Studies on mating in the budding yeast

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Studies on mating in the budding yeast

A dissertation presented

by

Lori Bromer Huberman

to

The Department of Molecular and Cellular Biology

in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

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Budding yeast are capable of existing in both a haploid and diploid state. Haploid cells have two mating types, MATα and MATα. When cells from the two mating types come in contact they signal using reciprocal pheromones and pheromone receptors, starting a regulated pheromone response that includes transcription of pheromone-response genes, polarization in the direction of highest pheromone concentration, and cell cycle arrest. Once cells have chosen a mating partner, they must fuse their cell walls, plasma membranes, and nuclei to form a single diploid cell.

We studied two aspects of this process. The first is the role of differentiation in gene expression between MATα and MATα cells in controlling mating type and intercellular communication. We created cells that regulate gene expression like one mating type, but express the pheromone, pheromone receptors, and related genes of the opposite mating type. Through characterization of these cells, we identified a MATα-specific gene that blocks the pheromone produced by MATα cells, which we call AFB1 for a-factor barrier. We also show that while changing the regulation of various genes involved with pheromone induction does not cause sterility, it can greatly reduce mating efficiency, providing insight into the robustness of the pheromone response.

Second, we studied the regulation of cell wall fusion during mating. The cell wall provides an elastic force to resist the turgor pressure of the cell, preventing lysis. During cell
wall fusion, the two cells must dissolve their cell walls specifically at the point of contact without exposing their plasma membranes to the extracellular environment, but the mechanism of this regulation is unknown. We provide support for the hypothesis that cell wall fusion is controlled through contact-limited diffusion of cell wall remodeling enzymes. When cells are unattached, secreted cell wall remodeling enzymes diffuse into the extracellular environment, weakening but not breaching the cell wall. However, when two cells are attached, the cell wall remodeling enzymes become trapped between the cell walls, specifically increasing the concentration of these enzymes at the point of contact, and causing cell wall dissolution.
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CHAPTER 1

Introduction
ABSTRACT

The budding yeast, *Saccharomyces cerevisiae*, is capable of both sexual and asexual reproduction. When two asexually reproducing haploid cells of opposite mating types come in contact they are capable of fusing to form a single diploid. The mating type of a yeast cell is controlled by transcription factors expressed at the *MAT* loci. Cells that express the transcription factors encoded at the *MATa* locus express the pheromone a-factor and the α-factor receptor Ste2 as well as several other *MATa*-specific genes, while cells that express the transcription factors encoded at the *MATα* locus express the pheromone α-factor and the a-factor receptor Ste3 as well as several other *MATα*-specific genes. When *MATa* and *MATα* cells come in contact with one another, they signal through the reciprocal receptors to induce three, interconnected, pheromone-induced responses. The first is the expression of pheromone response genes. The second is arrest in the G1 phase of the cell cycle. The third response is polarization of the cell in the direction of highest pheromone concentration to form a mating projection known as a shmoo. Once two cells have successfully signaled towards each other, they must go through the process of cell fusion, which has four stages. The first stage is agglutination or attachment of the cell walls of the two cells at their shmoo tips. Next, the two cells fuse their cell walls, which must be carefully regulated both spatially and temporally to ensure that cells do not expose their plasma membranes to the extracellular environment and cause osmotic lysis. Once the two cell walls have fused, the cells fuse their plasma membranes to cause cytoplasmic mixing. Finally, the haploid nuclei of the two cells must travel towards each other and fuse to form a single diploid nucleus. Taken together, mating in the budding yeast provides an excellent model system for biological processes important in higher eukaryotes.
INTRODUCTION

The life cycle of the budding yeast, *Saccharomyces cerevisiae*, makes it an excellent model organism. Budding yeast cells have three cell types controlled by the expression of transcription factors at the *MAT* locus, which can be divided into two classes. The first class is haploid. This class has two cell types, called mating types: *MATα* and *MATα*. When separate, the haploids of commonly used lab strains can replicate asexually by going through mitosis and generating daughters that are genetically identical to their mothers. However, when cells of opposite mating types come in contact with each other, they can fuse to become a single diploid cell. This diploid can replicate asexually via mitosis to create identical daughters or, if starved for nitrogen and grown on a non-fermentable carbon source, can sporulate via meiosis and generate four haploid cells – two of each mating type (Figure 1.1). The ability of budding yeast to replicate in both a sexual and asexual fashion and their genetic tractability has made it possible to use them to study many aspects of biology\(^1\)\(^-\)\(^4\). However, we are most interested in the mating of the budding yeast: the process by which two haploid cells fuse to become a single diploid.

In order for two haploid cells to mate, they must first determine that a potential partner exists. To do this, yeast signal through reciprocal pheromones and pheromone receptors\(^5\). The yeast pheromones are small molecules that are secreted from the cell. *MATα* cells secrete the pheromone α-factor, a 12-amino acid, farnesylated peptide\(^6\). *MATα* cells secrete the pheromone α-factor, which is a 13-amino acid peptide without any added moieties\(^7\),\(^8\). These pheromones are ligands for reciprocal pheromone receptors\(^9\),\(^10\). *MATα* cells express the α-factor receptor, Ste2 on their surface\(^9\),\(^11\), and *MATα* cells express the α-factor receptor, Ste3 on their surface\(^10\). The pheromone receptors are G-protein coupled receptors\(^12\) and, when bound to pheromone, signal through their associated G-proteins to activate a mitogen-activated protein (MAP) kinase
Figure 1.1. Life cycle of the budding yeast. Budding yeast can exist in either a diploid or a haploid state. There are two haploid mating types, which can both replicate asexually by proceeding through mitosis. If they are brought in contact with each other, they signal to each other and fuse to form a single diploid. Diploids can replicate asexually by proceeding through mitosis. However, if they are fed a non-fermentable carbon source and starved for nitrogen, they proceed through meiosis, producing four haploid spores – two of each mating type – and starting the process over again. (Modified from A. Murray with permission.)
cascade\textsuperscript{5}, induce cell cycle arrest in G1\textsuperscript{13}, and polarize in the direction of highest pheromone concentration to form a mating projection known as a shmoo\textsuperscript{14,15}. Although the pheromones and receptors differ between the mating types, all signaling downstream of the pheromones and receptors is thought to be the same in \textit{MATa} and \textit{MATa} cells\textsuperscript{5}.

Once two cells have polarized towards each other, they fuse to form a single diploid cell. To do this, cells must fuse three envelopes: the cell wall, the plasma membrane, and the nuclear envelope\textsuperscript{16}. The yeast cell wall is a complex network of proteins and carbohydrates that, among other things, provides an elastic force to resist the turgor pressure that would otherwise cause the cell to lyse\textsuperscript{17}. To fuse the cell walls, both cells dissolve their cell walls at the point of contact while simultaneously fusing the boundaries of the cell walls to form a single, continuous structure. Once a hole has formed between the two cells, the plasma membranes are able to come in contact and fuse, comingling the cytoplasms of the two cells. As the opening between the cell walls increases in size, the two nuclei, which travel to the fusion zone are able to fuse, creating a diploid cell\textsuperscript{16}.

Although many of these processes have been well studied, there are still unanswered questions. We were particularly interested in two aspects of yeast mating. The first, which is described in Chapter 2, centers on the genes required for mating type determination and efficient zygote formation. Much is known about the regulation of mating type from the \textit{MAT} locus\textsuperscript{18}, but we still lack a complete view of the identification and regulation of the mating type-specific genes activated with and without pheromone induction. We were interested in learning more about what these genes are and how they affect mating efficiency. The second question, which is described in Chapter 3, involves cell wall fusion. Specifically, we were interested in investigating the question of how cells regulate cell wall dissolution spatially and temporally
such that cells dissolve their cell walls only at the point of contact with a mating partner. We hope that by investigating these processes, we can increase the body of knowledge surrounding budding yeast mating – a model for many aspects of cell biology in higher eukaryotes.

OVERVIEW OF THE PHEROMONE RESPONSE PATHWAY

MAP kinase cascade

Intercellular signaling between cells of opposite mating types is important for efficient mating and is one of the more well-studied aspects of mating in budding yeast. Signaling is achieved through seven-transmembrane spanning G-protein coupled receptors, which are expressed on the plasma membrane of each cell and serve to bind the pheromones produced by the opposite mating type \(^6,10\). When a G-protein coupled receptor binds the pheromone of the opposite mating type, it goes through a conformational change causing GDP to be exchanged for GTP on Gpa1, the inhibitory α-subunit of the G-protein associated with the pheromone receptors \(^19,20\). In its GTP-bound state, Gpa1 does not associate as tightly with the Gβγ subunits (Ste4 and Ste18, respectively), and they are released \(^21,22\). Once freed from Gpa1, the farnesyl and palmitoyl groups attached to Ste18, the Gγ subunit, associate the Gβγ subunits with the plasma membrane \(^23\), and Ste4 is able to interact with two scaffold proteins, Far1 \(^14\) and Ste5 \(^24\), as well as the p21-activated kinase, Ste20 \(^25,26\). Together these three proteins affect the three general pheromone responses: gene transcription \(^24,27\), cell cycle arrest \(^13\), and positive chemotropism \(^14\) (Figure 1.2).

The pheromone-induced transcriptional response is initiated by a MAP kinase cascade \(^5\), and the Gβγ subunits act, in part, to bring the various parts of the MAP kinase cascade together \(^24,26\). The scaffold protein, Ste5, binds the members of the MAP kinase cascade: Ste11, Ste7, and Fus3, bringing them into close physical proximity \(^28-30\). Ste4 binding to Ste20 and Ste5, in
Figure 1.2. Pheromone response pathway. When a pheromone molecule (α-factor or α-factor) binds the yeast G-protein coupled receptor (Ste2 or Ste3), GDP is exchanged for GTP on the inhibitory Gα subunit (Gpa1) of the G-protein, freeing the Gβγ subunits (Ste4/18) to initiate the pheromone response by binding the two scaffold proteins, Ste5 and Far1, as well as the p21-activated kinase, Ste20. Once in close proximity to Ste11, Ste20, activated by Cdc42, phosphorylates Ste11, which phosphorylates Ste7, which phosphorylates Fus3, causing Fus3 to translocate into the nucleus where Fus3 phosphorylates several targets, including Dig1/2, Ste12, and Far1. Phosphorylated Dig1/Dig2 free the activated Ste12 to induce transcription of pheromone-response genes. Phosphorylated Far1 inhibits the cyclin-dependent kinase (Cdc28/Cln) from initiating START, thus, causing cell cycle arrest. Far1 bound to Cdc24 also translocates out of the nucleus through Msn5. Cytoplasmic Far1 binds to the Gβγ subunits, and Cdc24 activates Cdc42, which, in conjunction with several other proteins, activates polarization of the cytoskeleton in the direction of highest pheromone concentration.
conjunction with the binding of Ste20 and Ste11 by the adapter protein Ste50 ref. 31-33, brings Ste20, which is activated by the small rho-like GTPase Cdc42 ref. 34, 35, physically close enough to facilitate phosphorylation of Ste11 by Ste20 and initiates the MAP kinase cascade 36, 37. Once Ste11 has been phosphorylated, it phosphorylates Ste7 ref. 36, which in turn phosphorylates Fus3 ref. 37, 38.

Fus3 is able to shuttle in and out of the nucleus, and during pheromone stimulation it can be found near the shmoo tip in complexes with Ste5 and the rest of the MAP kinase cascade to be activated via phosphorylation by Ste7 or in the nucleus 39-41, where it binds several targets. To activate the pheromone-induced transcriptional response, phosphorylated Fus3 enters the nucleus and binds to and phosphorylates the proteins Dig1 and Dig2, which act to repress the transcription factor Ste12 in vegetatively growing cells 42, 43. Upon Fus3 binding and phosphorylation, Dig1 and Dig2 are inactivated, freeing Ste12 ref. 42, which in combination with phosphorylation of Ste12 by Fus3 ref. 44, activates Ste12 to initiate transcription of the pheromone-response genes 45. In the nucleus, activated Fus3 also phosphorylates another scaffold protein, Far1 ref. 44, which initiates additional aspects of the pheromone response 14, 46.

**G1 cell cycle arrest**

Activated Far1 is involved with pheromone-induced cell cycle arrest in G1 13, 46, 47. Cell cycle arrest is important for efficient mating 48 so that when nuclear fusion occurs the two nuclei are in the same stage of the cell cycle. Along with its role as a scaffold protein, Far1 also acts as a cyclin-dependent kinase inhibitor through its interactions with the Cdc28/Cln protein complex 47. When phosphorylated by Fus3, Far1 inhibits the kinase activity of the Cdc28/Cln protein complex 49. This reduces the ability of Cln1/2/3 to phosphorylate targets required for
progression into S phase\textsuperscript{49} and the ability of Cln3 to promote the transcription of G1-specific gene targets\textsuperscript{50}.

\textbf{Polarization and shmoo formation}

The karyopherin, Msn5, facilitates Far1 transport from the nucleus to the cytoplasm\textsuperscript{51} where Far1 activates polarization in the direction of highest pheromone concentration by acting as a scaffold protein to bring the polarization machinery to the site of pheromone stimulation\textsuperscript{14}. In response to pheromone, Far1, bound to the guanine nucleotide exchange factor Cdc24\textsuperscript{ref. 52, 53}, exits the nucleus\textsuperscript{54}. Once in the cytoplasm, the Far1-Cdc24 complex binds to Ste4\textsuperscript{ref. 55}, putting Cdc24 in close proximity to the small rho-like GTPase Cdc42\textsuperscript{ref. 14, 34}, which is involved in maintaining cell polarity\textsuperscript{34} and also binds to Ste20\textsuperscript{ref. 56, 57}. Active Cdc42 bound to the activated G\textsubscript{βγ} subunits through Ste20 moves the orientation of the cell from the site of the most recent bud scar to the direction of highest pheromone concentration\textsuperscript{58}. Aside from its role in cell polarity, Cdc42 also helps to activate the kinase activity of Ste20 by binding to the inhibitory CRIB domain of Ste20, enabling activation of the kinase domain\textsuperscript{35}, and, thus, phosphorylation of Ste11\textsuperscript{ref. 27}.

Once cells have established a new site of polarity, Cdc42, together with Cla4\textsuperscript{ref. 59}, Bni1\textsuperscript{ref. 60, 61}, and Gic1 and Gic2\textsuperscript{ref. 62}, signals to reorganize the cytoskeleton. The actions of these and additional proteins cause formation of actin patches\textsuperscript{63} and actin cables\textsuperscript{61} directed towards the site of receptor stimulation, which also polarizes secretion in this direction\textsuperscript{64}. Polarization of secretion is important for shmoo formation because secretory vesicles carry the additional plasma membrane and cell wall remodeling enzymes needed to increase the size of the plasma membrane and cell wall at the location of polarization\textsuperscript{17, 65, 66}. Additionally, it is possible that
Cdc42 is involved in regulating docking and fusion of these vesicles with the plasma membrane\textsuperscript{67, 68}.

The polarization of the actin cytoskeleton is also important for the localization of pheromone receptors at the point of highest pheromone concentration\textsuperscript{69}, which acts to generate positive feedback for polarization towards a strong pheromone source. Polarization of the cell in the direction of highest pheromone concentration is important for efficient mating, enabling the cell to find and choose a mating partner\textsuperscript{70}, and cells are able to polarize in the direction of highest pheromone concentration with a high degree of accuracy\textsuperscript{15, 71}. Once two cells have identified each other as possible mating partners, polarization towards the point of contact ensures that the necessary fusion machinery is present enabling cells to fuse to form a single diploid\textsuperscript{72-74}.

**Attenuation of the pheromone response**

It is important for efficient mating that cells are capable of attenuating the pheromone response\textsuperscript{75, 76}. There are several mechanisms for this. One protein involved is the GTPase activating protein Sst2\textsuperscript{ref. 75, 76}, which serves to activate the GTP hydrolyzing activity of Gpa1\textsuperscript{ref. 77, 78}. This is important both for inactivation of the pheromone response as well as to stop pheromone independent signaling through the pheromone response pathway\textsuperscript{75, 79}. Free Gpa1 has also been shown to have a role in attenuating the pheromone response through interaction with the MAP kinase Fus3\textsuperscript{ref. 80}. A third protein involved in reducing the sensitivity to pheromone induction in $MAT\alpha$ cells only is Bar1, the $\alpha$-factor protease\textsuperscript{75, 76, 81, 82}. By decreasing the concentration of $\alpha$-factor surrounding the $MAT\alpha$ cell, Bar1 can reduce the response to pheromone induction in $MAT\alpha$ cells\textsuperscript{82}.

**CELL FUSION**
Once cells have successfully induced expression of the pheromone response genes, arrested the cell cycle in G1, and polarized towards a potential partner, the two cells must fuse to become a single diploid. The process by which this occurs has four distinct steps: agglutination or attachment of the two cells at their shmoo tips, cell wall fusion, plasma membrane fusion, and nuclear fusion.

**Agglutination**

Agglutination is the process by which two stimulated cells attach at their shmoo tips, and is accomplished by the action of four cell wall proteins: Sag1\textsuperscript{ref. 83, 84}, Aga1\textsuperscript{ref. 85}, Aga2\textsuperscript{ref. 86}, and Fig2\textsuperscript{ref. 87}. Sag1 is a cell wall protein with sequence similarities to immunoglobulins\textsuperscript{88} that is expressed only in \textit{MAT}α cells\textsuperscript{83, 84}. The \textit{MAT}α-specific protein, Aga2, is the ligand for Sag1\textsuperscript{ref. 86, 89}, and the interaction of these two proteins is extremely strong, with a K\textsubscript{D} on the order of \(10^{-9}\) M\textsuperscript{90}. Aga2 does not attach directly to the cell wall, but rather attaches via disulfide bonds to the haploid-specific glycoprophatidylinositol (GPI)-anchored protein, Aga1\textsuperscript{ref. 85, 91}. Deleting any of these proteins has a small to insignificant effect on mating efficiency on solid media, but a significant effect in liquid media\textsuperscript{83-85, 92}.

The role of Fig2, a protein expressed in both \textit{MAT}α and \textit{MAT}α cells\textsuperscript{87}, in mating is somewhat more complex. Along with its role in agglutination, Fig2 is also involved in accurate detection of pheromone gradients, shmoo formation, cell fusion\textsuperscript{87}, and pheromone-induced invasive growth\textsuperscript{93}. Additionally, cells deleted for \textit{FIG2} show decreased viability when pheromone stimulated and during mating, particularly when the osmolarity of the extracellular environment is decreased\textsuperscript{94}. In contrast to simple agglutinins, \textit{fig2Δ} cells show an increased mating efficiency in liquid media and a slightly decreased mating efficiency on solid media\textsuperscript{87}. In its role as a mating agglutinin, the presence of Fig2 seems to be able to compensate for mutations...
in the other three mating agglutinins\textsuperscript{93}. However, deleting all of the mating agglutinins in given cell type causes a significant mating defect even on solid media\textsuperscript{93}.

