression in LMH cells. (A), LMH cells were treated with the indicated concentrations of p38 kinase inhibitor (SB203580) alone, or 30 minutes prior to addition of 75 μM ARS. Cells were harvested 4 hours after addition of ARS (4.5 hours after inhibitor). HO-1 mRNA was quantitated on dot blots and normalized to GAPDH. Data represent mean + SEM, n=3. *Significantly less than control (ARS only), P < 0.01. (B), Prior to treatment, cells were transfected with pCHO7.1-Luc, and pPGK-βgal. After transfection, cells were treated with either 30 μM MEK inhibitor (PD98059), or 20 μM p38 inhibitor (SB203580), or both, 30 minutes prior to addition of 75 μM ARS. Cell lysates were harvested 6 hours after addition of ARS (6.5 hours after inhibitor(s)). Luciferase activities were normalized to β-galactosidase activities and protein content. Fold inductions versus no ARS control are presented. Data represent mean + SEM, n=3. *Significantly greater than no ARS control, P < 0.005. †Significantly less than ARS treated pCHO7.1-Luc, P < 0.001. §Significantly less than ARS treated pCHO7.1-Luc, P < 0.01.
inhibitor blocked 68% of the arsenite-mediated increase in luciferase gene activity. This pattern of inhibition is consistent with the patterns of p38 and ERK activation by arsenite (Figure 6.2). Because p38 is activated to a greater extent than ERK (Figure 6.2), it is not surprising that inhibition of arsenite induction by the p38 inhibitor was greater than by the MEK inhibitor. When added in combination, both inhibitors also strongly inhibited (84% inhibition) the increase in luciferase gene activity.
Conclusions

The major findings described in this chapter are: 1) sodium arsenite activates the MAP kinases ERK, JNK, and p38 in LMH cells; 2) activated components of the ERK and p38 MAP kinase pathways are capable of inducing HO-1 gene expression, while dominant negative components block arsenite induction of HO-1; and 3) inhibitors of MEK and p38 differentially inhibit the arsenite induction of HO-1.

Arsenite potently induced both endogenous HO-1 and transiently transfected HO-1 reporter constructs in LMH cells, making this a good system for studying the arsenite-mediated cellular stress response. The results described in this chapter show that there are clear differences between the activation pathways of arsenite and the other treatments tested (heat shock, cadmium, and heme), since all of these conditions elicited different patterns of MAP kinase activation (Figure 6.1).

Some researchers have proposed that heme induces HO-1 by a stress-mediated mechanism\textsuperscript{28,49,74,94,111,169}. However, in kinase assays, heme, at concentrations that strongly induce endogenous HO-1, failed to activate any of the MAP kinases (Figure 6.2). Therefore, since heme induces endogenous HO-1 in LMH cells\textsuperscript{75}, it is likely to do so via a non-MAP kinase-mediated pathway. This is consistent with the results of Cable et. al.\textsuperscript{76}, who proposed that heme induces HO-1 through a pathway not involving a stress-mediated mechanism.
In LMH cells arsenite activates ERK, JNK, and p38 (Figures 6.1 and 6.2), in agreement with the studies done by Liu et al. in Rat-1 and PC-12 cells\textsuperscript{131}.

Activated components of the ERK pathway, (Ras, Raf, MEK), and an activated component of the p38 pathway (MKK6) were able to induce luciferase gene expression from the pCHO7.1-Luc reporter construct (Figure 6.3). In contrast, MEKK1 and MLK3, components upstream of JNK, were not capable of inducing expression of this HO-1 promoter-reporter construct (Figures 6.3 and 6.6). MEKK1 has been reported to activate a number of kinases, including JNK, IкB kinase, and ERK in some experimental systems (but only when overexpressed)\textsuperscript{162,190,191}. Since MEKK1 was unable to induce luciferase gene expression, these pathways of activation are not likely to be involved in mediating the arsenite induction of HO-1. Experiments involving dominant negative components of the ERK and p38 pathways, and the inhibitors of MEK (PD98059) and p38 (SB203580), also provided strong evidence that these two pathways play essential roles in HO-1 gene expression in the presence of arsenite. The combination of MEK and p38 inhibitors was unable to completely block the arsenite induction of pCHO7.1-Luc reporter gene expression. Due to amplification in kinase signaling pathways, a small amount of active kinase may account for the induction observed in the presence of both inhibitors (Figure 6.7). However, arsenite signaling is complex, and may also utilize a pathway that does not involve a phosphorylation event. These results suggest that ERK
and p38 mediate the MAP kinase induction of HO-1, and that JNK is unlikely to be involved.

In summary, arsenite induced MAP kinases that are involved in cellular responses to mitogens and cellular stressors. Disruption of the ERK or p38 MAP kinase pathways by dominant negative components or inhibitors blocked nearly all of the arsenite-mediated induction of HO-1. In contrast, JNK did not seem to play a role in mediating the induction of the HO-1 gene by arsenite.
CHAPTER VII
CONCLUSIONS

Summary and Discussion

Heme metabolism and its regulation were studied in the chicken hepatoma cell line, LMH. LMH cells exhibited regulation of ALA synthase mRNA levels and heme biosynthesis, analogous to that observed in normal chicken hepatocytes. Porphyrin overproduction and accumulation were observed in response to treatment with chemicals that are routinely used for induction in models of porphyria. HO-1 mRNA and activity levels were characterized and correlated with those observed in primary CELCs. Some minor differences were observed in the efficacies of cobalt and arsenite treatments and in the effects of iron chelation on LMH cell metabolism. For the first time, an induction of HO-1 mRNA in CELCs was observed in response to heat shock. Regulation of heme degradation by prototypic inducers and by treatments that cause oxidative stress was studied. These data support the use of LMH cells for further investigation into the regulation of heme metabolism.