**Cell Wall Fusion**

Even after cells have successfully attached by their shmoo tips via mating agglutinins, their plasma membranes are still separated by their cell walls, a distance greater than 200nm\textsuperscript{95}. To proceed, the cell wall that lies between the two membranes must be dissolved, and the boundaries of the remaining cell walls, which surround the site of cell fusion, must fuse to form a single, continuous structure that will surround the newly formed zygote\textsuperscript{16}. This spatially regulated cell wall dissolution and fusion is a dangerous task because of the osmotic pressure differential between the cytoplasm and the extracellular environment\textsuperscript{96, 97}. If the cell wall is opened at the wrong time or in an inappropriate location, exposing the plasma membrane directly to the environment, there will be no elastic force to resist the turgor pressure of the cell, water will rush into the cell from the extracellular environment, and the cell will lyse\textsuperscript{96, 97}.

Because of the inherent dangers in this process it seems reasonable to assume that it is tightly regulated, and a significant amount of work has been done to investigate this. Mutations in genes involving cell fusion tend not to cause sterility, particularly when there is one wildtype partner, making screening for them difficult. However, a significant number of proteins have been implicated in cell wall fusion (Figure 1.3). One of these is the membrane-spanning protein, Fus1\textsuperscript{ref. 98, 99}. Fus1 is localized to the shmoo tip during pheromone-stimulation\textsuperscript{98} by the exomer complex component, Chs5\textsuperscript{ref. 100, 101} and lipid rafts at the plasma membrane\textsuperscript{72}, and has been hypothesized to act as a scaffold protein that stabilizes the localization of fusion machinery at the fusion zone\textsuperscript{102}. 

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Figure 1.3. Cell wall fusion. During the pheromone response, the cellular localization of Fus2 is dependent on Cla4, which localizes Fus2 to the nucleus in S, G2, and M phases, and Fus3, which activates cytoplasmic localization of Fus2 in response to pheromone. Cytoplasmic Fus2 associates with Rvs161, which may bind secretory vesicles. Fus2 travels along actin cables in a Myo2-dependent fashion, presumably with Rvs161 and secretory vesicles, to the shmoo tip, where Fus2 binds the scaffold protein Fus1, and together with GTP-bound Cdc42, is hypothesized to stimulate the secretory vesicles to release their cargo (believed to be cell wall remodeling enzymes) into the cell wall. Fus1 also binds the polarisome, which is necessary for tight clustering of the secretory vesicles, and Sho1, which inhibits glycerol production to allow for cell wall fusion.
Efficient fusion requires high levels of pheromone production\textsuperscript{66}, osmotic regulation\textsuperscript{96}, and polarization of vesicles at the fusion zone\textsuperscript{66,103}. Although Fus1 is not known to be necessary for pheromone production and secretion, it is involved in both osmotic regulation\textsuperscript{102} and polarization of vesicles at the fusion zone\textsuperscript{103}.

Cells that cannot regulate the amount of internal glycerol present in their cytoplasm have cell fusion defects, implicating the high-osmolarity glycerol response as a regulator of cell fusion\textsuperscript{96}. Through an interaction with the osmosensor, Sho1\textsuperscript{ref. 104}, Fus1 negatively regulates glycerol production and promotes cell fusion\textsuperscript{102}. There are several reasons that the regulation of glycerol production might be important during mating. One is that cells whose internal osmolarity more closely matches that of the extracellular environment may be able to proceed through cell wall fusion in a safer fashion. Another possibility is that cells need to reduce the internal osmotic pressure in order to allow the two shmoo tips to flatten and make a larger region of cell wall apposition, which could act both to increase the safety of cell wall fusion and to increase the concentration of secreted cell wall remodeling enzymes that build up in this region by increasing the diffusional path length these enzymes must travel prior to exiting the cell wall.

When prezygotes are observed using electron microscopy, it is possible to see a large number of vesicles tightly clustered around the fusion zone\textsuperscript{66}. In \textit{fus1} mutants, the vesicles are largely absent, indicating that Fus1 is involved with localization of these vesicles to the fusion zone\textsuperscript{103}. When mutations are made in \textit{SPA2}, a member of the polarisome\textsuperscript{105} that is involved in cell fusion\textsuperscript{106}, the vesicles are present but dispersed, indicating that Spa2, and perhaps the entire polarisome, is involved in vesicle clustering\textsuperscript{103}. In the double \textit{fus1 spa2} mutant, vesicles are largely absent from the fusion zone and the ones that are there are dispersed\textsuperscript{103}. Fus1 also interacts with Bni1\textsuperscript{ref. 102}, another member of the polarisome\textsuperscript{105} involved in cell fusion\textsuperscript{106}.  

The tight polarization of vesicles at the fusion zone is a complex and highly regulated process. During pheromone stimulation, transcription of pheromone-induced genes can occur in any stage of the cell cycle. However, it is important that cell fusion only occur during G1 so that the ploidy of the nuclei is the same. To at least partially control this, the localization of Fus2, another protein involved in cell wall fusion, is tightly regulated. In mitotic cells, Fus2 is sequestered in the nucleus, which is controlled via phosphorylation by Cla4 in a cyclin-dependent kinase-dependent manner. When pheromone-stimulated cells arrest in G1, Fus3 phosphorylates Fus2, enabling it to exit the nucleus.

Once cytoplasmic, Fus2 is free to associate with Rvs161, a protein that binds to curved membranes, such as those of vesicles, and plays a role in endocytosis and cell fusion. To localize to the fusion zone, Fus2 travels along actin cables in a type V myosin motor (Myo2)-dependent fashion, presumably while associated with Rvs161 and the vesicles seen localized to fusion zone. Fus1 anchors Fus2 at the fusion zone, and they bind GTP-bound Cdc42, which together with its guanine nucleotide exchange factor, Cdc24, has a role in cell fusion separate from its role in either cell polarization or in the MAP kinase signaling pathway. The process by which the vesicles fuse with the plasma membrane is still unclear. However, it has been hypothesized that Fus2 and Rvs161 in conjunction with Cdc42 stimulate fusion of the vesicles with the plasma membrane and release of the contents into the extracellular space. The contents of the fusion vesicles are not known, but it seems reasonable to assume that they are cell wall remodeling enzymes involved in cell wall dissolution and fusion. A decrease in β-1,3-glucan in the cell wall at the shmoo tip appears to be a prerequisite for fusion, and a negative regulator of β-1,3-glucan synthesis, Lrg1, is necessary for efficient fusion. Three putative glucanases, Scw4, Scw10, and Scw11, have also been implicated in mating.
and may be among the enzymes packaged into the fusion secretory vesicles as cells lacking both Scw4 and Scw10 have decreased mating efficiency in crosses with genetically identical partners\(^{121}\).

It is easy to understand why limiting cell wall fusion to moments in G1 when the osmolarity of the cell is low enough to prevent lysis and the pheromone concentration is high is beneficial. However, prior to fusion the cell wall must be dissolved, and none of the elucidated regulations of cell wall fusion limit this dissolution spatially and temporally to the site of fusion with a polarized partner. In Chapter 3, I will present evidence for a mechanism by which cell wall dissolution is limited to the fusion zone with a mating partner by a contact-driven increase in the concentration of cell wall remodeling enzymes.

**Plasma membrane fusion**

The next step in cell fusion, plasma membrane fusion, is another dangerous process that begins as soon as a pore has formed between the two cell walls\(^{103}\). Although the prezygote is now safely incased in a cell wall, which protects it from the dangers of osmotic lysis, it must still fuse the plasma membrane, which separates the inside of the cell from the external environment. The plasma membrane consists of a lipid bilayer, and both leaflets of the bilayer must be fused to achieve cytoplasmic mixing (Figure 1.4). For this to safely occur the outer leaflets of the two plasma membranes fuse first, creating a hemifusion stalk. At this point the outer leaflet of the two cells is a continuous structure, but the inner leaflets are unfused, so the cytoplasms of the two cells are still separate. Over time, the hemifusion stalk can either expand until the curvature of the two inner leaflets is such that it is energetically favorable for the two inner leaflets to fuse, forming a fusion pore, or dissociate, leaving the two plasma membranes unattached\(^{123}\). The formation of hemifusion stalks and subsequent formation of fusion pores requires specialized
Figure 1.4. Plasma membrane fusion. A. After cell wall fusion, the two plasma membranes appose each other. B. Plasma membrane fusion is energetically unfavorable, so the lipid bilayers are thought to first deform to decrease the energetic barrier to fusion. C. First the outer leaflets of the plasma membrane fuse, causing formation of a hemifusion stalk. D. Then the inner leaflets of the plasma membranes fuse, causing formation of a fusion pore and enabling cytoplasmic mixing. Proteins, such as Prm1 and Fig1, may help in any one of these steps.
conditions to make the process energetically favorable, which include membrane curvature, the relative lipid content of the membranes, and stabilizing the fusion intermediates. When these processes are not carefully controlled, instead of creating a fusion pore, holes in the plasma membranes that leave the cytoplasms open to the extracellular environment can form. To safely achieve plasma membrane fusion, it is thought that membrane proteins, conceptually analogous to the SNAREs involved with the fusion of secretory vesicles, are required. To this end, several proteins have been implicated in plasma membrane fusion.

The first protein identified to play a role in membrane fusion is Prm1, a pheromone stimulated membrane protein with four transmembrane domains that localizes to the fusion zone during mating. When PRM1 is deleted from both mating partners, approximately half of the prezygotes stall after cell wall dissolution with the two plasma membranes about 8nm apart. Several years later, Fig1, a protein involved in the low affinity Ca\textsuperscript{2+} influx system, was also shown to be involved in plasma membrane fusion. Prm1 and Fig1 appear to stabilize fusion pores. When they are absent from mating pairs, prezygote lysis occurs in a Ca\textsuperscript{2+}-dependent manner, potentially because of the role for Ca\textsuperscript{2+} in membrane wound repair. There are several hypotheses for how Prm1 and Fig1 might go about stabilizing fusion pores. One is that they act to hold the two apposing membranes together, which is supported by the presence of a hydrophobic loop on Prm1 that is not transmembrane. Another possibility is that the two proteins, perhaps aided by oligomerization of Prm1 via disulfide bonds, surround the fusion pore either to hold an as yet undiscovered fusase in place or to corral the lipids in the fusion pore to stabilize the pore. Work on how this occurs and which model is correct is still ongoing.

Several other proteins have been implicated in plasma membrane fusion. One of these is Kex2, a Golgi-resident Ca\textsuperscript{2+}-dependent protease involved in the maturation of many
proteins\textsuperscript{135-137}, including $\alpha$-factor\textsuperscript{138}. The mechanism through which Kex2 promotes plasma membrane fusion is unclear, but it is likely through modifications of a substrate(s) necessary for efficient membrane fusion\textsuperscript{133}. Ergosterol in the plasma membrane has also been shown to play a role in membrane fusion\textsuperscript{139}, suggesting that it has a role in both fusion and polarization\textsuperscript{72, 139}. Perhaps surprisingly, along with its role in cell wall fusion, Fus1 appears to be involved with efficient plasma membrane fusion pore enlargement after formation\textsuperscript{140}. Plasma membrane fusion is arguably one of the least well studied of any of the processes described here, and at the moment it is difficult to form a coherent model for how membrane fusion during mating occurs.

**Karyogamy**

In order for the binucleate cell to form a single diploid nucleus, after plasma membrane fusion, the cell must proceed through nuclear fusion, also termed karyogamy. Nuclear fusion has two distinct parts. The two nuclei must first migrate towards each other, in a process known as nuclear congression, which is accomplished by microtubules that interact with the spindle pole body on each nucleus. Once the two nuclei come in contact with each other, they must go through nuclear envelope fusion\textsuperscript{16}. Kar4, a transcription factor whose expression is induced by Ste12 in a pheromone-regulated manner, is required to activate transcription of many of the genes involved in karyogamy. This regulates the timing of karyogamy by ensuring that the genes involved are not transcribed until after the first wave of the pheromone response\textsuperscript{141}.

Prior to cell fusion, the nucleus migrates towards the shmoo tip in preparation for fusion via cytoplasmic microtubules emanating from the spindle pole body. The microtubule minus ends attach to the spindle pole body\textsuperscript{142}. To facilitate nuclear congression, the protein Bim1 attaches to microtubule plus-ends\textsuperscript{143, 144} and forms a complex with Kar9\textsuperscript{145, 146}. Kar9 is thought to interact with the type V myosin motor protein, Myo2, which pulls the microtubules, and thus
the nucleus, along actin cables to the shmoo tip\textsuperscript{147,148}. Once at the fusion zone, Bim1 and Kar9 anchor polymerizing plus-ends to the shmoo tip via interactions with Myo2 and the polarisome\textsuperscript{149}. Two other proteins, Kar3 and Cik1, which together act as a kinesin motor\textsuperscript{150}, bind the depolymerizing plus-ends of microtubules\textsuperscript{151} and anchor them to the shmoo tip\textsuperscript{152} via interactions with the G\textsubscript{a} subunit, Gpa1\textsuperscript{ref.153}.

After plasma membrane fusion, the two nuclei continue to move towards each other via the action of microtubules and microtubule motor proteins, and there are two models for how this may occur. One possible model is that after pores have formed between the plasma membranes of the two cells, microtubules emanating from each of the nuclei contact each other in a Kar3-dependent fashion. Once the two microtubules are attached, Kar3 together with Cik1 stimulates plus-end depolymerization of the microtubules, shortening them, and effectively pulling the nuclei towards each other\textsuperscript{154}. A second model is that the microtubules from one nucleus interact with the spindle pole body of the other nucleus in a Kar3-dependent fashion. Force is then generated by motors on the two spindle pole bodies that enables each spindle pole body to slide along microtubules anchored to the other spindle pole body, thus, pulling the two nuclei together\textsuperscript{155}. These two models are not mutually exclusive; so, it is possible they each explain an aspect of nuclear congression.

Fusing cells that successfully bring their nuclei in close contact are able to begin the last stage of cell fusion: nuclear envelope fusion. The nuclear envelope consists of two concentric membranes and a spindle pole body, each of which must be fused in order to generate a diploid nucleus\textsuperscript{156}. The molecular mechanisms of nuclear fusion are still being elucidated, but some proteins have been identified to play a role in each phase. The first step in nuclear fusion is fusion of the outer membrane\textsuperscript{156}. Prm3, a protein which resides on the cytoplasmic side of the
nuclear envelope is involved in this process, perhaps as a fusase or as the facilitator of a fusase.\textsuperscript{157, 158} Prm3 interacts with Kar5, which is involved with both the initiation of outer membrane fusion and the subsequent expansion of the outer membrane fusion pore.\textsuperscript{157} Sec66, a protein involved in transport into the ER, has also been implicated in outer membrane fusion.\textsuperscript{159} Additionally, Kar5 might be involved with linking the inner and outer membranes together at the fusion pore, enabling inner membrane fusion at the fusion pore.\textsuperscript{157} To this end, Kar5 may form a complex with the DnaJ-like chaperone protein, Jem1, and the ATPase, Kar2, which are necessary for the next step: inner membrane fusion.\textsuperscript{157, 159, 162} The last step in the process is fusion of the spindle pole body.\textsuperscript{156} The proteins involved in this step are not clear, but several have been put forward as possible players, including Jem1 and Mps3, a protein involved in insertion of the spindle pole body into the nuclear envelope after mitotic division.\textsuperscript{164} Mps3 has also been hypothesized to play a role in working with Kar5 to hold the inner and outer membranes together for coordinated fusion of the nuclear envelope.\textsuperscript{157}

Following successful formation of a diploid nucleus, the newly formed zygote reenters into the mitotic cycle as a diploid. The methods by which it does this are not clear, but it likely involves the proteins mentioned previously as attenuators of the pheromone response, Bar1 and Sst2, as well as the MATa-specific protein, Asg7, which together with the a-factor receptor, Ste3, causes internalization of the Gβ subunit of the G-protein and will be discussed in a subsequent section of this review. Aside from Ste3’s interaction with Asg7, there are currently no MATa-specific proteins known to be involved in attenuation of signaling through the pheromone-response pathway.\textsuperscript{167} However, in Chapter 2 I will discuss the identification of a MATa-specific a-factor barrier protein that would attenuate signals through Ste3 and the
observation that cells that are MATα at the MAT locus but express Ste2 instead of Ste3 only arrest transiently during pheromone stimulation.

**MATING TYPE DETERMINATION**

**MAT locus**

An important feature of the budding yeast cell cycle and mating in particular is the presence of three different cell types: two haploid mating types – MATα and MATa and diploid cells – MATα/α. The cell fate of a budding yeast cell is controlled at the MAT locus on Chromosome III (Figure 1.5). Each cell type expresses a different combination of transcription factors at the MAT locus, and in combination with several constitutively expressed transcription factors these control the expression of a wide variety of genes.\textsuperscript{18,167}

Expression of MATα-specific genes is the default state of cells lacking expression of any transcription factors at the MAT locus.\textsuperscript{168} Because of this, the two open reading frames present in the MATα locus, MATα1 and MATα2, do not have any known function in haploid cells.\textsuperscript{169} The MATα locus also has two open reading frames, which encode the genes MATα1 and MATα2.\textsuperscript{170} Mata1 acts as a transcriptional activator to turn on expression of α-specific genes, while Mata2 acts as a transcriptional repressor to turn off expression of α-specific genes.\textsuperscript{168} In cells expressing both the MATα and MATa loci, such as diploids, Mata2 and Mata1 form a complex, which turns off expression of all haploid-specific genes.\textsuperscript{171} Because only cells expressing transcription factors from a single MAT locus can mate, I will focus on these cell types in this review.

**Cell type specific gene expression**

The control of mating type from the MAT locus has been extremely well studied. However, determining all of the genes expressed in each of the mating types is a more difficult
Figure 1.5. Control of haploid mating type by the MAT locus. A. MATa-specific genes are repressible, so the transcription factor expressed at the MATa locus, Mata1, has no known function in haploid cells. Cells that are MATa at the MAT locus express MATa-specific genes and do not express MATα-specific genes. B. The MATα locus expresses two transcription factors, Mata1 and Mata2. Mata1 activates transcription of MATα-specific genes. Mata2 represses transcription of MATα-specific genes.
task. Prior to the advent of high throughput techniques such as microarrays, RNA sequencing, and chromatin immunoprecipitation, in order to screen for a gene, a specific function needed to be identified, so the identification of mating type-specific genes was generally limited to functions such as mating for MATα and MATα cells or meiosis for MATα/α cells. In 2004, Galgoczy, et al. did a genome-wide study of the three different cell types and assembled a more complete list of MATα-, MATα-, and MATα/α-specific genes based on Matα1, Matα2, and Mata1/Mata2 binding sites. However, these experiments were done in the absence of pheromone and, while they did identify sites of MAT transcription factor binding, they did not probe the potential intricacies of the differences between pheromone induction in MATα and MATα cells. Genome-wide studies of the transcriptome of pheromone-stimulated haploid cells have been done. Although the analysis of α-factor stimulated MATα cells was fairly straightforward, comparing this data set to that of α-factor-stimulated MATα cells at similar levels of pheromone induction is extremely complex due to the hydrophobicity of α-factor. In Chapter 2, I describe a system that allows for controllable analysis of the transcriptome of pheromone-stimulated MATα cells.