HO-1 is induced by a wide array of chemical and physical agents. However, very few studies have been done previously to elucidate the signaling mechanisms utilized by these stimuli. Some evidence has suggested that at least two separate mechanisms of induction exist, one that is heme-dependent,
and another (mediated by transition metals) that is heme-independent, but the exact mechanism of signal transduction from the cell surface through second messengers to transcription factors and promoter elements was not delineated.

In Chapter V, HO-1 gene expression in response to sodium arsenite was examined in detail. Studies using transfected HO-1 deletion constructs showed that robust induction by arsenite correlated with the presence of putative AP-1 consensus sites in the distal promoter. Site-directed mutagenesis of these elements revealed an important role for AP-1 transcription factor elements (located at -1578, -3656, and -4597 base pairs upstream of the cHO-1 transcription start site) in the arsenite-mediated induction of HO-1.

The role of MAP kinases as mediators of the arsenite induction of HO-1 was examined. Several investigators have presented evidence that arsenite activates the MAP kinases in several cell lines. All three MAP kinase families activate transcription factors that target AP-1 sites. Transfection of LMH cells with plasmids containing constitutively activated and dominant negative components of each MAP kinase pathway suggested that ERK and p38, but not JNK, modulate most of the arsenite-mediated induction of HO-1. From studies using stably transfected PC12 and transiently transfected Rat-1 cells, Liu et. al. suggested that the cellular response to arsenite is partially regulated by a Ras-dependent mechanism and partially by a Ras-independent mechanism. A response involving both the Ras-dependent ERK, and the Ras-independent p38 pathways (as observed here) is consistent with this result.
Additionally, the recently described MAP kinase, ERK5, is proposed to be activated via a Ras-dependent but Raf independent pathway\textsuperscript{193}.

Several possible mechanisms through which arsenite activates both ERK and p38 provide an explanation for cooperative activation of HO-1 gene induction: 1) ERK and p38 may target transcription factors that bind to separate promoter elements required for the tightly controlled expression observed for HO-1; 2) ERK and p38 may activate transcription factors that bind to a single promoter element; or 3) ERK and p38 may target a shared downstream kinase. AP-1 elements are potential targets for the combined action of ERK and p38. ERK can increase c-Fos expression \textit{in vitro}, while p38 activates ATF2, and also increases c-Fos expression. Each kinase activating one of its substrates would lead to formation or activation of AP-1 transcription factor complexes\textsuperscript{122,132,135,140,194,195}. In a recent study by Numazawa \textit{et al.}, c-Fos protein expression and ERK activation were shown to be involved in glutathione depletion-mediated oxidative stress induction of HO-1 in human fibroblasts\textsuperscript{119}. There are also several other putative promoter elements (Myc/Max, CREB, and STAT3 sites) present in the cHO-1 distal promoter region that may serve as targets for transcription factors activated by MAP kinases (See Figure 5.5).

Another explanation, requiring multiple mechanisms of MAP kinase activation for the full response to arsenite, may involve effects of this chemical on phosphatase activities. Although evidence presented here supports a role for ERK and p38 in HO-1 expression, these studies do not exclude the
possibility that the activity of one or both of these MAP kinases may be increased through phosphatase inhibition, in addition to or instead of activation of their upstream kinase cascades. Phosphatases have critical sulfhydryl residues that are susceptible to the type of oxidation mediated by arsenite. Inhibition of phosphatases may also lead to an increase in MAP kinase activity. In a study of MAP kinase activation by arsenite, Cavigelli et al.\textsuperscript{150} suggested that arsenite may stimulate AP-1 transcriptional activity by inhibiting a JNK phosphatase. A model representing several possible mechanisms for induction of HO-1 by arsenite is presented in Figure 7.1.
**Figure 7.1:** Possible mechanisms for induction of HO-1 by sodium arsenite.

Most of the arsenite-mediated induction of HO-1 gene expression is transduced by the ERK and p38 MAP kinase pathways (indicated by heavy arrows). Inhibitors that were used to elucidate ERK and p38 involvement are represented by X's through arrows (PD98059, specific inhibitor of MEK; SB203580, specific inhibitor of p38). MNK1/2 is a possible site for cooperation between the ERK and p38 pathways. Also shown at the bottom of the figure are possible mechanisms for cooperation by transcription factors activated by ERK and/or p38.

The remainder of the arsenite signal may be transduced by several other mechanisms as shown. Arsenite activated JNK in LMH cells, but effects on HO-1 gene expression were not observed (light arrows). By inhibiting a MAP kinase phosphatase (MKP) as suggested by Liu et al.\textsuperscript{150}, arsenite may increase MAP kinase activity (indicated by interrupted arrows, ---). This possibility is illustrated for the JNK pathway, but is applicable to other MAP kinases as well. Alternatively, a signaling mechanism that does not involve MAP kinases may be utilized (indicated by dashed arrows, ------). This mechanism may be phosphorylation dependent (other protein kinases) or it may be a pathway that is independent of phosphorylation events. The question marks represent the unknown effects of JNK activation by arsenite (?), and possible signaling through pathways that do not involve MAP kinases (?). \[\mathbf{P}\] = Phosphorylation event.
Sodium Arsenite

Ras → Raf → MEK1/2 → MKK6 → MEKK1/MLK3 → JNK → JNK-P → MKP → non-P

PD98059

ERK

SB203580

p38

MNK1/2

Transcription Factors

Other Kinases

Transcription Factors

? → ?

HO-1
Future Directions

The data presented here support the use of the LMH chicken hepatoma cell line as a good model system for studies involving the regulation of the major enzymes involved in heme biosynthesis and degradation. Other facets of the regulation of heme metabolism may be elucidated through long-term studies and stable transfections, which are now possible using LMH cells.

The sequence reported in Appendix E contains 7.1 Kb of the HO-1 promoter. Several HO-1 promoter luciferase reporter gene deletion constructs were prepared, and their responsiveness to arsenite was characterized. In addition, three putative AP-1 elements were mutated and tested for induction by arsenite. The plasmids and assay system developed throughout the research presented in Chapters V and VI provide useful tools that will facilitate the elucidation of promoter elements and signaling mechanisms utilized by the multitude of stimuli that increase HO-1 gene expression.

Additionally, these studies link two major research fields. Research directed at elucidating the physiological consequences of MAP kinase activation by stress-causing stimuli has emerged concurrently with research directed at delineating the larger role of HO-1 as a cellular stress response protein. In particular, HO-1 has been shown to play a role in protecting cells and tissues from oxidative stress brought about by ischemia/reperfusion\textsuperscript{196,197}, hypoxia\textsuperscript{116}, tissue damage\textsuperscript{198}, hypertension\textsuperscript{199}, and physical stress\textsuperscript{200}. 
Arachidonic acid and cyclooxygenase metabolites have also been implicated as inducers of HO-1\textsuperscript{201}. The effects of these treatments on MAP kinase activation and phosphorylation of MAP kinase substrates also have been elucidated recently\textsuperscript{130,202,203}. When considered together, these studies conceptually link the activation of MAP kinases with induction of HO-1 as integral players in an elaborate cellular stress responsive mechanism.

Although the data presented in Chapter VI indicate that both ERK and p38 MAP kinases are modulators of HO-1 gene expression in response to arsenite, the entire signaling pathway has yet to be delineated. Activity of MAP kinases is maintained by a balance between phosphorylation by upstream kinases and dephosphorylation by dual-specificity and tyrosine phosphatases\textsuperscript{143,204-207}. Therefore, MAP kinase activity may be increased either by activation of upstream kinases or by inhibition of regulatory phosphatases. One study by Cavigelli\textit{et al.} suggested that arsenite induced JNK activity in HeLa cells by inhibition of a JNK phosphatase\textsuperscript{159}. Further investigation into a phosphatase inhibition mechanism for HO-1 induction is necessary to delineate the contribution of phosphatases to arsenite induction of HO-1.

This work provides a solid foundation for further research, which may investigate: 1) upstream components of the pathway leading from arsenite through MAP kinases to HO-1 gene expression, 2) other non-MAP kinase signal transduction pathways (phosphorylation dependent or independent) that mediate arsenite induction of HO-1, 3) other HO-1 promoter elements or targets.
of MAP kinases after activation by arsenite, and 4) a possible indirect role for JNK in HO-1 gene expression.


responsible for uroporphyrinogen oxidation induced by AH receptor ligands in chicken liver and kidney. Drug Metab. and Disposition 25, 779-783.


## APPENDIX A: MEDIA AND BUFFERS

### Media

**Comparison of Waymouth's and Williams' E Media:**

<table>
<thead>
<tr>
<th>Component</th>
<th>Waymouth's MB 752/1 Medium, powder</th>
<th>Williams' Medium E (1), powder</th>
</tr>
</thead>
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<tr>
<td><strong>Amino Acids:</strong></td>
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<td>(mg/L)</td>
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<td>L-alanine</td>
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<td>30</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>-</td>
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<td>26.07</td>
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<tr>
<td>L-cystine•2HCl</td>
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<td>50</td>
</tr>
<tr>
<td>L-glutamic acid</td>
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</tr>
<tr>
<td>L-glutamine</td>
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<td>50</td>
</tr>
<tr>
<td>Glycine</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>L-histidine</td>
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<td>-</td>
</tr>
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<td>L-histidine•HCl•H2O</td>
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<td>L-serine</td>
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</tr>
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<td>L-threonine</td>
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<td>L-tryptophan</td>
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<td>CaCl2 (anhyd.)</td>
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<td>200</td>
</tr>
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<td>Unit</td>
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<td>----------</td>
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<td>CuSO₄·5H₂O</td>
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</tr>
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</tr>
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<tr>
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<td>0.5</td>
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<td>1</td>
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<tr>
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</tr>
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<tr>
<td>choline chloride</td>
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<tr>
<td>folic acid</td>
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<tr>
<td>i-inositol</td>
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<tr>
<td>menadione sodium</td>
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</tr>
<tr>
<td>bisulfate</td>
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<td>niacinamide</td>
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<td>pyridoxine·HCl</td>
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<td>1</td>
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<tr>
<td>thiamine·HCl</td>
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<tr>
<td>vitamin A acetate</td>
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<td>0.2</td>
</tr>
<tr>
<td>vitamin B12</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Williams’ E Medium Complete was supplemented with:
   1.5 μM 3,5,3'-triiodo-L-thyronine
   0.76 μM dexamethasone
   200 μM glutamine

Waymouth’s MB 752/1 Complete Medium was supplemented with:
   100 U/mL penicillin
   100 μg/mL streptomycin
   10% (v/v) fetal bovine serum (GIBCO)

Opti-MEM Reduced Serum Media was purchased as a liquid from Life Technologies, Inc. No modification or supplementation was made.
Buffers