MATα cells

Aside from the transcription factors expressed at the MATα locus and genes involved in mating type switching, a process eliminated from most domesticated laboratory strains, there are 7 MATα specific genes: STE2, MFA1, MFA2, STE6, BAR1, AGA2, and ASG7, all of which function in mating (Figure 1.6A). As previously mentioned, STE2 encodes for a seven-transmembrane G-protein coupled receptor that binds to α-factor and activates the MAP kinase cascade while MFA1 and MFA2 encode for the pheromone α-factor. Each of these α-factor genes is responsible for approximately half of the α-factor production. Deletion of a single
Figure 1.6. MATα- and MATα-specific genes. A. MATα cells express the pheromone, α-factor, and the α-factor receptor, Ste2. α-factor is secreted through the ABC transporter, Ste6. MATα cells also express the α-factor protease, Bar1, and the α-agglutinin, Aga2. B. MATα cells express the pheromone, α-factor, and the α-factor receptor, Ste3. They also express the α-agglutinin, Sag1, and the uncharacterized ORF YLR040C, which we will demonstrate encodes the novel α-factor barrier protein, Afb1.
factor gene has little effect on mating efficiency, but deletion of both \textit{MFA1} and \textit{MFA2} causes sterility in \textit{MATa} cells\textsuperscript{173}. Because of the extreme hydrophobicity of \textit{a}-factor, it cannot exit the cell via the secretory pathway. Instead \textit{STE6} encodes a plasma membrane ATP-binding cassette transporter that transports mature \textit{a}-factor out of the cell\textsuperscript{174}. Although the other 3 genes encode proteins that make mating more efficient, \textit{Ste2}, \textit{a}-factor, and \textit{Ste6} are the only \textit{MATa}-specific proteins that are essential for zygote formation\textsuperscript{175}.

\textit{Bar1} is an aspartyl protease that is secreted by \textit{MATa} cells to cleave \textit{a}-factor\textsuperscript{81,176}, and is important for efficient mating\textsuperscript{70}. As would be expected, cells lacking \textit{Bar1} are more sensitive to \textit{a}-factor arrest\textsuperscript{75,76}, but perhaps paradoxically, these cells also have a more difficult time finding a mating partner\textsuperscript{70,177}. This can be explained by the fact that \textit{a}-factor diffuses radially from each \textit{MATa} cell, so in a dense mating mixture the direction of highest pheromone concentration could be an average of many \textit{a}-factor producing points as opposed to in the direction of a nearby mating partner. \textit{Bar1} that exits the cell wall and diffuses away from the \textit{MATa} cell decreases the distance free \textit{a}-factor peptides travel prior to degradation, thus decreasing the number of \textit{a}-factor producing points that any individual \textit{MATa} cell senses and privileging the \textit{a}-factor secreted from nearby cells\textsuperscript{177}. Complementarily, \textit{Bar1} that is trapped in the cell wall of the \textit{MATa} cell creates an \textit{a}-factor sink, which helps the \textit{MATa} cell to distinguish between two close, potential \textit{MATa} partners such as might be found in an ascus after sporulation or in a dense mating mixture by keeping the \textit{a}-factor concentration low enough that every pheromone receptor on the surface of the \textit{MATa} cells is not bound to \textit{a}-factor\textsuperscript{178}. The \textit{a}-factor sink surrounding each \textit{MATa} cell also increases the chance that each \textit{MATa} cell will chose a different \textit{MATa} partner, since \textit{MATa} cells are unlikely to polarize towards the sink of a nearby \textit{MATa} neighbor and will tend to avoid each other as they polarize\textsuperscript{179}. 

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As discussed previously, once cells have accurately detected a gradient, shmoed towards each other, and come in contact, the mating agglutinins attach the two cells at the shmoo tip\textsuperscript{16}. The α-agglutinin is a complex of two proteins, Aga\textsubscript{1}\textsuperscript{ref.85} and Aga\textsubscript{2}\textsuperscript{ref.86}. Aga\textsubscript{1} is not mating type specific and is necessary for cell surface attachment of Aga\textsubscript{2}\textsuperscript{ref.85}. Aga\textsubscript{2}, which is MAT\textalpha-specific is the ligand for the α-agglutinin\textsuperscript{86,89}. The MAT\textalpha mating agglutinins are dispensable when cells mate on solid media but are necessary when cells mate in liquid\textsuperscript{86}.

The final MAT\textalpha-specific protein is Asg7, which is important for overcoming pheromone-stimulation in early zygotes\textsuperscript{166}. Immediately after two haploid cells fuse, they will express all of the MAT\textalpha-specific proteins and the MATα-specific proteins, including the pheromones and pheromone receptors. It is possible to imagine that due to both autocrine signaling and the pheromones present in a dense mating mixture, the pheromone receptors would continue to bind ligand, which would keep the newly fused zygote in G1 cell cycle arrest until the pheromone receptors could be endocytosed. When Asg7, which is only expressed in MAT\textalpha cells\textsuperscript{180}, comes in contact with Ste3, which is only expressed in MAT\textalpha cells\textsuperscript{10}, in the early diploid, Asg7 likely binds to Ste4, the G\textbeta subunit, causing Ste4 to be internalized\textsuperscript{165}. Since internalized Ste4 can no longer recruit Ste5 to the plasma membrane, signaling through the MAP kinase cascade is decreased\textsuperscript{165}, allowing early diploids to proceed through mitosis\textsuperscript{166}.

**MAT\textalpha cells**

There are 5 known MAT\textalpha-specific genes: STE3, MF\textalpha1, MF\textalpha2, SAG1, and YLR040C\textsuperscript{ref.167} (Figure 1.6B). As described previously, Ste3 is the seven-transmembrane G-coupled α-factor receptor\textsuperscript{10} and MF\textalpha1 and MF\textalpha2 encode for the pheromone α-factor\textsuperscript{7,8}. Unlike in MAT\textalpha cells the production of α-factor from MF\textalpha1 and MF\textalpha2 is not distributed equally between the two genes\textsuperscript{181}. The majority of α-factor production occurs from MF\textalpha1 and deletion of this gene causes a 75%
decrease in mating efficiency\textsuperscript{181}. \textit{MFα2} produces much less α-factor, and the effect of its deletion on mating efficiency is correspondingly lower\textsuperscript{181}. α-factor is secreted through the normal secretory pathway, and does not necessitate a dedicated α-factor secretion mechanism\textsuperscript{7}. As in \textit{MATa} cells, these are the only \textit{MATα}-specific proteins required for zygote formation\textsuperscript{175}.

As mentioned earlier, \textit{MATα} cells also express the α-agglutinin, Sag\textsubscript{1}\textsuperscript{ref. 83}, a GPI-anchored protein expressed in the cell wall\textsuperscript{84}. The N-terminal half of the protein has sequence similarities to immunoglobulins\textsuperscript{88}, and the a-agglutinin, Aga2, acts as the ligand for Sag\textsubscript{1}\textsuperscript{ref. 86, 89}. Sag\textsubscript{1} is only necessary for mating in liquid media\textsuperscript{83, 84}.

It seems reasonable to hypothesize that \textit{MATa} cells in a dense mating mixture would have similar problems in polarizing in the direction of highest pheromone concentration as \textit{MATa} cells due to the α-factor secreted by multiple, potential \textit{MATa} partners. However, although an α-factor barrier protein has been purported to exist\textsuperscript{182, 183}, it has not been definitively identified. In Chapter 2, I provide evidence to suggest that the final \textit{MATα}-specific gene, \textit{YLR040C}, encodes for an α-factor barrier protein, which we name \textit{AFB1} for α-factor barrier. Much of what is known about \textit{AFB1} has been gathered through high throughput experiments about its expression patterns. Briefly, \textit{AFB1} has a Mat\textsubscript{α1} binding site that controls its expression\textsuperscript{167}, has been shown to be translated by ribosome profiling\textsuperscript{184}, and localizes to the cell wall\textsuperscript{185, 186}. This serves to show that although the body of knowledge surrounding budding yeast haploid cell types is considerable, there is still much to be learned. The experiments I describe in Chapter 2 seek to improve our understanding of the differences in \textit{MATa} and \textit{MATα} cells and the roles of the proteins that embody these differences.

**CLOSING REMARKS**
The study of budding yeast mating helps bring to light the mechanisms involved in many of the daily cellular functions of higher eukaryotes: from fertilization to cellular differentiation to intercellular signaling to development of cellular polarity. I have given a brief overview of the current state of knowledge about many of the processes involved in budding yeast mating, which highlights both how much we have discovered and how much is left to uncover. Although we know much about the control of the cell types in budding yeast through the transcription factors expressed from the \textit{MAT} locus, we have not determined the role of all of these genes in intercellular signaling and fusion. In Chapter 2, I will discuss experiments to further elucidate the differences between the two haploid cell types in both gene expression and pheromone response as well as to provide a peek into the necessity for careful regulation of the expression of these genes for efficient mating. Once two cells have successfully located each other, they must go through the dangerous process of fusing to form a single zygote. In Chapter 3, I will provide evidence for a hypothesis that addresses the careful spatial and temporal regulation of cell wall fusion necessary to reduce the chance of osmotic lysis. The evidence presented in both of these chapters helps to pave the way for future research, and in Chapter 4 I will discuss the conclusions we can draw and possible future directions of the study of mating in the budding yeast.
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CHAPTER 2

*Genetically engineered transvestites reveal novel mating genes in budding yeast*
ABSTRACT

Mating type in yeast is controlled by transcription factors expressed from the $MAT$ locus; however, the characterization of the genes these factors regulate necessary to define a mating type is incomplete. Each mating type expresses a pheromone which binds to a G-protein coupled receptor expressed by the opposite mating type, and signaling through these receptors is essential for efficient mating. To find additional mating type-specific proteins required for efficient zygote formation, we have constructed transvestite strains that swap the pheromone, pheromone receptor, and pheromone processing factors of one mating type for another. Using these strains we were able to compare gene expression in pheromone-stimulated $MAT\alpha$ and $MAT\alpha$ cells and identified a novel $MAT\alpha$-specific protein that interferes with $\alpha$-factor, which we have named $AFB1$. Although the transvestite strains were capable of mating, the mating efficiency of these cells was low. Through characterization of the transvestite cells, we provide further evidence that all of the $MAT\alpha$-specific proteins have been identified and that sufficient $\alpha$-factor expression is necessary for efficient mating. We also show that while changing the regulation of various genes involved with pheromone induction does not cause sterility, it can cause a significant decrease in mating efficiency, arguing that mating is a fragile process.
INTRODUCTION

Many higher eukaryotes reproduce when gametes produced by individuals from two different genders come in contact and fuse. However, genetic studies of this process are difficult because sterile mutants cannot reproduce. The budding yeast, *Saccharomyces cerevisiae*, is an attractive solution to this problem because although it is able to replicate sexually when two haploid cells of opposite mating types (MATa and MATα) come in contact with one another and fuse to form a single diploid cell, it can replicate asexually in both its diploid and haploid states\(^1\)\(^2\). Mating type is controlled by transcription factors expressed from the mating type (MAT) locus\(^3\); however, we do not know if the list of genes that these factors control to define a mating type is complete.

Mating depends on pheromone-mediated, intercellular communication. Each mating type expresses a pheromone which binds to a G-protein coupled receptor expressed by the opposite mating type, and signaling through these receptors is essential for mating\(^4\). MATα cells produce α-factor\(^5\)\(^6\) and express the a-factor receptor, Ste3, on their surface\(^7\) (Figure 2.1A). MATa cells produce a-factor\(^8\) and express the α-factor receptor, Ste2, on their surface\(^9\)\(^10\) (Figure 2.1A). In the absence of MATα cells, MATa cells express a-factor and Ste2 at low levels\(^11\)\(^12\), but when Ste2 binds α-factor, a mitogen-activated protein (MAP) kinase cascade, which is conserved in other ascomycete fungi, is started, stimulating the cell to produce higher levels of its own pheromone, a-factor, and other proteins involved with mating\(^4\)\(^13\)\(^15\). Pheromone stimulation arrests MATα cells in G1\(^16\), polarizes them in the direction of highest pheromone concentration\(^17\), and induces polarized cell growth to form a mating projection known as a shmoo\(^18\). MATα cells produce a similar, coordinated response using the reciprocal G-protein coupled receptor (Ste3) to detect a-factor (Figure 2.1A)\(^4\)\(^7\)\(^12\)\(^13\)\(^17\)\(^19\).
Figure 2.1. Wild-type mating types and transvestite mating types. A. MATa cells express the pheromone a-factor, which is secreted through the ABC transporter, Ste6, the α-factor receptor, Ste2, and the α-factor protease, Bar1. MATα cells express the pheromone α-factor and the α-factor receptor, Ste3. B. α-playing-a cells are MATα cells that express a-factor instead of α-factor, Ste2 instead of Ste3, the a-factor transporter, Ste6, and the α-factor protease, Bar1. a-playing-α cells are MATa cells that express α-factor instead of a-factor, Ste3 instead of Ste2, and are bar1Δ.
Cells that have mutations in the proteins required for secreting, processing, and responding to pheromone are sterile\(^4\), and previous work demonstrated that reciprocal pheromones and receptors are the only proteins that are absolutely necessary to form zygotes\(^{20}\).

However, there are other mating type-specific proteins, such as the \(\alpha\)-factor protease, Bar1\(^{1, 21, 22}\), and the mating agglutinins\(^{23-25}\) that serve to make mating more efficient. We were interested in identifying additional mating type-specific genes necessary for efficient mating and asking how much the quantitative details of mating gene expression contributes to the efficiency of mating.

To do this, we constructed “transvestite” strains (Figure 2.1B). These genetically engineered strains have one allele at the mating type locus but express the pheromone, pheromone receptor, and proteins responsible for secreting or processing pheromones that are normally induced by the other \(MAT\) allele; thus, a \(MAT\alpha\) transvestite would express \(a\)-factor instead of \(\alpha\)-factor and the \(\alpha\)-factor receptor (Ste2) instead of the \(a\)-factor receptor (Ste3). By studying the behavior of these cells, we were able to learn more about the differences between \(MAT\alpha\) and \(MAT\alpha\) cells. \(MAT\alpha\) cells that express \(\alpha\)-factor and Ste3, which we call \(a\)-playing-\(\alpha\) cells, mate 3 times worse than genuine \(MAT\alpha\) cells, while \(MAT\alpha\) cells that express \(a\)-factor and Ste2, which we call \(\alpha\)-playing-\(a\) cells, mate 50 times worse than genuine \(MAT\alpha\) cells. The mating defects of the \(\alpha\)-playing-\(a\) cells are due in part to the expression of a novel, \(MAT\alpha\)-specific \(a\)-factor barrier protein. We also show that although \(\alpha\)-playing-\(a\) cells are able to form shmoos in response to \(\alpha\)-factor, they only transiently arrest the cell cycle. Additionally, our results show that the quantitative details of pheromone secretion and processing have strong effects on mating efficiency.

**RESULTS**

*Transvestite cells can mate*
To study mating-type specific genes necessary for efficient mating, we constructed two types of transvestite strains. The first is a-playing-α: MATa cells that have been engineered to produce α-factor and the a-factor receptor by replacing the open reading frames of STE2 with STE3, MFA1 with MFα1, and MFA2 with MFα2. We also deleted the α-factor protease, BAR1, and the gene ASG7, which causes internalization of Ste3 and Ste4ref. 26, inhibiting signaling in newly formed zygotes27. However, these cells are still MATa at the MAT locus (Figure 2.1B).

The second type of transvestite is α-playing-α. These cells are MATα at the MAT locus, but have been engineered to produce a-factor and the α-factor receptor by replacing the open reading frame of STE3 with STE2, MFA1 with MFα1, and MFA2 with MFα2. We also drove the expression of BAR1 with an engineered version of the haploid specific promoter, P_{FUS1}ref. 28, and the expression of the a-factor transporter, STE6 with the MFα1 promoter (Figure 2.1B).

We determined whether the manipulated genes are the only mating-type specific proteins required for efficient mating, by crossing these cells with wild-type cells of their original mating type (e.g. α-playing-α crossed to MATα). When two wild-type cells mate, although zygotes will initially express the pheromones and receptors of both mating types, the presence of the transcription factors expressed from both the MATα and the MATα loci turns off transcription of these genes3, and the zygotes are able to escape pheromone-induced G1 arrest27. Conversely, the zygotes produced by crossing the transvestite cells with cells of the same original mating type will express pheromones and receptors from both mating types but the transcription factors from a single MAT locus, raising the concern that these zygotes may be self-stimulating and persist in pheromone-induced G1 arrest. To confirm that diploids formed by mating transvestite cells with wild-type cells are able to divide, we mated the transvestites to wild-type strains with different nutritional auxotrophies and harvested diploids from media lacking both nutrients. We identified
both a-playing-α/MATα and α-playing-a/MATα diploids, which are capable of normal progression through the cell cycle and generally have normal cell morphology (Figure 2.2A and 2.2B). It is possible to find an occasional population of α-playing-a/MATα diploids with abnormal morphology, but even these are capable of budding (Figure 2.2C). The ability of these diploids to bud indicates that it is possible to measure the mating efficiency of transvestites crossed with wild-type cells of the same original mating type by complementation of nutritional auxotrophies.

We used quantitative mating assays to measure the mating efficiency of the transvestite cells. Cells of the two mating types are incubated together at high density and then plated on media that distinguishes diploid cells from either parental haploid. When wild-type MATα cells are mated with wild-type MATα cells, 63% of haploids form diploids (Figure 2.3). However, the mating efficiency of the α-playing-a cells crossed with MATα cells is one third that of a wild-type cross, and the mating efficiency of the α-playing-a cells crossed with MATα cells is 50-fold lower than the efficiency of a wild-type cross (p<10^{-6}) (Figure 2.3). We also crossed the transvestite strains to each other. Since the diploids formed by this cross will express the transcription factors from both the MATa and MATα loci, any diploids that form should not arrest due to self-stimulation, but the efficiency of this cross is more than 500-fold lower than a wild-type cross (p<10^{-6}) (Figure 2.3). Corroborating previous results^{20}, our observation that the transvestite strains are capable of forming viable diploids with cells of the same original mating type shows that there are no additional mating type-specific genes required for zygote formation other than the ones we manipulated. However, the low mating efficiency of the transvestites crossed to wild-type partners and to each other implies that there are additional requirements for efficient mating.

50
Figure 2.2. Transvestite/wild-type diploids are able to proceed through the cell cycle. **A.** α-playing-α/MATα diploids budding. Cells were grown in YPD and pictures were taken using DIC with 60x magnification. The scale bar indicates 10µm. **B.** α-playing-α/MATα diploids budding. Cells were grown in YPD and pictures were taken using DIC with 60x magnification. The scale bar indicates 10µm. **C.** α-playing-α/MATα diploids budding with abnormal morphology. Cells were grown in YPD and pictures were taken using DIC with 60x magnification. The scale bar indicates 10µm.
Figure 2.3. Transvestite cells can mate. Mating efficiency of cells with different nutritional auxotrophies grown to log phase and then mixed at a 1:1 ratio on a nitrocellulose filter, which was placed on a YPD plate for 5 hours. Mating efficiencies are the percentage of diploids that form colonies on double dropout plates compared to the number of colonies formed on single dropout plates. Error bars are standard deviations.
a-playing-α cells produce too little α-factor

To further investigate the requirements for efficient mating, we more carefully probed the mating defects of the transvestite cells. a-playing-α cells mate 2.8-fold less efficiently than wildtype (Figure 2.3). Because the genes that had been replaced in this strain were those encoding the pheromone and pheromone receptor, the obvious candidates for this difference were the ability of the a-playing-α cells to respond to a-factor and to produce α-factor.