Phosphate Buffered Saline (PBS):
10 mM KPi
0.15 M KCl
Adjust to pH 7.4

10X HEPES buffer:
200 mM HEPES
50 mM sodium acetate
10 mM EDTA
pH to 7.2 with NaOH
Filter to sterilize

20X SSC:
3.0 M NaCl
0.3 M sodium citrate
Adjust to pH 7.0 with 10 N NaOH
Autoclave to sterilize

Harvest Buffer (HO Activity assays):
0.1 KPi, pH 7.4
20% glycerol
1.0 mM EDTA
Adjust to pH 7.4

TE Buffer:
10 mM Tris•Cl, pH 7.4, 7.5, or 8.0
1 mM EDTA, pH 8.0

Z Buffer (β-galactosidase assays):
60 mM Na₂HPO₄ • 7 H₂O
40 mM NaH₂PO₄ • H₂O
10 mM potassium chloride
1 mM magnesium sulfate
50 mM β-mercaptoethanol
Adjust to pH 7.0
Glycylglycine Harvest Buffer (Immune complex kinase assays):
25 mM glycylglycine, pH 7.8
15 mM magnesium sulfate
4 mM EGTA
1 mM DTT *(added just prior to use)

Triton Lysis Buffer (Immune complex kinase assays):
20 mM Tris, pH 7.4
137 mM NaCl
25 mM β-glycerophosphate
2 mM sodium pyrophosphate
2 mM EDTA
1 mM sodium vanadate *
1% Triton X-100
10% glycerol
1 mM PMSF *
5 μg/mL leupeptin *
5 μg/mL aprotinin *
2 mM benzamidine
0.5 mM DTT *
*(added just prior to use)

Kinase Assay Buffer (Immune complex kinase assays):
25 mM HEPES pH 7.4
25 mM β-glycerophosphate-Na⁺
25 mM magnesium chloride
0.1 mM sodium vanadate *
0.5 mM DTT *
*(added just prior to use)

3X SDS Loading Buffer:
150 mM Tris•Cl (pH 6.8)
300 mM DTT
6 % SDS (electrophoresis grade)
0.3 % bromophenol blue
30% glycerol
Bicinchoninic Acid Protein Assay Stock Reagents:

Solution A:
- 161 mM sodium carbonate • H2O
- 5.67 mM sodium potassium tartrate
- 113 mM sodium bicarbonate
- 75 mM sodium hydroxide
- 3.63 mM bicinchoninic acid
  pH adjusted to 11.25 with NaOH

Solution B:
- 160 mM cupric sulfate

Working reagent:
- 50 mL Solution A
- 1 mL Solution B
  Mixed well, used within 1 week
### APPENDIX B: PREPARATION OF CHEMICALS FOR CELL CULTURE

<table>
<thead>
<tr>
<th>Treatment:</th>
<th>Abbreviation:</th>
<th>Dose in culture:</th>
<th>Preparation:</th>
</tr>
</thead>
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<td>γ-aminolevulinate</td>
<td>ALA</td>
<td>10 μL/mL medium, 18 μM final</td>
<td>0.587 mg/mL ALA in water</td>
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<tr>
<td>Cadmium Chloride</td>
<td>CdCl₂</td>
<td></td>
<td>0.22 mg/mL CdCl₂•2H₂O in water</td>
</tr>
<tr>
<td>Cobalt Chloride</td>
<td>CoCl₂</td>
<td>10 μL/mL medium, 200 μM final</td>
<td>1.79 mg/mL CoCl₂•6H₂O in water</td>
</tr>
<tr>
<td>Deferoxamine</td>
<td>DFO</td>
<td>25 μL/mL medium, 250 μM final</td>
<td>6.5 mg/mL DFO in water</td>
</tr>
<tr>
<td>Ferric nitrilotriacetic acid</td>
<td>FeNTA</td>
<td>10 μL/mL medium, 50 μM final</td>
<td>1 mL of 4.05 mg/mL FeCl₃ in water</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 mL of 14.2 mg/mL NTA in water</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3 mLs of water</td>
</tr>
<tr>
<td>Glutethimide</td>
<td>Glut</td>
<td>1 μL/mL medium, 50 μM final</td>
<td>10.8 mg/mL glutethimide in DMSO</td>
</tr>
<tr>
<td>Heme</td>
<td>methemalbumin</td>
<td>260 μL/3 mL medium, 20 μM final</td>
<td>100 μL of 6.5 mg/mL hemin in DMSO dilute into 3.9 mLs 1.1% BSA in 40 mM Tris pH 7.4</td>
</tr>
<tr>
<td>Hydrogen Peroxide</td>
<td>H₂O₂</td>
<td>1 μL/mL medium, 0.5 mM final</td>
<td>5 mM stock = dilute 8.22 M:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 μL in 17.64 mL MilliQ</td>
</tr>
<tr>
<td>Lipopolysaccharide</td>
<td>LPS,E.coli 0127:B8</td>
<td>1 μL/mL medium, 1.5 μg/mL final</td>
<td>1.5 mg/mL stock = 1.5 mg LPS in 1.0 mg MilliQ</td>
</tr>
<tr>
<td>Sodium Arsenite</td>
<td>NaO2As,ARS</td>
<td>45 μL/mL medium, 75 μM final</td>
<td>5 mM stock = 6.495 mg in 10 mL MilliQ sterile filter</td>
</tr>
<tr>
<td>TMH-ferrocene</td>
<td>TMH-F</td>
<td>1 μL/mL medium, 5 μM final</td>
<td>1.63 mg/mL in DMSO</td>
</tr>
</tbody>
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# APPENDIX C: LIST OF PLASMIDS