We began by testing the response to a-factor. We made mating mixtures of a-playing-α cells expressing YFP under the pheromone-inducible promoter, PFUSI, and MATa cells expressing mCherry under the ACTI promoter and assayed for the expression of YFP in the a-playing-α cells after 2.5 hours. The expression of YFP in the a-playing-α cells indicates that the a-playing-α cells are able to signal through Ste3 for expression of pheromone-induced genes (Figure 2.4). It was also possible to see the formation of auto-stimulated zygotes, which express both YFP under the FUSI promoter and mCherry under the ACTI promoter (Figure 2.4). Since the G-protein and downstream components of the pheromone response pathway should be the same in MATa and MATa cells, and the cells are able to express and signal through Ste3, we hypothesize that the response of the a-playing-α cells to a-factor is not causing a mating defect.

Pheromone production is important for zygote formation29,30, and it has been shown that MATa cells prefer to mate with the MATa cell that produces the highest amount of α-factor22. Since manipulation of the pheromone genes was integral to the design of the transvestite cells, we next measured the pheromone production of the a-playing-α cells. We grew cells in rich media and collected the supernatant, which we then used to stimulate MATa cells that are missing the α-factor protease, Bar1. By measuring the fraction of the MATa bar1Δ cells that arrest their cell cycles and shmoo (the shmooing index) when exposed to the supernatants of
Figure 2.4. a-playing-α cells respond to a-factor. a-playing-α $P_{FUS1}$-YFP cells in a mating mixture with $MATa P_{ACT1}$-mCherry cells. Yellow indicates YFP expression. Red indicates mCherry expression. The orange cell is a diploid expressing both YFP and mCherry. The picture was taken 2.5 hours after mixing the cells using DIC and fluorescence at 20x magnification. The scale bar indicates 10µm.
various strains and comparing this data to a standard curve generated with known quantities of synthetic α-factor, we are able to measure the amount of α-factor produced by these cells.

Unstimulated, α-playing-α cells produce 66-fold less α-factor than \( MAT\alpha \) cells \((p=0.01)\) (Figure 2.5). To measure the α-factor production of stimulated cells, we mixed the α-factor producing cells in a 10:1 mixture with \( MAT\alpha \) \( bar1\Delta \) cells and measured the α-factor present in the supernatant. Stimulated α-playing-α cells produce only 20-fold less α-factor than stimulated wild-type \( MAT\alpha \) cells \((p=9\times10^{-6})\) (Figure 2.5).

To test the effect of reduced pheromone production in \( MAT\alpha \) cells, we knocked out \( MFA1 \), which is the majority α-factor producer in \( MAT\alpha \) cells\(^{29}\). Using our assay, this manipulation results in a 12-fold reduction in α-factor production compared to wild-type \( MAT\alpha \) cells in unstimulated cells \((p=0.02)\), and a 9-fold reduction in α-factor production compared to wild-type \( MAT\alpha \) cells in stimulated cells \((p=10^{-5})\) (Figure 2.5). We then compared the mating efficiency of \( MAT\alpha mfa1\Delta \) cells, which have previously been shown to have decreased mating efficiency\(^{29}\), to that of α-playing-α cells and determined that while there is a significant difference in the mating efficiency of \( MAT\alpha mfa1\Delta \) cells and the mating efficiency of α-playing-α cells, \( MAT\alpha mfa1\Delta \) cells only mate 1.5-fold more efficiently \((p=0.003)\) (Figure 2.6). This led us to hypothesize that the reduced mating efficiency of the α-playing-α cells is due, at least in part, to low α-factor production.

To test this hypothesis, we increased α-factor production in the α-playing-α cells by placing the \( MFA1 \) gene under the control of the \( TDH3 \) promoter. Although this promoter is not pheromone-regulated, it is one of the most highly expressed promoters in the yeast genome\(^{31,32}\), and thus, we expected to increase α-factor production to at least wild-type \( MAT\alpha \) levels in the
Figure 2.5. **a-playing-α cells produce too little α-factor.** α-factor production is measured by growing cells in YPD, harvesting the supernatant, and exposing MATα bar1Δ cells to the supernatant. The shmooing index of the MATα bar1Δ cells is measured and then compared to a standard curve to determine the concentration of α-factor present in the media. Error bars are standard deviation.
Figure 2.6. Increasing the α-factor production of a-playing-α cells increases mating efficiency. Mating efficiency of cells with different nutritional auxotrophies grown to log phase and then mixed at a 1:1 ratio on a nitrocellulose filter, which was placed on a YPD plate for 5 hours. Mating efficiencies are the percentage of diploids that form colonies on double dropout plates compared to the number of colonies formed on single dropout plates. Error bars are standard deviations.
a-playing-α cells. Unstimulated a-playing-α $P_{TDH3}$*$MFα1$ cells secrete twice as much α-factor as unstimulated $MATα$ cells (p=0.04), but when stimulated, a-playing-α $P_{TDH3}$*$MFα1$ cells secrete 5-fold more α-factor than stimulated $MATα$ cells (p=10^{-4}) (Figure 2.5). Since the $TDH3$ promoter is not pheromone-regulated^{33}, this result suggests that α-factor production is at least in part regulated via post-translational mechanisms such as pheromone maturation and secretion. If low α-factor accounts for the low mating efficiency of the a-playing-α cells, we would expect the a-playing-α $P_{TDH3}$*$MFα1$ cells to have a mating efficiency approaching that of wild-type $MATα$ cells, which is indeed what we found (Figure 2.6). This corroborates previous results that sufficient α-factor production is important for efficient mating^{29} and leads to two additional conclusions: i) there are no additional $MATα$-specific genes beyond the ones we have manipulated that are detrimental to mating on solid media as a $MATα$ cell and ii) there are no additional $MATα$-specific proteins beyond α-factor and Ste3 that are necessary for efficient mating on solid media as a $MATα$ cell.

**AFB1 encodes a novel α-factor barrier protein**

We next decided to look into the decreased mating efficiency of the α-playing-a cells. Because pheromone production is important for efficient mating^{29,30}, we investigated the α-factor production of the α-playing-a cells. Both α-factor and a-factor go through significant processing before secretion^{5,8}. However, while α-factor is secreted merely as a small peptide^{5}, mature a-factor is prenylated, causing it to be very hydrophobic^{8,34}. The hydrophobicity of a-factor causes difficulties in biochemical quantification, so we measured the relative a-factor production of the α-playing-a cells by plating patches of a-factor producing cells and spraying supersensitive $MATα$ cells ($MATα$ $sst2Δ$, which lack a GTPase activating protein that normally controls the life time of signaling from the pheromone-activated G protein^{35-38}) over the patches in an a-factor
halo assay. Since supersensitive MATα cells deleted for SST2 arrest the cell cycle in response to low doses of α-factor, the α-factor produced by the cell patches will cause a halo with no cell growth to form around the α-factor-producing cell patches with a diameter that increases with the amount of α-factor produced by the cell patch (Figure 2.7A). The halo produced by the α-playing-a cells is smaller than that of wild-type MATα cells, implying that α-playing-a cells secrete less α-factor than wild-type MATα cells (Figure 2.7B).

Bar1 is a MATα-specific protease, which is secreted in order to cleave α-factor. Bar1 has two roles: it improves the accuracy of pheromone gradient detection, and it keeps the α-factor concentration at the surface of MATα cells low enough to avoid saturating the pheromone receptors. Biochemical evidence of a MATα-specific, α-factor-cleaving endopeptidase has been reported, but the gene that encodes this endopeptidase has not been identified. It is easy to imagine that an α-factor barrier protein, such as an endopeptidase, would provide a similar service in improvement of gradient detection for MATα cells and that secretion of such a protein by α-playing-a cells would cause lower net α-factor production and, thus, smaller halos. To test for the presence of a MATα-specific α-factor barrier protein secreted from α-playing-a cells, we compared the halo sizes of a mixture of MATα cells with α-playing-a cells and a mixture of MATα cells with MATα cells that produce no α-factor. If the α-playing-a cells secrete an α-factor barrier protein, we would expect the halo size of the MATα cells mixed with α-playing-a cells to be smaller than that of the MATα cells mixed with MATα mfa1Δ mfa2Δ cells because the α-factor barrier protein would interfere with the α-factor from both the α-playing-a cells and the MATα cells. However, if there is no α-factor barrier protein, we would expect the halo size of the MATα cells mixed with α-playing-a cells to be larger than that of the MATα cells mixed with MATα mfa1Δ mfa2Δ cells because both the MATα cells and the α-playing-a cells are capable of
**Figure 2.7.** *AFB1 encodes a novel a-factor barrier protein.* **A.** Halo assays are done by growing cell patches YPD overnight and then spraying super-sensitive *MATα sst2Δ* cells over the cell patches. Where a-factor produced by the cell patches has diffused into the YPD, the *MATα sst2Δ* cells will be unable to grow, forming a halo around the cell patch with a size that corresponds to the amount of a-factor secreted. **B.** Halo assays done on various cell patches containing a single cell type. *MATα mfa1Δ mfa2Δ* is a negative control and *MATα* is a positive control. **C.** Halo assays done on cell patches containing two cell types at a 1:8 ratio of *MATα* cells to the experimental cell of interest.
secreting a-factor. When we observed the size of the halos produced by these two cell mixes, we saw that the halo produced by MATα cells mixed with α-playing-a cells is indeed smaller than the halo produced by MATα cells mixed with MATα mfa1Δ mfa2Δ cells, indicating that α-playing-a cells secrete an a-factor barrier protein (Figure 2.7C).

We decided to search for the gene responsible for this activity by comparing the transcriptomes of MATα and α-playing-a cells. Although microarrays and RNA sequencing have been done on pheromone stimulated MATα cells, similar experiments done on pheromone-stimulated MATα cells have had to contend with the difficulties imposed by the extreme hydrophobicity of a-factor, which complicates quantification and, thus, direct comparison to MATα cells. Using the α-playing-a cells it is possible to easily and accurately investigate the transcriptome of pheromone stimulated cells that are MATα at the MAT locus but are stimulated by α-factor. We used this unique opportunity and compared the transcriptomes of stimulated and unstimulated MATα and α-playing-a cells using RNA sequencing. We chose a concentration of pheromone, 10nM, in a regime in which MATα bar1Δ and α-playing-a cells with BAR1 under its endogenous promoter have a similar shmooing index (Figure 2.8A). By doing this we hoped to mitigate differences in gene expression that occur merely because of differences in the level of pheromone-induced signaling.

Just as MATα cells do not secrete Bar1ref. 21, we would not expect MATα cells to secrete an a-factor barrier protein. Thus, we hypothesized that a MATα-specific a-factor barrier protein would be expressed more highly in both stimulated and unstimulated α-playing-a than stimulated and unstimulated MATα cells, respectively. 37 genes fit these parameters, and of these only one, YLR040C, is annotated as encoding for a secreted protein that is not already known to be important in mating in the Yeast Genome Database (http://www.yeastgenome.org) (Table 2.1).
Figure 2.8. α-playing-a cells shmoo in response to α-factor. A. Shmooing indices of MATa bar1Δ cells and α-playing-a P_{BAR1-BAR1} cells exposed to known concentrations of α-factor. Error bars are standard deviation. B. Shmooing indices of MATa cells and α-playing-a P_{FUS1-BAR1} cells exposed to known concentrations of α-factor. Error bars are standard deviation.
Table 2.1. Genes identified as differentially expressed using RNA sequencing

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Table 2.1 (continued). Genes identified as differentially expressed using RNA sequencing

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Table 2.1 (continued). Genes identified as differentially expressed using RNA sequencing

<table>
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<th>Log₂ Fold Change: Stimulated MATα vs. Stimulated α-playing-α</th>
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Table 2.1 (continued). Genes identified as differentially expressed using RNA sequencing

<table>
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<th>Log&lt;sub&gt;2&lt;/sub&gt; Fold Change: Stimulated MATa vs. Stimulated α-playing-a</th>
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Cells that are darker red are more highly expressed in α-playing-α\textsuperscript{*}P<sub>BAR1-BARI</sub> cells. Cells that are darker blue are more highly expressed in MATα\textsuperscript{bar1Δ} cells. Cells outlined in bold lines indicate a statistically significant difference between the fragments per kilobase of transcript per million mapped reads (FPKM) of the expression of the gene in α-playing-α\textsuperscript{*}P<sub>BAR1-BARI</sub> and MATα\textsuperscript{bar1Δ} cells (p<0.001).

*Genes deleted in the α-playing-α cells.

**Genes deleted in the MATα cells.
YLR040C is uncharacterized, controlled by the transcription factor Mata1⁴⁵, shown to be translated by ribosome profiling⁴⁶, localizes to the cell wall⁴⁷,⁴⁸, and is expressed 5-fold higher in stimulated α-playing-a than MATa cells and 10-fold higher in unstimulated α-playing-a than MATa cells (p<10⁻⁶) (Table 2.1). The experiments described below demonstrate that YLR040C encodes an a-factor barrier protein, leading us to name this gene AFB1 for a-factor barrier.

To determine whether AFB1 is indeed the a-factor barrier protein, we knocked it out in the α-playing-a cells. The halos produced by α-playing-a afb1Δ cells are larger than those of α-playing-a cells, indicating that more a-factor is secreted in α-playing-a cells lacking AFB1 (Figure 2.7B). We also placed this gene under a strong (ACT1) promoter in MATa cells and observed a decrease in halo size compared to wild-type MATa cells, indicating that Afb1 is able to block a-factor secreted by MATa cells (Figure 2.7B). To test whether Afb1 is responsible for blocking a-factor produced by other cells, we made cell mixtures of MATa cells with α-playing-a afb1Δ cells and compared the halo produced by this mixture to the halo produced by the mixtures of MATa cells with α-playing-a cells and to the halo produced by MATa cells with MATa mfa1Δ mfa2Δ cells. Corroborating our other results, the mixture of MATa cells with α-playing-a afb1Δ cells has a larger halo than either the MATa cells with MATa mfa1Δ mfa2Δ cells or the MATa cells with α-playing-a cells, indicating that when Afb1 is not present in the cell mixtures, the a-factor from the wild-type MATa cells as well as that from the α-playing-a cells is free to interact with the super-sensitive MATa cells (Figure 2.7C). Taken together our results are strong evidence that AFB1 encodes for an a-factor barrier protein.

In 1989, Steden et al. isolated a mutant that caused supersensitivity to pheromone arrest in MATα cells but not in MATα cells⁴⁹. This mutation did not affect the biochemical activity of the endopeptidase reported to be associated with MATα cells⁴³ and was localized to the middle of
a 125 kilobase region on Chromosome XII, 608 kilobases away from AFB1\textsuperscript{ref.49}. Thus, we do not believe that the mutation found by Steden \textit{et al.}\textsuperscript{49} was in AFB1. We cannot rule out the possibility that there is another protein with a-factor blocking activity, but we did not find a statistically significant difference in the gene expression of any of the 72 genes encoded in the region identified by Steden \textit{et al.}\textsuperscript{49} between MATa and α-playing-a cells (Table 2.2).

Although the expression of AFB1 has an effect on the a-factor secretion of α-playing-a cells, we did not know whether AFB1 was affecting the mating efficiency of α-playing-a cells. To test this, we crossed α-playing-a afb1Δ cells with wild-type MATa cells and observed a 4-fold increase in mating efficiency over α-playing-a cells (p<10\textsuperscript{-6}) (Figure 2.9). However, when AFB1 is deleted from wild-type MATa cells we do not see a significant decrease in mating efficiency (Figure 2.9). We hypothesized that this may be because small changes in a-factor production do not have a large effect on mating efficiency\textsuperscript{30}. To test this we deleted MFA1 from wild-type MATa cells. We saw a small decrease in the halo size of MATa mfa1Δ as compared to wild-type MATa cells, but as previously reported\textsuperscript{30}, when we measured the mating efficiency of MATa mfa1Δ cells, we did not see a significant difference in mating efficiency from a wild-type cross (Figure 2.7B and 2.9).

\textit{α-playing-a cells shmoo but arrest only transiently in the presence of pheromone}

Although the expression of AFB1 in α-playing-a cells was responsible for a portion of the reduced mating efficiency of α-playing-a cells, α-playing-a afb1Δ cells crossed with MATa cells still mate 11-fold less efficiently than wildtype (p<10\textsuperscript{-6}) (Figure 2.9). We hypothesized that the response of α-playing-a cells to pheromone could also be playing a role in the reduced mating efficiency of these cells. We first measured the shmooing index of α-playing-a cells with BAR1 under its endogenous promoter when stimulated with known quantities of synthetic a-factor and
Table 2.2. Change in expression of genes in the region identified by Steden et al. 1989 between MATα bar1Δ and P<sub>BAR1</sub>-BAR1 α-playing-a cells

<table>
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<tr>
<th>Gene</th>
<th>Log&lt;sub&gt;2&lt;/sub&gt; Fold Change: Stimulated MATα vs. Stimulated α-playing-a</th>
<th>Differentially expressed?</th>
<th>Log&lt;sub&gt;2&lt;/sub&gt; Fold Change: Unstimulated MATα vs. Unstimulated α-playing-a</th>
<th>Differentially expressed?</th>
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Table 2.2 (continued). Change in expression of genes in the region identified by Steden et al. 1989 between MATα bar1Δ and P_BAR1-BAR1 α-playing-α cells

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<th>Differentially expressed?</th>
<th>Log₂ Fold Change: Unstimulated MATα vs. Unstimulated α-playing-α</th>
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Table 2.2 (continued). Change in expression of genes in the region identified by Steden et al. 1989 between MATa bar1Δ and PBAR1-BAR1 α-playing-α cells

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<th>Differentially expressed?</th>
<th>Log₂ Fold Change: Unstimulated MATa vs. Unstimulated α-playing-α</th>
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Figure 2.9. *AFB1* is partially responsible for the low mating efficiency of α-playing-α cells. Mating efficiency of cells with different nutritional auxotrophies grown to log phase and then mixed at a 1:1 ratio on a nitrocellulose filter, which was placed on a YPD plate for 5 hours. Relative mating efficiencies are the percentage of diploids that form colonies on double dropout plates compared to the number of colonies formed on single dropout plates relative to a wild-type cross. Error bars are standard deviations.
compared it to the shmooing index of MATa bar1Δ cells. We found that α-playing-a P_{BAR1} BAR1 cells are as sensitive to low concentrations of α-factor as MATa cells (Figure 2.8A).