<table>
<thead>
<tr>
<th>NAME OF PLASMID</th>
<th>Contains:</th>
<th>Reference or Source:</th>
</tr>
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<tbody>
<tr>
<td>MAP Kinase, Vectors, and Control Plasmids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pCMV/HA-ERK2</td>
<td>wild type ERK</td>
<td>Whitmarsh <em>et al.</em>^156</td>
</tr>
<tr>
<td>pSRα/HA-JNK1</td>
<td>wild type JNK</td>
<td>Dérijard <em>et al.</em>^164</td>
</tr>
<tr>
<td>pCMV5/MEK1</td>
<td>constitutively activated MEK1</td>
<td>Mansour <em>et al.</em>^161</td>
</tr>
<tr>
<td>S218E-S222D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pCMV5/MEK1ΔN3,</td>
<td>constitutively activated MEK1</td>
<td>Mansour <em>et al.</em>^161</td>
</tr>
<tr>
<td>S218E-S222D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pCMV5/MEK1 K97A</td>
<td>dominant negative MEK1</td>
<td>Mansour <em>et al.</em>^161</td>
</tr>
<tr>
<td>pCDNA3/MKK6</td>
<td>constitutively activated MKK6</td>
<td>Raingeaud <em>et al.</em>^166</td>
</tr>
<tr>
<td>S207E-T211E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pCDNA3/MKK6</td>
<td>dominant negative MKK6</td>
<td>Raingeaud <em>et al.</em>^166</td>
</tr>
<tr>
<td>S207A-T211A</td>
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<td></td>
</tr>
<tr>
<td>pCMV5/MEKK1</td>
<td>wild type MEKK1</td>
<td>Whitmarsh <em>et al.</em>^163</td>
</tr>
<tr>
<td>pCMV5/MEKK1 K432A</td>
<td>dominant negative MEKK1</td>
<td>Whitmarsh <em>et al.</em>^163</td>
</tr>
<tr>
<td>pCDNA3/HA-MLK3</td>
<td>wild type MLK3</td>
<td>Teramoto <em>et al.</em>^165</td>
</tr>
<tr>
<td>pCEF2/MLK3 K144R</td>
<td>dominant negative MLK3</td>
<td>Teramoto <em>et al.</em>^165</td>
</tr>
<tr>
<td>pCDNA1/TAM67</td>
<td>dominant negative c-Jun</td>
<td>Rapp <em>et al.</em>^168</td>
</tr>
<tr>
<td>pCMV5-Ras61L</td>
<td>constitutively activated Ras</td>
<td>Wartmann and Davis^167</td>
</tr>
<tr>
<td>pCMV5-Ras17N</td>
<td>dominant negative Ras</td>
<td>Wartmann and Davis^167</td>
</tr>
<tr>
<td>pCMV5-Raf-Flag</td>
<td>epitope tagged wild type Raf</td>
<td>Wartmann and Davis^167</td>
</tr>
<tr>
<td>pCMV5-Raf-BXB</td>
<td>constitutively activated Raf</td>
<td>Wartmann and Davis^167</td>
</tr>
<tr>
<td>GAL4-Luc</td>
<td>luciferase gene driven by yeast GAL4 elements</td>
<td>Roger Davis</td>
</tr>
<tr>
<td>4xTRE-Luc</td>
<td>luciferase gene driven by 4 TPA-responsive elements</td>
<td>Roger Davis</td>
</tr>
<tr>
<td>pBLUESCRIPT KS II+</td>
<td>DNA filler in transfections</td>
<td>Commercial</td>
</tr>
<tr>
<td>pSV-βgal</td>
<td>β-galactosidase w/SV40 promoter</td>
<td>Commercial</td>
</tr>
<tr>
<td>--------------------------</td>
<td>---------------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>pPGK/β-gal</td>
<td>β-galactosidase w/PGK promoter</td>
<td>Paul Dobner</td>
</tr>
<tr>
<td>pGL3-Control</td>
<td>Luciferase vector w/SV40 promoter and enhancer</td>
<td>Gregorio Gil Promega</td>
</tr>
<tr>
<td>pGL3-Basic</td>
<td>Luciferase vector w/no promoter or enhancer</td>
<td>Gregorio Gil Promega</td>
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**Chick Heme Oxygenase-1 Promoter Reporter Constructs**

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<thead>
<tr>
<th>pCHO.TATA-Luc</th>
<th>HO-1/luciferase reporter gene</th>
<th>Kim Elbirt</th>
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<tbody>
<tr>
<td>pCHO0.6-Luc</td>
<td>HO-1/luciferase reporter gene</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO1.6-Luc</td>
<td>HO-1/luciferase reporter gene</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO2.5-Luc</td>
<td>HO-1/luciferase reporter gene</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO3.6-Luc</td>
<td>HO-1/luciferase reporter gene</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO4.6-Luc</td>
<td>HO-1/luciferase reporter gene</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO5.6-Luc</td>
<td>HO-1/luciferase reporter gene</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO7.1-Luc</td>
<td>HO-1/luciferase reporter gene</td>
<td>Kim Elbirt</td>
</tr>
</tbody>
</table>