In designing the transvestite strains, we attempted to choose promoters that would have similar patterns of expression to those of the genes in the wild-type cells by choosing the promoter of the reciprocal gene in the opposite mating type (e.g. expressing a-factor from the α-factor promoters in α-playing-a cells). However, when choosing a promoter for BAR1 in the α-playing-a cells, we did not know of the reciprocal a-factor barrier protein, so we chose a mutant version of the FUS1 promoter (which normally drives the expression of a gene that is required for cell fusion and is pheromone-induced in both MATa and MATα cells) that has a low basal level of expression and high stimulated level of expression, which we refer to as P_{FUS1*}. We measured the shmooing index of α-playing-a P_{FUS1*-BAR1} cells at various concentrations of α-factor and did two different comparisons (Figure 2.8B). The first was to compare the shmooing index of α-playing-a P_{FUS1*-BAR1} cells to α-playing-a P_{BAR1-BAR1} cells, which lack detectable Bar1 activity, to ask whether expression from the FUS1* promoter produces active Bar1 (Figure 2.8). The α-playing-a P_{FUS1*-BAR1} cells make fewer shmoos at 50nM α-factor than α-playing-a P_{BAR1-BAR1} cells make at 2nM α-factor, indicating that α-playing-a P_{FUS1*-BAR1} cells are able to secrete Bar1 (p=0.02) (Figure 2.8). To ask if α-playing-a cells that express BAR1 under P_{FUS1*} respond to α-factor like wild-type MATa cells, we compared the shmooing index of α-playing-a cells to wild-type MATa cells. The α-playing-a P_{FUS1*-BAR1} cells form a significantly higher percentage of shmoos at each concentration of α-factor tested than wild-type MATa cells (p<0.005) (Figure 2.8B). This suggests that these cells secrete less Bar1 than wild-type MATa cells. We wondered whether this decreased Bar1 secretion could account for the decreased mating efficiency of the α-playing-a cells. To test this possibility, we placed BAR1 under the
FUS1* promoter in wild-type MATa cells and determined that MATa P_{FUS1*}-BAR1 cells are able to mate as efficiently as wild-type MATa cells when crossed to wild-type MATa cells (Figure 2.10). This implies that expressing BAR1 under the FUS1* promoter does not have a detrimental effect on mating efficiency at least when this is the sole manipulation to the mating machinery.

We also assayed the response of α-playing-a cells to α-factor in a microfluidics flow chamber that continuously supplies α-factor and allows us to monitor individual cells over time. Pheromone stimulation arrests MATa cells in G1 through phosphorylation of Far1, a protein that binds to cyclin-dependent kinase/cyclin complexes\(^{16,51,52}\). When MATa bar1Δ cells are exposed to 10nM α-factor, their cell cycle remains arrested for many hours even though they form multiple successive shmoos (Figure 2.11A and Movie A1). However, even at this high concentration of α-factor, α-playing-a bar1Δ cells form shmoos but arrest only transiently (Figure 2.11B and Movie A2). Cells that do not fully arrest in response to pheromone stimulation have been shown to have decreased mating efficiency\(^{53}\), so we hypothesize that the lack of sustained cell cycle arrest in pheromone-stimulated α-playing-a cells could contribute to their low mating efficiency.

**The control of pheromone-induced cell cycle arrest in α-playing-a cells is complex**

We hypothesized that the transient cell cycle arrest in α-playing-a cells is either due to a difference in the response of MATa and MATa cells to pheromone stimulation or to the interaction of Ste2 with MATa-specific genes in the α-playing-a cells. Our first step was to study the epistatic relationships of the genes involved in cell cycle arrest, so we manipulated the transcription factors expressed at the MAT locus. MATa cells express the transcription factors Mata1, which induces expression of α-specific genes, and Mata2, which represses expression of a-specific genes\(^{54}\). The α-playing-a cells express these transcription factors but also express Ste2
Figure 2.10. Expressing BAR1 under $P_{FUS1}$ does not decrease the mating efficiency of $MATa$ cells. Mating efficiency of cells with different nutritional auxotrophies grown to log phase and then mixed at a 1:1 ratio on a nitrocellulose filter, which was placed on a YPD plate for 5 hours. Relative mating efficiencies are the percentage of diploids that form colonies on double dropout plates compared to the number of colonies formed on single dropout plates relative to a wild-type cross. Error bars are standard deviations.
Figure 2.11. α-playing-a cells arrest only transiently in response to pheromone stimulation. **A.** *MATα bar1Δ* cells shmooing in continuously supplied SC+10nM α-factor in a microfluidics chamber. The picture was taken using DIC with 60x magnification 8 hours after the addition of α-factor. The scale bar indicates 10µm. **B.** α-playing-α *bar1Δ* cells shmooing and budding in continuously supplied SC+10nM α-factor in a microfluidics chamber. The picture was taken using DIC with 60x magnification 8 hours after the addition of α-factor. The scale bar indicates 10µm.
and α-factor. By deleting MATα2 in α-playing-α cells, it is possible to create a strain that expresses all of the MATα- and MATα-specific genes but only the α-factor receptor, Ste2, and the pheromone, a-factor. When we expose the α-playing-α bar1Δ mata2Δ cells to α-factor, these cells are capable of sustained arrest, implying that the expression of MATα-specific genes overrides the lack of prolonged arrest of α-playing-α cells (Figure 2.12A). An alternative manipulation, deletion of MATα1 in MATα cells, produces asexual haploid cells. The absence of Mata1 prevents expression of α-specific genes, and the presence of Mata2 prevents the expression of a-specific genes. We made such a strain responsive to α-factor by expressing Ste2 from the HIS3 promoter, which normally leads to modest expression of an enzyme required for histidine synthesis55,56. When we expose MATα mata1Δ P(HIS3-STE2) cells to α-factor, we observe that these cells also arrest indicating that the default for haploid cells exposed to pheromone is sustained G1 arrest (Figure 2.12B). This indicates that the interaction of the genes expressed in MATα and MATα cells involved in the control of cell cycle arrest is complex, leading us to hypothesize that multiple genes may control the lack of cell cycle arrest in α-playing-α cells.

To look for genes that might account for the lack of prolonged cell cycle arrest in α-playing-α cells, we compared the transcriptomes of MATα and α-playing-α cells in the presence and absence of α-factor. We investigated four genes that were expressed at higher levels in α-playing-α cells than MATα cells and were thus candidates for genes that had to be repressed to produce enduring cell cycle arrest: PCL1, TOS4, SRL3, and YGR035C (Table 2.1). We did not see any appreciable difference in the response to pheromone stimulation of α-playing-α cells deleted for these genes than the response to pheromone stimulation of α-playing-α wildtype for these genes, suggesting that none of them are individually responsible for the transient
Figure 2.12. Manipulating the genes expressed at the MAT locus causes extended arrest in α-playing-a cells in response to pheromone stimulation. **A.** α-playing-a bar1Δ mata2Δ cells shmooing in continuously supplied SC+10nM α-factor in a microfluidics chamber. The picture was taken using brightfield with 60x magnification 8 hours after the addition of α-factor. The scale bar indicates 10µm. **B.** MATa mata1Δ PHIS3-STE2 cells shmooing in continuously supplied SC+10nM α-factor in a microfluidics chamber. The picture was taken using brightfield with 60x magnification 8 hours after the addition of α-factor. The scale bar indicates 10µm.
pheromone-induced arrest of α-playing-a cells (Figure 2.11B and 2.13A-D). We also
investigated $GYP8$, which is expressed more strongly in $MATa$ than in α-playing-a cells (Table
2.1). We deleted this gene from $MATa$ bar$1A$ cells and overexpressed it from the $ACT1$
promoter in α-playing-a cells. We did not see a reproducible change in the response to either of
these strains to α-factor when compared to the parent cells (Figure 2.11 and 2.13E-F). We
hypothesize that the control of cell cycle arrest in α-playing-a cells is complex and involves
multiple genes: either a combination of the genes that we manipulated individually or other
genes whose differential transcription lies below the threshold that we set for our targeted genetic
manipulations.

How robust is the mating response?

Investigating how efficiently the transvestite cells mate with wild-type partners is useful
to learn more about the regulation of genes necessary in each mating type for efficient mating.
Investigating how efficiently the transvestite cells mate with each other can tell us more about
how robust the process of mating is. Crossing a-playing-α cells to wild-type $MATa$ cells reduces
mating efficiency three-fold, and crossing α-playing-a cells to wild-type $MATa$ cells reduces
mating 60-fold, relative to a wild-type $MATa$ x $MATa$ cross, but crossing the two transvestite
strains resulted in a 650-fold decrease in mating efficiency compared to wildtype, leading us to
believe that mating defects are synergistic ($p<10^{-6}$) (Figure 2.14). If this synergism is largely due
to reduced pheromone production by the transvestite strains, increasing pheromone production
should increase the efficiency of the inter-transvestite cross. We increased α-factor production
from a-playing-α by placing $MFα1$ under the control of the $TDH3$ promoter and a-factor
production from α-playing-a cells by deleting $AFB1$. When these strains were mated to each
other, they mate 90 times better than the cross between the parental a-playing-α and
Figure 2.13. The control of pheromone-induced cell cycle arrest in α-playing-a cells is complex. A. α-playing-a bar1Δ pcl1Δ cells shmoong and budding in continuously supplied YPD+10nM α-factor in a microfluidics chamber. The picture was taken using DIC with 40x magnification 8 hours after the addition of α-factor. The scale bar indicates 10µm. B. α-playing-a bar1Δ tors4Δ cells shmoong and budding in continuously supplied SC+10nM α-factor in a microfluidics chamber. The picture was taken using DIC with 60x magnification 8 hours after the addition of α-factor. The scale bar indicates 10µm. C. α-playing-a bar1Δ srl3Δ cells shmoong and budding in continuously supplied SC+10nM α-factor in a microfluidics chamber. The picture was taken using DIC with 60x magnification 8 hours after the addition of α-factor. The scale bar indicates 10µm. D. α-playing-a bar1Δ ygr035cΔ cells shmoong and budding in continuously supplied SC+10nM α-factor in a microfluidics chamber. The picture was taken using DIC with 60x magnification 8 hours after the addition of α-factor. The scale bar indicates 10µm.
Figure 2.13 (continued). The control of pheromone-induced cell cycle arrest in α-playing-a cells is complex. E. MATα bar1Δ gyp8Δ cells shmooring in continuously supplied SC+10nM α-factor in a microfluidics chamber. The picture was taken using DIC with 60x magnification 8 hours after the addition of α-factor. The scale bar indicates 10µm. F. α-playing-a bar1Δ PACT1-GYP8 cells shmooring and budding in continuously supplied YPD+10nM α-factor in a microfluidics chamber. The picture was taken using DIC with 20x magnification 8 hours after the addition of α-factor. The scale bar indicates 10µm.
Figure 2.14. Mating is not robust to changes in pheromone production. Mating efficiency of cells with different nutritional auxotrophies grown to log phase and then mixed at a 1:1 ratio on a nitrocellulose filter, which was placed on a YPD plate for 5 hours. Relative mating efficiencies are the percentage of diploids that form colonies on double dropout plates compared to the number of colonies formed on single dropout plates relative to a wild-type cross. Error bars are standard deviations. Note the log scale.
α-playing-α cells ($p<10^{-6}$) (Figure 2.14). Thus, improving pheromone production increases the mating frequency of the inter-transvestite cross to the point where it is only eight-fold less efficient than a standard $MAT\alpha \times MAT\alpha$ cross ($p<10^{-6}$) (Figure 2.14). It is possible that focusing on the production of and response to pheromone caused us to miss some of the mating defects caused by our genetic manipulations. However, we believe that at least in the case of the α-playing-α cells we have identified the main defect. To test this, we crossed the “pseudo”-α-playing-α cells ($MAT\alpha mfa1\Delta$) with the α-playing-α cells. Since we hypothesize that low α-factor production is the main defect in the α-playing-α cells, we expect the mating efficiency of this cross to be similar to the transvestites crossed each other, and that is indeed what we see (Figure 2.14). This indicates that genetic manipulations that cause relatively modest mating defects in isolation, such as the deletion of one of the α-factor genes, can lead to much greater effects when combined with a compromised partner. We interpret this to mean that yeast have evolved a complex and highly regulated process to control cell fusion and that careful regulation of this process is important for efficient mating.

**DISCUSSION**

Mating type in yeast is controlled by the transcription factors expressed at the $MAT$ loci\(^3\). $MAT\alpha$-specific genes have been well studied and consist of α-factor\(^8\), the α-factor exporter (Ste6)\(^57\), the α-factor receptor (Ste2)\(^9\), a protease that cleaves α-factor (Bar1)\(^21\), a protein involved in attenuation of the pheromone response in early diploids (Asg7)\(^26,27\), and the α-agglutinin (Aga2)\(^23,45\). The genes specifically expressed by $MAT\alpha$ cells have been less well studied, but previously characterized $MAT\alpha$-specific genes include α-factor\(^5,6\), the α-factor receptor (Ste3)\(^7\), and the α-agglutinin (Sag1)\(^24,45\). Because a useful way to study a system is to try to build it, we created transvestite strains that express the transcription factors at the $MAT$ locus of one mating
type but the known mating type-specific genes of the opposite mating type. Although these transvestite strains are able to mate with wild-type strains of their original mating type and with each other, the mating efficiency of these crosses is lower than that of a wild-type cross indicating that there are additional mating type-specific genes that have not been fully characterized. We identified one of these, AFB1, as encoding an α-factor barrier protein. Our results indicate that mating is a fragile process: modest quantitative changes in the expression of critical genes reduce the efficiency of mating and multiple such defects interact synergistically to dramatically reduce mating efficiency.

MATα cells that express α-factor and Ste3 instead of α-factor and Ste2, which we call α-playing-α cells had a mating efficiency that was 3-fold less than that of wild-type MATα cells, and the mating defects in this strain were shown to be mainly from decreased α-factor production by α-playing-α cells. The level of α-factor secretion has previously been shown to be important for efficient mating²⁹, and by increasing the amount of α-factor secreted from the α-playing-α cells we were able to increase the mating efficiency of these cells to close to wild-type levels.

The mating defects associated with MATα cells that express α-factor and Ste2 instead of α-factor and Ste3, which we call α-playing-a cells, proved to be more complex. α-playing-α cells also showed decreased pheromone production when compared to wild-type MATα cells, and we were able to identify the function of the previously uncharacterized MATα-specific open reading frame, YLR040C, which we named AFB1 for α-factor barrier. AFB1 has been annotated as a secreted protein⁴⁷,⁴⁸ and we showed that the expression of this protein by α-factor-producing cells causes decreased α-factor secretion. Although there was no mating defect in wild-type MATα cells deleted for AFB1, as reported previously⁴⁵, we did see a significant increase in
mating efficiency when \textit{AFBl} was deleted from the \textit{\alpha}-playing-a cells. We hypothesize that \textit{AFBl} has two possible functions, which are not mutually exclusive.

The first is a reciprocal function to Bar1, which allows \textit{MATa} cells to more accurately detect an \textit{\alpha}-factor gradient. While there are asymmetries in ascomycete mating, such as the difference in the hydrophobicity of a-factor and \textit{\alpha}-factor\textsuperscript{5,8}, gradient detection is important for both \textit{MATa} cells searching for nearby, \textit{\alpha}-factor producing cells and for \textit{MATa} cells searching for nearby, a-factor producing cells\textsuperscript{40}. Modeling the effect of Bar1 in gradient detection by \textit{MATa} cells has elucidated two general functions for Bar1: one for Bar1 that exits the cell wall of \textit{MATa} cells\textsuperscript{40} and another for Bar1 that is trapped in the cell wall of \textit{MATa} cells\textsuperscript{41,42}.

Bar1 that exits the cell wall acts to decrease the lifetime of any given \textit{\alpha}-factor molecule, reducing the distance \textit{\alpha}-factor can travel and privileging the \textit{\alpha}-factor secreted from nearby cells for detection by a \textit{MATa} cell\textsuperscript{40}. Meanwhile, Bar1 trapped in the cell wall of \textit{MATa} cells serves as an \textit{\alpha}-factor sink, which both makes it easier for \textit{MATa} cells to distinguish between two, close, potential \textit{MATa} partners by reducing the chance of saturating the pheromone receptors\textsuperscript{42} and makes it more likely that \textit{MATa} cells will avoid each other and thus will end up choosing different \textit{MATa} partners\textsuperscript{41}. Since \textit{\alpha}-factor is more hydrophilic than a-factor, it is likely to have a higher effective diffusion constant than a-factor, which binds tightly to hydrophobic surfaces. As a result, it is more likely that \textit{MATa} cells will detect \textit{\alpha}-factor from distant \textit{MATa} cells than vice versa, making it less necessary for Afb1 to perform the reciprocal function to that accomplished by Bar1 that exits the cell wall. Accordingly, Afb1 is predicted to have a glycoposphatidylinositol (GPI) anchor\textsuperscript{48}, which would keep it associated with the plasma membrane. Thus, Afb1 is likely only to serve in distinguishing between two potential mating
partners and avoiding other $MAT\alpha$ cells, and for this reason it is unsurprising that removing Bar1 from $MAT\alpha$ cells causes a stronger mating defect than removing Afb1 from $MAT\alpha$ cells.

The second possible function is that $AFB1$ acts in concert with $ASG7$ to reduce self-stimulation in early diploids$^{26,27}$. Although translation of new mating-type specific genes is turned off in early diploids$^{54}$, these cells will still express both pheromones and both pheromone receptors until these proteins are either diluted out by cell growth or internalized and degraded. $Asg7$ is an $a$-specific gene that interacts with $Ste3$ and causes internalization of $Ste3$ and $Ste4$, the G-protein $\beta$-subunit, in early diploids$^{26}$. It is possible that Afb1 sequesters or degrades the $a$-factor secreted by the early diploid and from nearby, unmated $MAT\alpha$ cells in a dense mating mixture allowing the new diploid to form a first bud more rapidly.

We also observed that although $\alpha$-playing-$a$ $P_{BAR1}$-$BAR1$ cells have shmooing indices that are statistically indistinguishable from wild-type $MAT\alpha$ $bar1\Delta$ cells, $\alpha$-playing-$a$ $bar1\Delta$ cells only transiently arrest the cell cycle in response to pheromone stimulation. This is surprising because canonically it is thought that both $MAT\alpha$ and $MAT\alpha$ cells arrest the cell cycle in the same fashion: by signaling through $Far1^\text{ref.}^4,51$. However, while cell cycle arrest in $\alpha$-factor-stimulated $MAT\alpha$ cells has been well studied, the hydrophobicity of $a$-factor has made the study of cell cycle arrest in $a$-factor-stimulated $MAT\alpha$ cells more difficult. Using the $\alpha$-playing-$a$ cells, we were able to carefully study the effect of pheromone stimulation on $\alpha$-playing-$a$ cells over time, which allowed us to observe the transient cell cycle arrest of these cells. Once again we hypothesize that there are two possible explanations for the transient cell cycle arrest of $\alpha$-playing-$a$ cells. The first is that $MAT\alpha$ and $MAT\alpha$ cells do not respond to pheromone stimulation in the same way and that $MAT\alpha$ cells shmoo but do not experience enduring arrest. However, this seems unlikely.
because pheromone-stimulated arrest is important to ensure that nuclear fusion does not occur when the cells are in different phases of the cell cycle.