**AP-1 Mutants of pCHO-Luc Deletion Constructs**

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<thead>
<tr>
<th>pCHO2.5mut1-Luc</th>
<th>single AP-1 mutation</th>
<th>Kim Elbirt</th>
</tr>
</thead>
<tbody>
<tr>
<td>pCHO2.5mut2-Luc</td>
<td>single AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO4.6mut1-Luc</td>
<td>single AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO4.6mut2-Luc</td>
<td>single AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO4.6mut3-Luc</td>
<td>single AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO4.6mut13-Luc</td>
<td>double AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO4.6mut23-Luc</td>
<td>double AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO5.6mut1-Luc</td>
<td>single AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO5.6mut2-Luc</td>
<td>single AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO5.6mut3-Luc</td>
<td>single AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO5.6mut4-Luc</td>
<td>single AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO5.6mut13-Luc</td>
<td>double AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO5.6mut14-Luc</td>
<td>double AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO5.6mut24-Luc</td>
<td>double AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO5.6mut34-Luc</td>
<td>double AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
<tr>
<td>pCHO5.6mut134-Luc</td>
<td>triple AP-1 mutation</td>
<td>Kim Elbirt</td>
</tr>
</tbody>
</table>
APPENDIX D: STRUCTURES OF MAP KINASE INHIBITORS

PD 98059
2-(2'-amino-3'-methoxyphenyl)-oxanaphthalen-4-one, Inhibitor of MAPK/ERK Kinase (MEK)

SB203580
Pyridinyl Imidazole inhibitor of p38 MAP Kinase
APPENDIX E: SEQUENCE OF HO-1 PROMOTER

In the following sequence, restriction enzyme cut sites are underlined. Sites that define the end of a reporter construct (shown in Figure 5.1) are indicated in bold type, followed by construct length in Kb in parentheses. All putative transcription factor binding sites are italicized and underlined. Activator protein-1 (AP-1) sites that were mutated in functional studies of arsenite responsiveness are labeled AP-1*mut, are underlined and shown in bold type. The TATA box is underlined and shown in italicized bold type, and is labeled (+1). Numbering of bases is in reference to the transcription start site = +1.