The second possibility is that the interaction between Ste2 and proteins present in the α-playing-a cells causes these cells to continue to cycle through the cell cycle, similar to the effect seen in mata2Δ ASG7 cells\textsuperscript{20,27}. Unlike in the case of ASG7, the lack of sustained cell cycle arrest in α-playing-a cells is unlikely to be controlled by a single gene. By manipulating the transcription factors expressed at the MAT locus in α-playing-a and MATα cells, we were able to determine that two different scenarios restore the ability of α-factor to cause prolonged cell cycle arrest: expressing MATα-specific as well as MATα-specific genes and expressing Ste2 in a cell that expresses neither MATα-specific nor MATα-specific genes. One interpretation of these results is that the default for cells expressing haploid specific genes is arrest and genes expressed in the α-playing-a cells are responsible for the lack of enduring arrest in response to α-factor stimulation. However, previous studies of MATα-specific genes indicate that the only genes directly controlled by Mata1 are STE3, MFα1, MFα2, SAG1, and AFBI\textsuperscript{ref.45}, none of which are candidates for interfering with cell cycle arrest. We therefore investigated genes that might not have been identified in previous studies of unstimulated cells, focusing on those that are differentially expressed between pheromone-stimulated MATα and α-playing-a cells. Although we tested the effect of deleting or overexpressing several genes individually in the α-playing-a cells, we were unable to detect a change in the response of these cells to α-factor stimulation, indicating either that we were unable to identify the gene responsible for this effect, or more likely, that complex regulation of multiple genes controls the response of MATα cells expressing Ste2 to α-factor.
The strains engineered in this study provided a unique opportunity to investigate our knowledge of differences between MATa and MATα cells. We have identified the function of a novel a-factor barrier protein as well as showing that complex expression of multiple genes may control cell cycle arrest in MATα cells that express Ste2. Using the engineered transvestite strains we were able to compare the transcriptomes of pheromone-stimulated MATα cells and MATa cells in a controlled manner. The addition of the knowledge gained in this study provides a more complete picture of the already well-studied pheromone response pathway in budding yeast.

**MATERIALS and METHODS**

**Yeast strains and culturing**

Strains used in this study are listed in Table 2.3. All strains were derived from the W303 wild-type background (ade2-1 can1-100 his3-11,15 leu2-112 trpl-1 ura3-1) using standard genetic techniques. All media was prepared as described in Sherman et al. 1974 and contained 2% wt/vol of glucose. Cells were either grown in Synthetic Complete media (2% glucose) (SC) or Yeast Extract Peptone Dextrose (2% glucose) (YPD) at 30°C in culture tubes on roller drums or agar plates or at room temperature (25°C) for timelapse microscopy. Mating assays were done on agar plates containing SC without adenine (SC-ade), SC without uracil (SC-ura), or SC without adenine and uracil (SC-ade-ura). Bovine serum albumin (BSA) was used to reduce the non-specific absorption of α-factor to glass and plastic surfaces. A 10% wt/vol stock was prepared in deionized water and then diluted into media to 0.1% wt/vol. Synthetic α-factor (Biosynthesis, Lewisville, TX) was suspended in dimethyl sulfoxide (DMSO) and then diluted into YPD + 0.1% BSA or SC + 0.1% BSA at the appropriate concentration. Peptone, yeast extract, and yeast nitrogen base were obtained from BD (VWR). Bacto-agar was obtained from
US Biological (Swampscott, MA). Unless otherwise noted, all chemicals were obtained from Sigma-Aldrich.

**Quantitative Mating Assay**

Quantitative mating assays were modified from Reid and Hartwell, 1977\(^5\). Briefly, cells were grown to log phase (~5x10\(^6\) cells/mL). 5x10\(^6\) cells were harvested from each strain, mixed at a 1:1 ratio, sonicated, and filtered onto a 0.22µm nitrocellulose filter (Millipore, MA). Filters were placed on a YPD plate and incubated at 30\(^o\)C for 5 hours. To assay for the initial ratio of the haploid cells, a 2.5x10\(^{-5}\) dilution of the initial mating mixture was plated onto SC-ade and SC-ura plates. After 5 hours, cells were washed off the filters into 1mL of deionized water and then plated onto SC-ade, SC-ura, and SC-ade-ura plates at appropriate dilutions to result in the growth of ~400 colonies per plate. SC dropout plates were incubated for 2 days before counting the colonies on each plate. Mating efficiencies were determined by dividing the number of colonies on the SC-ade-ura plate by the number of colonies on whichever of the SC-ade or SC-ura plate had fewer colonies. Three technical replicates were done of each mating assay and averaged for a single biological replicate. Error bars are standard deviation of biological replicates. Statistical significance was determined using Student’s \(t\)-test.

**Bioassay for α-factor production**

The bioassay for α-factor production was modified from Goncalves-Sa and Murray, 2011\(^6\). To measure unstimulated α-factor production, cells were grown to log phase (~5x10\(^6\) cells/mL), washed into YPD + 0.1% BSA, and resuspended in BSA-coated culture tubes at 5x10\(^6\) cells/mL in YPD + 0.1% BSA. The supernatant of the media was then harvested after a 15 minute, 30 minute, or 120 minute incubation at 30\(^o\)C on a roller drum using BSA-coated 1mL syringes (BD from VWR) and filtered through 0.45µm BSA-coated syringe filters (Pall
Corporation, New York). 5x10^5 log phase MATa bar1Δ cells were then incubated in 1x, 0.5x, and 0.2x dilutions of the supernatant for 2 hours, sonicated, fixed using 60% ethanol at 20°C, and resuspended into 20% glycerol in phosphate buffered saline (PBS). The percent of the cells shmooing was counted and compared to a standard curve.

Stimulated α-factor production was measured in the same way except that the cells being tested were grown to log phase (~5x10^6 cells/mL), counted, and washed into YPD + 0.1% BSA and 5x10^6 cells/mL of the cells being tested were mixed with 5x10^5 cells/mL MATa bar1Δ cells. After 2 hours incubation at 30°C on roller drums, the cells were washed into fresh YPD + 0.1% BSA and put into BSA-coated culture tubes. The supernatant was then harvested and analyzed as described above.

To generate a standard curve, MATa bar1Δ cells were incubated in integer values of synthetic α-factor concentrations between 0nM and 7nM and a best fit line was generated with an R^2 of 0.9 to determine a constant (K) for the relationship between α-factor concentration and the percentage of shmoos (K=0.07). α-factor production in molecules/cell/minute was then determined by \( \frac{N \times K \times \% \text{ shmoos} \times \text{volume}}{r \times 2^D \times t \times l} \), where N is Avagadro’s constant, r is the starting number of cells, D is the number of doublings expected, t is the incubation time, and l is the dilution. The expected number of doublings was calculated by the incubation time divided by an expected 90 minute doubling time for yeast.

Culture tubes and syringes were BSA-coated by incubating overnight at 4°C with PBS + 2% BSA. The PBS + 2% BSA was poured out immediately prior to use of the culture tube or syringe. Filters were BSA-coated by filtering 1mL of PBS + 2% BSA through them prior to use. At least 200 cells were counted to determine the percentage of cells shmooing. Error bars are standard deviation. Statistical significance was determined using Student’s t-test.
**Shmooing index**

Cells were grown to log phase (~5x10^6 cells/mL), washed into YPD + 0.1% BSA with various concentrations of synthetic α-factor added at 5x10^5 cells/mL, and then incubated at 30°C on a roller drum for 2 hours. After incubation, the cells were sonicated, fixed using 60% ethanol at 20°C, and resuspended into 20% glycerol in PBS. At least 200 cells were counted to determine the percentage of cells shmooing. Error bars are standard deviation. Statistical significance was determined using Student’s t-test.

**Microscopy**

Microscopy was done at room temperature using a Nikon Ti-E inverted microscope with either a 20x Plan Apo VC 0.75NC air lens, 40x Plan Fluor 0.75NA air lens, or a 60x Plan Apo VC 1.4NA oil lens, and images were acquired with a Photometrics CoolSNAP HQ camera (Roper Scientific, AZ). Timelapse photography was done using Metamorph 7.7 (Molecular Devices, CA).

Pictures of the MATa/a and MATα/α diploids were acquired by growing cells to log phase (~5x10^6 cells/mL) at 30°C in YPD. Cells were then loaded into a microfluidics chamber (CellAsic, CA)\(^6\), which was pretreated by perfusing YPD through the chamber at 34kPa for 10 minutes. Once cells were loaded, YPD was perfused through the microfluidics chamber at 14kPa. Pictures were taken using a 60x Plan Apo VC 1.4NA oil lens (60x magnification) every 10 minutes for 10 hours using differential interference contrast with a 10ms exposure.

Pictures and movies of various strains responding to 10nM α-factor were done in a similar way. Cells were grown to log phase (~5x10^6 cells/mL) at 30°C in YPD, washed into rich media + 0.1% BSA (either YPD or SC as indicated in the figure legend), and loaded into a microfluidics chamber, which had been pretreated by perfusing PBS + 2% BSA through the
chamber at 34kPa for 10 minutes and then rich media + 0.1% BSA through the chamber at 34kPa for 10 minutes. Once the cells were loaded, rich media + 0.1% BSA + 10nM α-factor was perfused through the chamber at 14kPa. Pictures were taken every 10 minutes for 8 hours using either a 20x Plan Apo VC 0.75NC air lens (20x magnification), a 40x Plan Fluor 0.75NA air lens (40x magnification), or a 60x Plan Apo VC 1.4NA oil lens (60x magnification) with either differential interference contrast with a 10ms exposure or brightfield with a 6ms exposure.

For pictures of the a-playing-α cells responding to α-factor, MATα PACT1-mCherry cells were mixed with a-playing-α cells on a filter as described for the quantitative mating assay. Cells were washed off the filters into SC after 2.5 hours and placed directly onto glass slides (Corning). Pictures were taken immediately using a 20x Plan Apo VC 0.75NC air lens (20x magnification) with differential interference contrast with a 10ms exposure and fluorescence with a 300ms exposure.

**Halo Assay**

Halo assays were modified from Sprague, 1991. Cells whose α-factor production was to be measured were grown to saturation in YPD at 30°C. For halo assays on individual cells, 4.5x10⁸ cells of each strain were pelleted and resuspended in 20µL of deionized water. For halo assays on cell mixes, cells were mixed at a 1:8 ratio (MATα wildtype:cell type of interest) with a final cell count of 4.5x10⁸. Cells were pelleted and resuspended in 20µL of deionized water. 10µL of each strain or strain mix was spotted onto YPD plates and incubated overnight (~24 hours) at 30°C. Supersensitive MATα sst2Δ cells grown to stationary phase were then sprayed over the cell spots using an Oenophelia martini atomizer (www.amazon.com). Plates were then incubated overnight (~18 hours) at 30°C and pictures were taken using a Panasonic Lumix DMC-TZ5 camera (www.panasonic.com).
RNA isolation and sequencing

Cells were grown to log phase (5x10^6 cells/mL) in YPD + 0.1% BSA at 30°C. 10mL of culture was harvested by spinning at 4°C, washed in 1mL RNase-free ice-cold water, pelleted, and flash frozen in dry ice. 10nM α-factor was added to the remaining culture, incubated for 2 hours at 30°C, and harvested in the same manner. RNA isolation was done as described in Collart and Oliveira 2001^63 and suspended in sodium citrate. All necessary RNase-free chemicals were obtained from Invitrogen (NY) except for chloroform, which was obtained from VWR.

RNA libraries were prepared using the Illumina TruSEQ kit (www.illumina.com) and sequenced using an Illumina HiSeq 2000 with 50 base pair, single end reads with 89x mean coverage across the genome.

Sequence analysis

To analyze the sequencing data, the RNA sequences were aligned to the S288C reference genome r64 (downloaded from the Saccharomyces Genome Database www.yeastgenome.org) using TopHat^64. We then used Cufflinks to look for genes with significantly different levels of gene expression between MATα bar1Δ cells and α-playing-α P_BAR1^BAR1 cells. Significant differences in expression were identified using the default setting in Cufflinks^65.
Table 2.3. Strains used in Chapter 2.

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References


CHAPTER 3

Polarized secretion and restricted diffusion of cell wall remodeling enzymes induces cell wall dissolution in pheromone-stimulated yeast cells
ABSTRACT

Cell fusion is an important event in the life cycle of many organisms. In humans it is necessary for muscle cell formation and the fertilization of an egg by sperm. A useful model system for studying cell fusion is cell fusion of the budding yeast, *Saccharomyces cerevisiae*, which occurs when two haploid cells of opposite mating types signal through reciprocal pheromones and pheromone receptors, grow towards each other, and fuse to form a single diploid cell. Since yeast cells have both a cell wall and a plasma membrane, this requires both cells to first dissolve their cell walls at the point of contact and is a dangerous task because the osmotic pressure differential between the cytoplasm and extracellular environment is high enough that when the plasma membrane is unprotected, water rushes into the cell causing it to lyse. If a cell dissolves its cell wall at an inappropriate time or location, the cell will die. We hypothesize that cell wall dissolution during budding yeast mating is the result of a contact-driven increase in the local concentration of cell wall remodeling enzymes. When a cell is unattached, the secreted cell wall remodeling enzymes are able to diffuse directly out of the cell wall. However, when two cells are attached, the cell wall remodeling enzymes must diffuse laterally in order to escape the fusion zone, increasing the time spent in the cell wall and, thus, the concentration of cell wall remodeling enzymes leading to cell wall dissolution. To study this we tightly apposed pheromone-stimulated cells to non-permeable surfaces and observed cell lysis using microscopy. We found that pheromone-induced cell lysis increases in frequency with increasing pheromone concentration and decreases in frequency when putative glucanases previously shown to be involved in mating or genes known to be necessary for efficient cell wall fusion are deleted giving strong support to our hypothesis.
INTRODUCTION

Cell fusion is an important event in the life cycle of many organisms. In mammals, it is necessary for fertilization of an egg by sperm and formation of myoblasts, osteoclasts, giant cells, and placental cells\(^1\)\(^{-}\)\(^4\). It is also important in the development of *Caenorhabditis elegans* and *Drosophila melanogaster*, as well as in the life cycle of many algae, such as *Chlamydomonas reinhardtii* and fungi, such as *Neurospora crassa*\(^5\)\(^{-}\)\(^8\). Perhaps the simplest and most well studied form of cell fusion is the mating of the budding yeast, *Saccharomyces cerevisiae*\(^9\).

Budding yeast can exist in both a diploid and haploid state. In either state, cells can replicate asexually by budding, producing daughters that are genetically identical to their mothers. Haploid cells can be one of two mating types: *MATa* or *MATa*. When two haploid cells of opposite mating types come in contact with one another, they are capable of fusing to form a single diploid *MATa/MATa* cell\(^10\).

Intercellular signaling between budding yeast cells is important for efficient mating. Signaling is achieved through G-protein coupled receptors on the plasma membrane of each cell, which bind pheromones produced by cells of the opposite mating type\(^11\). *MATa* cells produce \(\alpha\)-factor and express the \(\alpha\)-factor receptor, Ste3, on their surface\(^12\)\(^{-}\)\(^14\). *MATa* cells produce \(\alpha\)-factor and express the \(\alpha\)-factor receptor, Ste2, on their surface\(^15\),\(^16\). When *MATa* cells are grown in cultures containing only other *MATa* cells, \(\alpha\)-factor and Ste2 are expressed at low levels\(^17\),\(^18\). However, when Ste2 binds \(\alpha\)-factor, a mitogen-activated protein (MAP) kinase cascade, which is conserved in other ascomycete fungi, is started, stimulating the cell to produce higher levels of its own pheromone, \(\alpha\)-factor, and the receptor for \(\alpha\)-factor, Ste2, as well as upregulating other proteins involved with mating\(^11\),\(^19\)\(^^{-}\)\(^21\). Pheromone stimulation arrests *MATa* cells in G1, polarizes
them in the direction of highest pheromone concentration, and induces polarized cell growth to form a mating projection known as a shmoo^{19,22-24}. $MAT\alpha$ cells produce a similar, coordinated response using the reciprocal G-protein coupled receptor (Ste3) and mating pheromone^{12-14,18-20,22,23}.

After $MAT\alpha$ and $MAT\alpha$ cells have successfully communicated and grown towards each other, they must fuse^{10}. The two cells initially bind to each other at their shmoo tips using mating agglutinins^{25-27}, but their plasma membranes are still separated by approximately 100nm thick cell walls^{28}. Before the mating partners can fuse, the cell wall that lies between the two membranes must be dissolved and the boundaries of the remaining cell walls, which surround the site of cell fusion, must fuse to form a single, continuous structure that will surround the newly formed zygote^{9}. The osmotic pressure differential between the cytoplasm and the extracellular environment makes this spatially regulated cell wall dissolution and fusion a dangerous task^{29,30}. If the cell wall is opened at the wrong time or in an inappropriate location, exposing the plasma membrane directly to the environment, there will be no elastic force to resist the turgor pressure of the cell, water will rush into the cell from the extracellular environment, and the cell will lyse^{29,30}.

Various studies have been done on the molecular basis for cell wall dissolution. In 1996, Brizzio et al. showed that high pheromone concentrations are required for efficient fusion and hypothesized that numerous vesicles found at the shmoo tip might contain cell wall remodeling enzymes^{31}. Later, Cappellaro et al. found several proteins with homology to known cell wall glucanases, including $SCW4$ and $SCW10$, whose deletion makes mating less efficient^{32}. The genes for two putative glucanases $SCW10$ and $SCW11$, another gene found by Cappellaro et al.^{32}, were also found to have binding sites for Ste12, the transcription factor that regulates genes in
response to pheromone stimulation, in their promoters. The vesicles found in the shmoo tip are hypothesized to be transported to the cell fusion zone by a complex containing Rvs161, an amphiphysin-like protein that binds curved membranes and is involved in cell fusion, and Fus2, another protein known to be involved in cell fusion. Once Fus2 and its hypothesized vesicle cargo has reached the plasma membrane, it is anchored there by Fus1, a membrane spanning protein involved with cell fusion that interacts with the polarisome, a protein complex associated with polarized actin polymerization, presumably ensuring tight clustering of the secretory vesicles. However, prior to cell fusion, the cell wall must be dissolved, and none of the methods that have been proposed to regulate cell wall dissolution limit this remodeling to the site of fusion with a polarized partner.

The problem of remodeling the cell wall is not unique to mating. Even when cells are growing isotropically, there must be a balance between cell wall synthesis and destruction to allow the continual increase in cell diameter and volume. Cell wall-modifying enzymes can either be attached to the plasma membrane or cell wall or be secreted and free to diffuse through the cell wall, and these enzymes can be involved in synthesizing and cross-linking the polysaccharides that make up much of the cell wall or in cleaving these bonds. These two processes must be carefully balanced: an excess of synthesis over degradation will lead to an increased cell wall thickness and eventually slow growth, whereas an excess of degradation will thin the cell wall to the point that it is unable to resist the osmotic pressure inside the cell.