5'  
ACGGCTAGA GTGGGCTTCC AGCCCTCTGC CTGGCTGCTGT TAGCCTGGAA -7023  
Mlu I-Nhe I/Xba I(7.1)  
AGCAAAAGGG GTACGACACA TTACAGGCAG CAGAGGAAAA ACACATATGG -6973  
Pu Box  
CAATGGAAACC CTATTGCTCT AGCTTTTCTTT GCACAAGTGC TTTGTGATG -6923  
CAGCACCCTCT CACCAAAACC CTTCTCCTCC TTTCCCTACC ATCAGTTTAT -6873  
CTGGAAATCCT ACCCACAGCC GTGTGGCCCG TTGCGATGCC GGCAGTTACC -6823  
AAAGCCCTTG TAAGCACAAC GGCCTTTTGAC TGCGAGTTGT AGCAGCCTTG -6773  
CAGGCTGAAG GGGCTGCTGT CTGGGCTGTTA GGTTGTGCGT TCAGCAAACCT -6723  
CTGGCACTGT ACCCGGTTCTC TTGCTGGCTCC GTTGCAGTGG GCACGTATGC -6673  
ATTCTTCAC GATCTCTTGC CCTTGGGCTT CACCGTGCTC TGTCGTGAGG -6623  
TGTTGACTCC CTGGTGCCCC TAGCAGAGAG CTGTGTTCCC TAAAGCAGGA -6523  
GGCCCTCATA GCCACCTCTA CACTGGGTGG AGCATGCTGT TGCTGGGAGA -6473  
GCTGGTTCAA GTCGTTGAGC GCAGGGGGG AGTGAGAGCA TCAGGACATCT -6423  
CGGAAACAGCA AAGCAGCCCCT ACAGCAGCCA GGAGTGACTT GCACATGGGG -6373  
GAGAAACCCC TTCTGAGCAA ACCACAACA GTGCTGATCT CTGTACGGCA -6323  
GCTGGGAGAG TGGGTGCGGA GCCTGGGGT CCCTGGCTGATG GAGATTTCTCTG MRE  
TTGAACCTGG GAGAAGTTGCC TTTTTATTG CACATTAAG GAGCAAAACTC -6223
TTGAACCTCT GCTGAAGGAA CGTGTGTGTT CTGTGCCAGA GTGGGAAGG -6173
GAGAAGAGGA ATGCAGCCCA GTGGCCACAT TTGCTCTCCA AGTGAGAGCA -6123
CAGTGGGTCT GAGAGGAGGC ATGCGATGGG GCTGAGGCGG CTGTAGTGCA AP-1
AGACAGGTGC TGCTCCTGGA GGAGGTGCTT CCAAACCATC CCAAAATAGC -6023
AAGAGAGTGA GCTACCCTCT CCCATCCCCT TCCCCCTCTGC GCTTGACCA -5973
GACCCCAATG CACATCTCAA TCCATAAATC AGCCAAAGAC ATGCAAGAAA -5923
CAGTTGCTCT GAAAGGGCCT TGTTGTATCC ACAGCATGTC CTCAGAGTCC -5873
TCAGCTGTCC CTGTGCTATC CCTGTTGTA GACCGGGTG GAGCTTGAAA -5823
AGCCCTCCGG AGTGGTGAGG TCGCATCCTC GGAGGTGTTG AAAGAACCGTG -5773
TGATG TGGC ACTGAGGGGC ATGGTGCAAGG AGCCGGTG GGATGGGCTG -5723
ATGGTTGGAC CGGCAGATCT TAGAGCTTTT TTCCAACCTT AATTCTATGG -5673
TCCAATGATT CGTGGATTAA AAAAAAA AAAAAACCGA CCCCCATAAGG -5623
CTGTCTCCGT ATTTCTCCCA GCAGATGGCT GTAGTGCTCT GCAGCTTTGC -5573
AGCCTGAGCT CTGCAAGCCG CAGAGGAAGC CCTCTTGCTT CGCAGTGACC -5523
GCCTTAGAGC AGCCCTGCTT ACACAGGACA CCGAACAACA CAAAGTTGTTG -5473
CTTGTGTCTA GGAATTACAC TGCAACCTTT AGCCTGACAC AGACTCACAC -5423
GGTGACCGCT CCGGAGCGTG CACATGGGAG CTGTGTGCAC ACGGGGGCTG -5373
AAGCATCCAT CAAAACCCAC CTCGAGGAGCA GAGCATGAC CAACTAGCAC -5323
CCTTTTGCAAT TGCCGGAGTG CTGTTTTTTA TGTAAGCTGA AAAAGCCCAG -5273
Octamer AACGTCTTGT CGCCGGTTCA GATTTGCTC TTATCTCTAA AAATTAACCG -5223
CATATTTAAA GCTCATGAGA ATTTCCCTGA TGTTTTGGGT CTGTCTTTCT -5173
Octamer TGGCATATCA GCAACCACATT CCTCAAGGCA AAAATCCCA ACTCAAATAG -5123
CACATGAAAT TTTATTTATA AGAAACAGTTA ATGAACCGAT CTTCCTGATTT -5073
CCCACATCAT CTCACTGATT ACAGCAAGAG TACCCCTTGC TGGTACACTG -5023
GGAAGGCTGT TCTCTACCCC ACAGAATTTT CATTTGCTC TACCGTGCCA -4973
Octamer
AATCTTCCTC AAAGCTTTTG CCTGGTAAAGC TCCATAAGTT CAGCAGTGCCC -4923
Hind III
TGTTGTGGCA CTTCTGAAATA AAAAGCTCTT TTGCACTCAGT TGTGTCTTCTG -4873
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ATCACCAGCA TCTGGTGCTA GACCTCTAAA CCCACAGGCT TCTGGGTGAG -4723
GGTTCCTCA AAGATGCTGAC TCACTCCTCC CCAAGAGGCC CATTCTGCTG -4673
AGTCAGGGTC ACGCCAGGCC ACGGGTTTTT GCTGAGCAAC GCTTCTGGGC -4623
coreB/AP-1
TGGGGCGAAAG GGCCCTCTAG TTGCTGAGTC ACACCCAGAGA GGGCCAGTGA -4573
coreB/AP-1*mut MycMax/Fml I(4.6)
GGCTGTGTAT CAGGAGCCGC CTTTCTCGGC TGCCGTTGCTG AGGTTCAGGC -4523
Sp I
TGTTGTCTTC GTGCCCTGCTC CGGCTTCTAA GAGAGCCGAG AGAAGATCTCC -4473
AGAAATAAAC CCCACCCCG CAGCAGTCA TGGACGCCG ATCTCTCTAGA -4423
CTCCAGCTGC GAGCCACACA GCGGGGGTGT GGAAGCAGCG GGGTACAGTG -4373
GGTTTCCGCT ACCTGCAAGA CTTGCTTCTC TGCTTCTGCTC CCTGGGCGTC -4323
CCTGAGCTGC GGTACAAAGT CTTGTCGCTG GCCTGCTGAG GATCCCTGCA -4273
ATGCAGCACC TCCACGGCTG CGCCGCTGTC ATGCAAGGTG CACTTTGCTT -4223
CATGAGGAGC TAGGTGGGAT TTGTATTCGC TAGCTTGCTT TGCTCCTTC -4173
Nhe I
CACAACCCTC TTGGTCTCAC AGACCCCAAG CGACCCAGGT GCAGGGTGCT -4123
GTCCACCGCA GCACCGGCC CACACCGAGG CACCATATCA TACATCTGGA -4073
ACAATGCGTA TTGATTACAC CGGCTCCTGA TTCCATCACC CTGAGAACCC -4023
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CTGTACGGTTG GTATTGCAAC TGGGTTGGGT TTTTCCCTCT CCATTACACA -3673
GCAAGATCTG GTTGCTGAGT CAGCCCCCCT CCCAGCCAGG CTGAATTCG -3623
Bgl II(3.6) AP-1*mut
CTTGTCATG GTTTCAGTCC TCCATCAGTT CCCCCCTGC TGGCCAGAAC -3573
Eco RI
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coreB
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AATGCATCAG AGCCAAATGA GAGAGGCTTG TCCAGAAGGC AGGAGAATT -3473
Bgl II
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Pu Box
GAATCATTAA AGTTGGAAG GACTTTAATA AAGTTCTCAG GTCCAACCTCC -3323
CCTGCAAATGA ACAGGGCACC CTCACAGCTC ATCAGGGTCG TCAAGCCCCC -3273
MRE
TCCAGCCTGA CCCCCGGGTTG CTCCAGGGAT AGACCATCCA CCACCTCTCT -3223
GGATGACCCG CTCCAGTTG TTGACTACCTA TATTATTTAA AACTTTTATA -3173
TTTATATCAA CCTAAAATCTC CCCCCATTTA GTTTGAAAATC AAAACCTTCTT -3123
GTCTTATTCT AACAGATCTCT GCTAAAGAGCT GTCGCCCTTT CGATCCATCA -3073
CATTTCCCTT CCCCCATGGG CAACAGTGAC CTCCAGTCTA CTTCGTATGC -3023
TGAAGCTCTAT TCGTTTCCCT TAAACCCATCC CATGACTTTAA ACATTTTCTC -2973
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CTCGAGGAGCA CTGATCAAG CCAGAAAAGC TTCCAGCCAG CAATTGCAAA -2723
Hind III
ACTGATGACA GCGCTGCTTCC AGTTCTCCCT CCATCTCGCT GCAAGGCCCTC -2673
TGGGCTTTTC TGGGATGAGG AACCTGACCT CACAGCCTCT CCCACCTCAG -2623
CREB
TAAACCAACCAAATCCAGG ACAAAACAGT CCTGGGACAT GGTATGCTTC -2573
CCTGCTCTTA TGGAGGAGCT CACAGGAGG GGAAGCTGTC CTTCGCTTCT -2523
GTGACCTTGTT CTCTTGCTGC CATCCACAGA GAAAGCAAAG GCCCAGATGC -2473
Tth 111 I(2.5)
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GAGAGGAAG GCCCTCAAGT TGCAACAAGGG GAGGTTCAAGG TTGGATGTAA -2373
GGAAAAATGT CTCTTCAGGA AGAGCCGCTGC TGCAATGCCA CAGGCTGCAC -2323
AGGGAGGTTG TGAAGTCACT GTGACTCTAT GAGATCTGT GACTATGAGA -2273
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ACAATGGGAT ACCACTCTCT GAGTUTCACCC TCCCATCTA CCTCAGCCCT -2173
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AAAGGGAGAA CATGGTTTGA GGAGGTTAGG TTTTCATATT ATTTCAACT -1973
CATGTAATGA ATATATCATC TGAGTTTCGT ACCTTTTCTT CTTCCCCCCA -1923
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CAGTGAAGAG AGTGAGAAGT GTGCTATAGA CACACGATGC CAGTGGAAAA -1823
TGCTCATTTTC AGAGCCGACG CAGTGGCAA AATGGCAGTA ATATCTTCAG -1773
MR
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AAAATAAGCA GTAAGTGCCC TAGGGTTAAG AGCTAGCTTT TGCTAGAAATG -1623
Nhe I(1.6)
CTCTGTAGCT TTTAAAGGCA GAGCAAGACA GAAAAAGCAT GGCTGAGTCA -1573
coreB/AP-1*mut
GGCTGGGAGC GCTGAGTAAAT CCTCCTCAG TGTGCACAGT GGCCAGATGT -1523
CAGGCCAGCA CAGAGCTGGT TGCGTCACA ATCCCTCCAG GCCACTCCTA -1473
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GCCAGGGGAC AGATAGACAG AAGACTTCCC TTCCAGCCCA CAGCAGCAGG -1373
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TGCCTTCGCC AAGCAGCAGT GAATGATGCA TCTCTCATTC TGTTTGCTGT -1273
STAT3
AGCTTCCAGC GTAGCTTCCAG ATGGAAGAGG GGCCCCACTA CATCTGCAGG -1223
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ARE
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GCTGTTGCAA ATATCTGCAG CCTGCTCTAG TTTCCCCAAA GCCCTGCATC -1073
ACACCTTGGC AGTCTCCTGC ACACAGCAGG TGTGACAACC CCCAGGGTAT -1023
CGGGGGGATG GGCTGCTGGTC CTCCCCCCATC ACCTCACACA CAGTGTCTGCT MRE
CACACGAGGG CCCACATGCC AGCCCAATTC AGTACTTCTG TTGTGTAAGG C/EBP
GAGAAAGGAA AGCATATCCCC TGTGCTCAG TGCAGACGCA CCTGTCAGC -873
ACATGGAAG AATCATAGAG TCATGGAATC ATAGAATCAT TTGAGTGGG -823
AGGGACCTTT AAAGGTCATC TGATCCAAA CCCCTGCAAT GAAACAGGAAT -773
GCCCTAGCT CAGTCAGACA TTGAAAGGAC CTTTAGATAT TGAAGTATCC -723
CAGGAGCCTT CTCTTCTCCA GGCTGAACAG CCCAGCTTCT CTCAGCCTGT -673
CCTTGTGTAAGG AGCTGTTCTCA TCCCTGGGAC CATTCTCTTG GCCCTCTCCT Pfl MI
GGACGCACTC CACGAGATCC ATGCTCCTCC TGTACTGAGG GCTCCACATT -573
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GTCAACCCCC TCTCCCTGCT GCCCACACTC CTTTGGATGC TGCCCCAGGAC -473
ACAGGTGGCT TTCTGGGCGG TGAGGGGCACA CTGCTGGCTC ATGTACAGCT -423
GCCATTCCAT AGTACCCCTCA AGTTCTTTTG GCCAGGGCTG AGCTTTGAGG -373
GTCCCTGCTG CGCTCCCTCTG CGCGAAGCGG GATGTCTCTC ACCCCACAGT NF-κB
TCAGACCTCT CTGGCTCCGGT GGCAGCGGAG CTCCCCGTGC CTGTAAGGCG -273
TCTGAAGAGTG CTCAGAGCTG TGGGTGATAA AACACTGACA CGGCTCTCTT MRE
TCTAGGACAG ATGCTGCAAG AGCTGCAAGT CCTCTGTGGG GTGAGACTGC -173
AGCAGGCGTGT AATTCTCTCT GCCCTCCACAG CGTCCCTCGG GGGGCGGGG -123
GCACACGACT GGGAAAGGAA GGCGACCTG TGCGAACAGG CGTGTGCTCA MRE
CATGAGGCTT GCACCTGCTG TTCTCAGGGT GCCCCCTGAT AATAAGCGTGG MRE/MyeMax/Pml I (TATA) TATA Box
GACAGGCCGC CGGTGACAAA GCGAGCAGCT TACGTCCTCCG GAGAGGCGTGG +28
GAGAGCTCAA GTAAGGAAAAC AACAGGGGAAG CTCGAG -3' Xho I