In an isotropically growing cell, synthetic and remodeling enzymes are secreted uniformly around the cell, whereas the polarized growth that accompanies both budding and shmooing requires similarly polarized secretion of these enzymes (Figure 3.1). Due to this polarized secretion during pheromone stimulation, we hypothesize that cell wall remodeling
Figure 3.1. Secretion in isotropically growing and polarized cells. A. Isotropically growing cells must increase the size of their cell walls equally in all directions to grow larger while maintaining a spherical shape, so cell wall remodeling enzymes are secreted equally in all directions. B. Polarized cells grow in a particular direction, so they must polarize secretion of cell wall remodeling enzymes in order to preferentially expand their cell walls in the direction of polarization.
enzymes, such as Scw4, Scw10, and Scw11, are preferentially released at the shmoo tip, which causes cell wall weakening and allows for continual expansion of the shmoo in the direction of highest pheromone concentration. As a shmoo approaches a suitable partner, the concentration of pheromone increases, tightening the polarization, and increasing the concentration of cell wall remodeling enzymes in the part of the cell wall that has polarized towards the location of highest pheromone stimulation\textsuperscript{48-52}. If the remodeling enzymes are diffusible, the maximum concentration they can reach in a shmoo that has not bound to a partner is limited: even though the secretion rate of cell wall remodeling enzymes is high, the enzymes are able to diffuse through the cell wall, keeping their concentration in the cell wall low enough to balance the need for rapid growth with cell wall rupturing (Figure 3.2A). However, when two shmoo tips are attached to each other via mating agglutinins, it takes longer for cell wall remodeling enzymes to diffuse out of the fusion zone because they must now travel laterally through the cell wall in order to escape, thus increasing the local concentration of the remodeling enzymes and causing the cell walls of the shmoo tips to dissolve specifically at the point of attachment (Figure 3.2B).

Previous studies have reported cell death after exposure to high pheromone concentrations\textsuperscript{53, 54}. Zhang et al. proposed that this death was due to inappropriate activation of cell fusion machinery, resulting in cell wall dissolution and eventual cell lysis\textsuperscript{54}. Although, Zhang et al. observed that this lysis can be regulated by increasing cell wall integrity and deleting certain proteins involved in cell fusion, they did not hypothesize a mechanism through which this process is regulated\textsuperscript{54}. We propose that the reported death is due to tight apposition of cells to non-permeable surfaces, so in this study we investigated the hypothesis that the cell wall dissolution required for mating is the result of a contact-driven increase in the local concentration of cell wall remodeling enzymes. We tightly apposed pheromone-treated cells to a non-
Figure 3.2. Model: Pheromone-stimulated cell wall dissolution is the result of a contact-driven increase in the local concentration of cell wall remodeling enzymes. A. When pheromone stimulated cells are unattached, the cell wall remodeling enzymes secreted from the shmoo tip are able to exit the cell wall along the shortest possible path, i.e. the line perpendicular to the tangent of the curve of the cell. This causes cell wall weakening and allows for continual expansion of the shmoo in the direction of highest pheromone concentration but does not breach the cell wall. B. When two pheromone-stimulated cells are attached by mating agglutinins, the cell wall remodeling enzymes secreted into the fusion zone must now travel a much further distance to exit the cell wall, i.e., laterally along the tangent of the curve of the cell, increasing the local concentration of cell wall remodeling enzymes in the fusion zone. The action of cell wall remodeling enzymes dissolves the two cell walls specifically at the point of contact while simultaneously interlocking them, allowing the plasma membranes of the two cells to come in
(Figure 3.2 continued) contact with one another and fuse. C. To mimic the attachment of two cells by mating agglutinins, we tightly appose cells to non-permeable membranes, forcing cell wall remodeling enzymes to exit the cell wall laterally along the tangent of the curve of the cell and increasing the concentration of cell wall remodeling enzymes at the point of attachment to the non-permeable surface. This causes a hole to form in the cell wall of the cell, exposing the plasma membrane to the extra-cellular environment and causing the cell to lyse due to the osmotic pressure differential.
permeable surface, mimicking the effect of cell-cell attachment during mating (Figure 3.2C). This manipulation induces cell wall lysis whose frequency is reduced by the deletion of putative glucanases and genes known to be involved in cell wall fusion during mating as well as decreasing the osmotic pressure difference between the cell and its environment and increased by increasing the osmotic pressure difference between the cell and its environment.

RESULTS

Cells lyse when attached to a non-permeable surface

We set out to investigate the hypothesis that cell wall remodeling enzymes are constitutively secreted into the extracellular environment during pheromone stimulation and only dissolve the cell wall when their diffusion is restricted by collision with a barrier. We began by looking at the response of pheromone-stimulated cells grown in bulk culture. To do this, MATα cells that were either deleted or wild-type for the α-factor protease, Bar155 were grown to log phase and then incubated in media with α-factor. Because bar1Δ cells are significantly more sensitive to α-factor than BAR1+ cells56, we stimulated bar1Δ cells with 50nM α-factor and BAR1+ cells with 10µM α-factor, observed all cells after 5 hours of pheromone stimulation, and found that roughly 10% of the cells in each of the bulk cultures appear to lyse (Figure 3.3). We investigated the lysis of the bar1Δ and BAR1+ cells and noticed that most of the lysed cells appeared to be in cell clumps as opposed to floating freely as single cells (Figure 3.4). Although both mating agglutinins are required for pheromone-induced agglutination to occur57, cultures containing only a single mating type can still form clumps due to incomplete separation after budding58. Therefore, we theorized that the cells lyse because they are attached to another cell or potentially have come in contact with the non-permeable surface of the culture tube, causing a
Figure 3.3. Pheromone-stimulated cell lysis is dependent on attachment to a non-permeable surface. MATα cells that were either deleted or wild-type for the α-factor protease gene, BAR1, were pheromone stimulated in rich media in three different environments for five hours, imaged, and then the number of lysed and live cells was counted. BAR1+ cells were grown in 10µM α-factor. bar1Δ cells were grown in 50nM α-factor. Bulk culture refers to cells that were incubated in test tubes in liquid media. Concanavalin A chamber refers to a chamber many times the diameter of a single yeast cell in which cells were attached to a glass coverslip using the lectin, concanavalin A. The chamber was filled with rich media containing α-factor using capillary action and the cells were observed using microscopy. Flow chamber refers to a microfluidics chamber whose floor and ceiling are separated by the height of a single yeast cell through which new media is constantly perfused. The floor of the chamber is glass, so the cells can be observed using microscopy.
A. MATα bar1Δ cells were grown in rich media containing 50nM α-factor in a culture tube in liquid media for 5 hours and then imaged using 20x magnification. Yellow arrows point to cells that have lysed. The scale bar indicates 10µm.

B. MATα BAR1+ cells were grown in rich media containing 10µM α-factor in a culture tube in liquid media for 5 hours and then imaged using 20x magnification. Yellow arrows point to cells that have lysed. The scale bar indicates 10µm.

Figure 3.4. Pheromone-stimulated cell lysis in bulk culture occurs mainly in cell clumps.
high concentration of cell wall remodeling enzymes to build up in the part of the cell wall that is tightly apposed to the non-permeable surface.

Bulk culture limits our ability to observe individual cells and accurately control their environment. We used two techniques to overcome these limitations and study the effect of attaching pheromone-stimulated cells to a non-permeable surface. To mimic the attachment of two cell walls via mating agglutinins, we first attached cells to the non-permeable surface of a glass coverslip using the lectin, concanavalin A, which binds to carbohydrates in the cell wall. In order to image the yeast cells for an extended period of time, we created a chamber that was several hundred times the diameter of a yeast cell. The chamber was filled with medium containing α-factor using capillary action and then sealed and observed.

We found that $MATa$ $bar1Δ$ cells attached covalently to a non-permeable surface were 1.6 times more likely to lyse than those in bulk culture, indicating that attachment to a non-permeable surface increases the rate of cell lysis ($p<0.02$) (Figure 3.3). We did not see a significant change in the rate of lysis of $MATa$ $BAR1^+$ cells (Figure 3.3). This may be because as the cells incubated in the relatively small volume of media in the chamber, the Bar1 secreted by the wild-type cells began to cleave the α-factor present, decreasing the α-factor concentration and, thus, the level of pheromone-stimulation the cells in the chamber were experiencing, causing less polarized shmoos. Indeed, not all of the $MATa$ $BAR1^+$ cells attached to the concanavalin-A coated coverslip were pheromone-stimulated (Figure 3.5A). Also, because the pheromone was uniformly present in the media, the cells polarized randomly, which meant that many of the cells, both $BAR1^+$ and $bar1Δ$, polarized away from the non-permeable surface (Figure 3.5B-C).
Figure 3.5. Bar1 produced by wild-type MATα cells reduces the α-factor concentration and cells with essentially infinite space to expand can polarize away from the non-permeable surface. MATα BAR1+ cells were attached to a glass coverslip using concanavalin A and incubated in a chamber with a finite amount of rich media with 10μM α-factor but infinite space to expand for 5 hours. Cells were imaged using 20x magnification. A. Yellow arrows point to budding cells. The scale bar indicates 10μm. B. Yellow arrows point to cells that are polarizing away from the non-permeable surface of the glass coverslip. The scale bar indicates 10μm. C. MATα bar1Δ cells were attached to a glass coverslip using concanavalin A and incubated in a chamber with a finite amount of rich media with 50nM α-factor but infinite space to expand for 5 hours. Cells were imaged using 20x magnification. Yellow arrows point to cells that are polarizing away from the non-permeable surface of the glass coverslip. Yellow (*) indicate cells that have lysed. The scale bar indicates 10μm.
To at least partially address these problems we used a second technique to mimic the attachment of two cell walls via mating agglutinins. We trapped cells in a microfluidics chamber whose floor and ceiling are separated by the height of a single yeast cell through which new media is constantly perfused. Cells are loaded into this device and then trapped between a silicone ceiling and a glass floor, which means that not only are the cells tightly apposed to two non-permeable surfaces, but they are also more likely to polarize towards an impermeable surface. Using an inverted microscope, it is possible to image cells over time through the glass floor as media is perfused through the chamber. Once again we imaged both \textit{MATa BAR1}\textsuperscript{+} and \textit{MATa bar1}\textsuperscript{Δ} cells in \textit{α}-factor for 5 hours. In the flow chamber, the rate of lysis of the \textit{MATa BAR1}\textsuperscript{+} cells was more than twice as high as the rate of lysis in bulk cultures or when attached to concanavalin A-coated coverslips (p<0.02) (Figure 3.3). Similarly, the rate of lysis of the \textit{MATa bar1}\textsuperscript{Δ} cells in the flow chamber was more than twice as high as in bulk culture and 1.5 times the rate of lysis when attached to concanavalin A-coated coverslips, suggesting that a larger area of attachment to a non-permeable surface causes increased cell lysis (p<0.02) (Figure 3.3 and Movie A3).

We asked whether the lysis rate is dependent on the concentration of \textit{α}-factor in the media, by perfusing different concentrations of \textit{α}-factor through the flow chamber and determining the percentage of cells that lyse in 5 hours. We decreased the concentration of \textit{α}-factor the \textit{MATa bar1}\textsuperscript{Δ} cells were exposed to and compared the percentage of lysed cells to that seen in 50nM \textit{α}-factor. As expected, decreasing the \textit{α}-factor concentration decreased the percentage of cells that lysed in the flow chamber. In 5nM \textit{α}-factor, less than 1% of cells lysed in the flow chamber, and as the concentration of \textit{α}-factor was increased, causing cells to form
more tightly polarized shooms, the percentage of lysed cells increased up to 22% in 50nM α-factor (p<0.02) (Figure 3.6).

The flow chamber traps cells by wedging them into a space minutely smaller than a single cell in height. When cells are arrested, such as by pheromone stimulation, the cells increase in size as they continue to grow without dividing. Because of this, it is possible that the increased frequency of cell lysis in the flow chamber as compared to bulk culture and when cells are attached to concanavalin A-coated coverslips is not due to an increased amount of cell surface apposed to a non-permeable surface but rather because the physical strain put on the cell wall is too high, particularly when media is perfused through the chamber at 14 kPa (2psi). We therefore used a different method to arrest the cell cycle without interfering with cell growth. Like pheromone treatment, treating cells with benomyl causes cells to become larger without dividing, but unlike pheromone-arrest, benomyl-arrested cells are unpolarized and arrest in mitosis instead of G1 (Figure 3.7A). If cells in the flow chamber lysed because they were squashed, a similar percentage of benomyl-arrested and α-factor arrested cells should lyse in the flow chamber. Alternatively, if lysis reflects polarized secretion of cell wall remodeling enzymes towards an impermeable surface, the rate of lysis should be significantly lower in benomyl-arrested cells than in pheromone-arrested cells. Although it is possible to find the occasional lysed benomyl-arrested cell, less than 0.5% of these cells lyse, indicating that lysis in the flow chamber is specific to pheromone-arrest as opposed to arrest in general (Figure 3.7B).

**1M sorbitol can mitigate the lysis of cells attached to a non-permeable surface**

Yeast cells require cell walls at least in part due to osmotic pressure. Since the osmolarity of the cytoplasm is higher than the typical extracellular environment, without the rigidity of a cell wall, water would rush into the cell and cause it to lyse. One interpretation of
Figure 3.6. Increasing α-factor concentration increases the tightness of polarization and lysis frequency of MATa bar1Δ cells. MATa bar1Δ cells were grown in a flow chamber for 5 hours perfused with rich media with 5nM, 10nM, 20nM, or 50nM α-factor and imaged using 20x magnification. A. Percentage of cells that lysed after 5 hours. B. Cells grown in 5nM α-factor. Yellow arrows indicate cells that have lysed. The scale bar indicates 10µm. C. Cells grown in 10nM α-factor. Yellow arrows indicate cells that have lysed. The scale bar indicates 10µm. D. Cells grown in 20nM α-factor. Yellow arrows indicate cells that have lysed. The scale bar indicates 10µm. E. Cells grown in 50nM α-factor. Yellow arrows indicate cells that have lysed. The scale bar indicates 10µm.
Figure 3.7. **Benomyl arrested cells rarely lyse in the flow chamber.** Cells were grown in a flow chamber for 5 hours perfused with rich media with 0.1mM benomyl or rich media with 50nM α-factor and imaged using 20x magnification. **A.** Benomyl-arrested cells in the flow chamber. The scale bar indicates 10µm. **B.** Percentage of cells that lysed after 5 hours (p<10^{-6}).
the death of pheromone-treated cells pressed against an impermeable surface is that they are digesting part of their cell walls leading to membrane expansion through a hole in the cell wall and eventual lysis. If this interpretation is correct, it should be possible to affect the rate of lysis by manipulating the osmotic pressure differential between the cell and the medium\textsuperscript{62}.

Although the deaths seen in the flow chamber appear to be caused by osmotic lysis, it is possible they are due to another cause. We did two experiments to determine whether the pheromone-induced deaths are due to osmotic lysis: increasing the osmotic pressure differential between the cytoplasm and the extracellular environment and decreasing the osmotic pressure differential between the cytoplasm and the extracellular environment. To change the osmolarity of the media we added 1M sorbitol so that the osmolarity of the extracellular environment more closely mimicked the osmolarity of the cytoplasm. Deaths due to osmotic lysis should be mitigated by the presence of 1M sorbitol. Because \textit{MATa bar1Δ} cells exposed to 50nM $\alpha$-factor in the flow chamber have the most severe lysis phenotype, we chose these conditions to assay for whether osmoprotection mitigates cell death.

We first tested the effect of increasing the osmotic pressure differential between the cytoplasm and the extracellular environment. Cells were exposed to rich media with 50nM $\alpha$-factor and 1M sorbitol for 5 hours. When in hyperosmotic conditions, cells adapt to the osmotic stress by synthesizing glycerol, which can take place in a matter of minutes\textsuperscript{63-66}. Because of this we were unsurprised to find that approximately one fifth of the cells lysed while incubated in the 1M sorbitol. However, if our hypothesis is correct, it seems reasonable to assume that many of the live cells also have holes in their cell walls and that the presence of the 1M sorbitol is protecting these cells from death. Thus, if we replace the sorbitol-containing media with media lacking sorbitol, we would expect to see rapid cell death as water diffuses into these cells and
causes them to burst. To test this, we washed the media containing 1M sorbitol and α-factor out of the flow chamber after the cells had been exposed for 5 hours and replaced it with media containing only 50nM α-factor. As expected, immediately following the sorbitol washout, the number of lysed cells in the flow chamber more than doubled, supporting the idea that the cells in the chamber are lysing due to a breach in their cell walls as opposed to death for some other reason (Figure 3.8A-C and Movie A4).

To test the effect of decreasing the osmotic pressure differential between the cells and the extracellular environment, we exposed cells to 50nM α-factor in the absence of 1M sorbitol for 80 minutes, at which point cells are just beginning to lyse (Movie A3). We determined the percentage of cells lysed at this point and then perfused the chamber with media containing 1M sorbitol and α-factor and observed the percentage of lysed cells 60 minutes after the change of media. Since the sorbitol is washed in after the cells have begun to shmoo, the cells will have less time to induce the hyperosmotic response, and if the cell death is due to osmotic lysis, we should observe fewer cell deaths when 1M sorbitol is present in the media. When we observe the fold change in cell death between 80 minutes and 140 minutes after α-factor addition in the absence of 1M sorbitol, there is an 8.9-fold increase in the percentage of dead cells (Figure 3.8D). However, when 1M sorbitol is added to the media 80 minutes after α-factor addition, there is only a 1.4-fold increase in the percentage of dead cells between 80 and 140 minutes after α-factor addition, further indicating that the observed pheromone-induced cell death is due to cell wall dissolution (Figure 3.8D).

**Cells lacking cell wall remodeling enzymes lyse less frequently than wild-type cells**

Several cell wall remodeling enzymes have been implicated in mating, including three putative glucanases, Scw4, Scw10, and Scw11 ref. 32. If our hypothesis is correct and if these
Figure 3.8. 1M sorbitol protects cells from pheromone-induced cell lysis. A. Cells were grown in a flow chamber for 7 hours. For the first 5 hours the chamber was perfused with rich media with 1M sorbitol and 50nM α-factor. At the end of 5 hours, the media in the chamber was replaced with rich media with 50nM α-factor and no sorbitol. Cells were imaged using 20x magnification, and the percentage of cells lysed 10 minutes before and 10 minutes after the 1M sorbitol was washed out was determined (p=2x10^{-4}). B. Cells imaged after 4h50m in rich media with 1M sorbitol and 50nM α-factor (10 minutes prior to the washout of the sorbitol). The scale bar indicates 10µm. C. Cells imaged 10 minutes after the media was replaced with rich media with 50nM α-factor and no sorbitol. The scale bar indicates 10µm. D. Cells were grown in the flow chamber for 80 minutes perfused with rich media with 50nM α-factor. After 80 minutes, the chamber was perfused with rich media with 1M sorbitol and 50nM α-factor. Cells were imaged using 20x magnification, and the fold change in cells lysed immediately prior to and 60 minutes after the sorbitol wash-in was determined. In control chambers, no sorbitol was added to the media, and the fold change in cells lysed 80 minutes and 140 minutes after the addition of α-factor was determined (p=9x10^{-5}).
enzymes constitute a majority of the cell wall remodeling enzymes required for cell wall fusion, deleting these genes should reduce the frequency of pheromone-induced cell death in the flow chamber. To test this prediction, we grew MATa bar1Δ cells with SCW4, SCW10, and SCW11 deleted alone and in combination and monitored their lysis in a flow chamber where they were exposed to 50nM α-factor for 5 hours.

Deleting SCW4 and SCW10 individually did not decrease the number of cell lysis events in the flow chamber (Figure 3.9A). However, deleting SCW11 caused a 20% reduction in cell lysis compared to MATa bar1Δ cells and additionally deleting SCW4 in this strain caused cell lysis to reduce by 40% compared to MATa bar1Δ cells (p<10^-3) (Figure 3.9A). Cells that had SCW10 deleted in combination with either of the other two proteins did not have a reduced cell lysis frequency (Figure 3.9A). However, all three of these proteins have additional functions in vegetative cell wall maintenance67, 68, and cells deleted for SCW10 in combination with other cell wall proteins have abnormal cell morphology, slow growth, and increased sensitivity to the cell wall-weakening agent calcoflour white32. Therefore, it is possible that the cell walls of these cells are more brittle than wildtype causing these cells to lyse more frequently in the constraints of the flow chamber. To test this, we observed MATa bar1Δ scw4Δ scw10Δ scw11Δ cells growing vegetatively in the flow chamber in rich media without α-factor and saw that these cells die in the flow chamber even when they are not large and arrested (Figure 3.9B). However, the fact that deleting SCW11 alone and in combination with SCW4 has a significant effect on the rate of cell lysis indicates that these putative glucanases are involved in the observed cell lysis.

**FUS1 and FUS2 are required for cell wall breakdown**

Although Scw4 and Scw11 have been implicated in mating, they are also involved in other aspects of yeast cell wall maintenance, such as breakdown of the cell wall during daughter
Figure 3.9. The deletion of the putative glucanases Scw4 and Scw11 mitigates pheromone-induced cell lysis. 

A. Percentage of cell lysis in MATa bar1Δ cells lacking different combinations of putative glucanases implicated in mating relative to MATa bar1Δ cells grown in a flow chamber for 5 hours perfused with rich media with 50nM α-factor. 

B. MATa bar1Δ scw4Δ scw10Δ scw11Δ cells grown in a flow chamber for 5 hours perfused with rich media and imaged using 20x magnification. Yellow arrows point to dead cells. The scale bar indicates 10µm.
separation after budding\textsuperscript{67,68}. Because of this, we could not be sure if the decrease in cell lysis events in the flow chamber in cells lacking these genes compared to wildtype is specific for pheromone stimulation or because of unrelated differences in the cell wall structure of these strains. The genes \textit{FUS1} and \textit{FUS2} have both been shown to be involved in cell fusion and specifically cell wall fusion during mating but do not have a known function in vegetative cell wall maintenance\textsuperscript{40}. When \textit{FUS1}, \textit{FUS2}, or, both \textit{FUS1} and \textit{FUS2} are deleted in both parents, prezygotes are formed, but cells are unable to dissolve their cell walls to facilitate cell fusion\textsuperscript{40}. Also, in \textit{fus1} and \textit{fus1fus2} mutants, the tightly polarized vesicles seen in the fusion zone of wild-type prezygotes hypothesized to contain cell wall remodeling enzymes are largely absent and more widely dispersed than in wild-type cells\textsuperscript{69}. We hypothesize that if cell lysis in the flow chamber is indeed due to pheromone-stimulated cell wall breakdown, mutations known to impair cell wall fusion should reduce the frequency of pheromone-induced cell lysis events in the flow chamber. Indeed, deleting \textit{FUS1} and \textit{FUS2} alone and in combination caused more than a 14-fold reduction in cell lysis in the flow chamber when cells were exposed to 50nM α-factor for 5 hours in rich media (p<0.002) (Figure 3.10). This gives further evidence that the cell lysis events in the flow chamber are due to pheromone stimulation as opposed to simply a result of physically constraining growing cells. Since \textit{FUS1} and \textit{FUS2} have also been shown to be involved in cell wall fusion, their role in pheromone-induced cell death supports our hypothesis that the cell lysis observed in the flow chamber is due to breakdown of the cell wall.

\textbf{DISCUSSION}

The mating of budding yeast is risky and elaborately choreographed. When two haploid yeast cells mate, they signal through reciprocal pheromones and receptors, stimulate each other to signal ever more strongly, arrest their cell cycles, use pheromone gradients to direct their
Figure 3.10. The deletion of *FUS1* and *FUS2* mitigates pheromone-induced cell lysis.

Percentage of *MATa bar1Δ* cells deleted for different combinations of *FUS1* and *FUS2* lysed relative to *MATa bar1Δ* cells lysed. Cells were grown in a flow chamber for 5 hours perfused with rich media with 50nM α-factor and imaged using 20x magnification.
polarization towards each other, and eventually fuse their cell walls, cell membranes, and nuclei to form a single diploid cell\textsuperscript{9, 19, 24, 48}. Although many aspects of yeast mating have been well studied, the mechanism by which cells fuse their cell walls is still unclear. Cell wall fusion is a particularly dangerous step in yeast mating. The plasma membranes of the two partner cells cannot touch each other and fuse until the cell walls that lie between them have been dissolved\textsuperscript{9}. Because the osmolarity inside a cell is so much higher than outside, the elasticity of the cell wall opposes the osmotic pressure difference between the cytoplasm and the environment, thus keeping water from rushing into the cell and causing it to lyse. A cell that dissolves any part of its cell wall that does not touch a closely apposed mating partner will die\textsuperscript{29, 30}.

Pheromone-induced cell death has been previously attributed to inappropriate cell wall dissolution, but a hypothesis to explain why cells were dissolving their cell walls was not given\textsuperscript{54}. Many hypotheses can be generated to explain how cell wall dissolution is regulated in time and space to promote mating and prevent accidental deaths. Most of them posit additional signaling systems in addition to the known mechanisms of pheromone signaling, but these hypothetical, additional signaling molecules have yet to be uncovered despite a variety of searches\textsuperscript{9, 37, 69, 70}. We therefore sought a hypothesis that required no new components but appealed to the physical differences between mating cell pairs and isolated, pheromone-stimulated cells. Our model proposes that growing cells secrete hydrolytic, cell wall-remodeling enzymes that diffuse through the cell wall, breaking bonds within it. These remodeling enzymes weaken the cell wall enough to allow the cell wall expansion required for cell growth but are not present in the cell wall long enough to breach it (Figure 3.2A). Pheromone stimulation induces increased production of cell wall remodeling enzymes and directs their secretion towards the shmoo tip (Figure 3.1B). When two cells are attached via mating agglutinins, it takes longer for the cell
wall remodeling enzymes to diffuse through the two cell walls, allowing the concentration of cell wall remodeling enzymes between the two cells to rise and reducing the thickness of the cell wall. As the wall becomes thinner, the concentration of the enzymes rises further until eventually the wall that separates the shmoo tips has been completely dissolved, exposing the two plasma membranes to each other and allowing their fusion to create a single, diploid cell (Figure 3.2B).

Our data provides strong support for the hypothesis that increased secretion of remodeling enzymes and longer distances for them to diffuse causes cell wall dissolution. By testing cells that are tightly apposed to a non-permeable surface rather than another cell, the only signal these cells can receive is a consistently high concentration of pheromone. The cell lysis events we observe are not due merely to the physical constraints of a flow chamber, since they also occur when the cells are chemically attached to a glass coverslip with essentially infinite space to expand and do not occur when cells are arrested in mitosis by treating them with benomyl, a condition that does not lead to polarized secretion. By manipulating the presence of an osmoprotectant in the media, we show that the frequency of lysis events can be increased by increasing the difference between the osmolarity of the cell and its environment and decreased by decreasing the difference between the osmolarity of the cell and its environment, implying that these lysis events are due to a breach in the cell wall. The lysis is specific to pheromone stimulation, as shown by its mitigation when *FUS1* or *FUS2* are deleted, and the cell wall dissolution is at least partially accomplished by the putative glucanases, Scw4 and Scw11, known to be involved in mating.

Taken together with previously published studies, our data supports a model that involves pheromone-induced, polarized secretion of cell wall remodeling enzymes. When cells are pheromone stimulated, a MAP kinase cascade activates transcription of pheromone-induced
Along with many others, these genes include the expression of mating agglutinins and cell wall remodeling enzymes, which are packaged into vesicles for secretion into the extracellular environment. Fus2 and Rvs161, a protein that binds to curved membranes and is involved in cell fusion, bind to these vesicles and travel along actin cables to the site of polarization in a Myo2-dependent fashion, where they are anchored to the plasma membrane by Fus1, which interacts with the polisome. Fus2 and Rvs161 in conjunction with Cdc42 may then function to facilitate fusion of these vesicles with the plasma membrane.

When cells are weakly stimulated, they form broad shmoos (Figure 3.6B). Although these cells are polarized, the zone of polarization is relatively large, and presumably, the vesicles containing cell wall remodeling enzymes are released into a relatively large area. The enzymes cleave carbohydrate bonds as they diffuse through the cell wall matrix, weakening the cell wall and allowing for further expansion in the direction of highest pheromone concentration. As a shmoo gets closer to a cell of the opposite mating type, the pheromone concentration increases and the shmoo tip becomes more tightly polarized. This tighter polarization focuses the secretion of cell wall remodeling enzymes into a smaller fraction of the cell surface, increasing the concentration of cell wall remodeling enzymes in this zone. Although the concentration of cell wall remodeling enzymes in this zone has increased, it is not typically high enough to cause dissolution of the cell wall unless the shmoo tip is pressed against an impermeable barrier, thus slowing the diffusion of the cell wall remodeling enzymes through the cell wall and into the extracellular environment (Figure 3.2A). However, when the two polarized cells attach at their shmoo tips via mating agglutinins, the presence of a second cell membrane traps the remodeling enzymes in the cell wall by requiring them to move laterally along the cell surface to exit the cell wall instead of perpendicularly to the tangent of the curve of the cell, which increases their
concentration and allows for cell wall dissolution (Figure 3.2B). As the cell wall dissolves, the two plasma membranes come into contact with one another, allowing membrane fusion to begin and pushing the Fus2-bound vesicles outward, which allows for the rest of the intervening cell wall to be dissolved and eventually full fusion of the newly formed zygote.

Understanding more about the cell fusion of budding yeast is an important step in understanding cell fusion in more complex organisms. Although animal cells do not have a cell wall, the extracellular matrix surrounding these cells must be dissolved prior to cell fusion. It is possible that the evidence provided here will help to shed light on these other forms of cell fusion.

**MATERIALS and METHODS**

**Yeast strains and culturing**

Strains used in this study are listed in Table 3.1. All strains were derived from the W303 wild-type background (*ade2-1 can1-100 his3-11,15 leu2-112 trp1-1 ura3-1*) using standard genetic techniques. All media was prepared as described in Sherman *et al.*, 1974 and contained 2% wt/vol of glucose.

Cells were either grown in Synthetic Complete media (2% glucose) (SC) or Yeast Extract Peptone Dextrose (2% glucose) (YPD) at 30°C in culture tubes on roller drums or at room temperature (25°C) for timelapse microscopy. Bovine serum albumin (BSA) was used to reduce the non-specific absorption of α-factor to glass and plastic surfaces; it was made into 10% wt/vol stocks in deionized water and then diluted into media to 0.1% wt/vol. Synthetic α-factor (Biosynthesis, Lewisville, TX) was suspended in dimethyl sulfoxide (DMSO) and then diluted into YPD + 0.1% BSA or SC + 0.1% BSA at the appropriate concentration. When appropriate, 1M sorbitol was added to YPD by dissolving sorbitol powder into YPD. YPD containing 1-(butylcarbamoyl)-2-benzimidazolescarbamate (benomyl) was prepared by heating
YPD to 65°C and adding 34mM benomyl in DMSO dropwise to a final concentration of 0.1mM. Peptone, yeast extract, and yeast nitrogen base were obtained from BD (VWR). Bacto-agar was obtained from US Biological (Swampscott, MA). Unless otherwise noted, all chemicals were obtained from Sigma-Aldrich.

**Microscopy**

Microscopy was done at room temperature using a Nikon Ti-E inverted microscope with a 20x Plan Apo VC 0.75NA air lens, and images were acquired with a Photometrics CoolSNAP HQ camera (Roper Scientific, AZ). Timelapse photography was done using Metamorph 7.7 (Molecular Devices, CA); pictures were acquired every 10 minutes using 10ms exposure for differential interference contrast images and 6ms exposure for brightfield images.

**Bulk culture lysis assay**

Cells were grown to log phase (~5x10⁶ cells/mL) at 30°C in YPD and counted using a Z2 Coulter counter (Beckman-Coulter, CA). Cells were washed in YPD + 0.1% BSA and resuspended at 10⁶ cells/mL into plastic 14 mL culture tubes (BD Falcon) in YPD + 0.1% BSA with the appropriate concentration of α-factor. These cultures were then incubated on a roller drum at 30°C for 5 hours. Cells were then put directly onto glass slides (Corning) with uncoated coverslips (VWR) and imaged using differential interference contrast. Prior to the experiment, the plastic culture tubes were coated in BSA by incubating overnight at 4°C with phosphate buffered saline (PBS) with 2% wt/vol BSA. The PBS + 2% BSA was poured out immediately prior to the addition of the cell cultures. To determine the percentage of cells that lysed, more than 50 cells were counted from each trial. Statistical significance was determined using Student’s t-Test.

**Concanavalin-A coated coverslip lysis assay**
Coverslips (VWR) were coated in concanavalin A (MP Biomedicals, OH) in a protocol modified from Joglekar et al., 2008\textsuperscript{74}. Briefly, coverslips were soaked in 1M NaOH for 1 hour at room temperature (25°C), rinsed 5 times with de-ionized, filtered water, and then incubated at room temperature for 1 hour in a solution of 10nM Na\textsubscript{2}HPO\textsubscript{4} pH 6.0 (Fisher Biotech) + 1M CaCl\textsubscript{2} + 0.5mg/mL concanavalin A. Coverslips were then rinsed 5 times with de-ionized, filtered water and air-dried over a 100°C heat block. To make a chamber, strips of parafilm (American National Can) were melted at 100°C on glass slides (Corning) and concanavalin A-coated coverslips were placed on top of the strips. The parafilm was allowed to cool to room temperature, creating channels with a glass slide ceiling, concanavalin A-coated coverslip floor, and parafilm walls.

Cells were grown to log phase (\(\sim 5 \times 10^6\) cells/mL) at 30°C in YPD and then washed in SC + 0.1% BSA. The appropriate amount of α-factor was added to the cells and the cells were immediately injected into the chamber using capillary action. The cells were allowed to adhere to the concanavalin A-coated coverslip for 10 minutes and then 200µL of SC + 0.1% BSA with the appropriate concentration of α-factor was flowed through chamber using capillary action to wash off excess cells. The chamber was then sealed with candle wax and imaged at 20x magnification every 10 minutes for 5 hours from the point of α-factor addition to the cells using differential interference contrast with a 10ms exposure. To determine the percentage of cells that lysed, more than 400 cells were counted from each trial. Statistical significance was determined using Student’s \(t\)-Test.

**Flow chamber lysis assay**

Cells were grown to log phase (\(\sim 5 \times 10^6\) cells/mL) at 30°C in YPD and then washed in YPD + 0.1% BSA. For experiments involving α-factor, the microfluidics chambers (CellAsic,
Hayward, CA) were pretreated by perfusing PBS + 2% BSA through the chamber at 34kPa for 10 minutes and then YPD + 0.1% BSA through the chamber for 10 minutes. After cells were loaded, YPD + 0.1% BSA with the appropriate concentration of α-factor was perfused through the chamber at 14kPa and pictures were taken at 20x magnification every 10 minutes for 5 hours using differential interference contrast with a 10ms exposure.

For experiments involving benomyl, the microfluidics chambers were pretreated by perfusing YPD through the chamber at 34kPa for 10 minutes. After the cells were loaded, YPD + 0.1mM benomyl was perfused through the chamber at 14kPa and pictures were taken at 20x magnification every 10 minutes for 5 hours using differential interference contrast with a 10ms exposure. The microfluidics chambers were pretreated the same way in experiments with YPD, but after the cells were loaded, YPD was perfused through the chamber at 14kPa and pictures were taken at 20x magnification every 5 minutes for 5 hours using brightfield with 6ms exposure. To determine the percentage of cells that lysed, more than 250 cells were counted from each trial. Statistical significance was determined using Student’s t-Test.

**Sorbitol wash-out assay**

Cells were grown to log phase (~5x10^6 cells/mL) at 30°C in YPD and then washed in YPD + 0.1% BSA. The microfluidics chambers (CellAsic) were pretreated by perfusing PBS + 2% BSA through the chamber at 34kPa for 10 minutes and then YPD + 1M sorbitol + 0.1% BSA through the chamber for 10 minutes. After cells were loaded, YPD + 1M sorbitol + 0.1% BSA + 50nM α-factor was perfused through the chamber at 14kPa for 5 hours. After 5 hours, the media containing 1M sorbitol was washed out and YPD + 0.1% BSA + 50nM α-factor was perfused through the chamber at 14kPa for 2 hours. Pictures were taken at 20x magnification every 10 minutes for 7 hours using differential interference contrast with a 10ms exposure. To determine
the percentage of cells that lysed, more than 500 cells were counted from each trial. Statistical significance was determined using Student’s $t$-Test.

**Sorbitol wash-in assay**

Cells were grown to log phase ($\sim 5 \times 10^6$ cells/mL) at 30°C in YPD and then washed in YPD + 0.1% BSA. The microfluidics chambers (CellAsic$^{25}$ were pretreated by perfusing PBS + 2% BSA through the chamber at 34kPa for 10 minutes and then YPD + 0.1% BSA through the chamber for 10 minutes. After cells were loaded, YPD + 0.1% BSA + 50nM α-factor was perfused through the chamber at 14kPa for 80 minutes. After 80 minutes, the YPD + 0.1% BSA + 50nM α-factor was washed out and YPD + 1M Sorbitol + 0.1% BSA + 50nM α-factor was perfused through the chamber at 14kPa for 60 minutes. Pictures were taken at 20x magnification every 10 minutes for 140 minutes using differential interference contrast with a 10ms exposure. To determine the percentage of cells that lysed, more than 600 cells were counted from each trial. Statistical significance was determined using Student’s $t$-Test.
Table 3.1. Strains used in Chapter 3.

<table>
<thead>
<tr>
<th>Strain Name</th>
<th>Genotype (all cells are in the W303 background)</th>
</tr>
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<tbody>
<tr>
<td>LBHY52</td>
<td>MATα bar1Δ::KanMX6 P_{ACTI}γCerulean-HIS3MX6 @ P_{ACTI}</td>
</tr>
<tr>
<td>LBHY77</td>
<td>MATα bar1Δ::KanMX6 fus1Δ::NatMX4 P_{ACTI}γCerulean-HISMX3 @ P_{ACTI}</td>
</tr>
<tr>
<td>LBHY80</td>
<td>MATα bar1Δ::KanMX6 fus2Δ::HphMX4 P_{ACTI}γCerulean-HISMX3 @ P_{ACTI}</td>
</tr>
<tr>
<td>LBHY84</td>
<td>MATα bar1Δ::KanMX6 fus1Δ::NatMX4 fus2Δ::HphMX4 P_{ACTI}γCerulean-HISMX3 @ P_{ACTI}</td>
</tr>
<tr>
<td>LBHY120</td>
<td>MATα bar1Δ::ADE2 HIS3:SPA2-YFP scw4Δ::KanMX6 ade2-1 can1-100 leu2-3,112 trp1-1 ura3-1</td>
</tr>
<tr>
<td>LBHY121</td>
<td>MATα bar1Δ::ADE2 HIS3:SPA2-YFP scw10Δ::NatMX4 ade2-1 can1-100 leu2-3,112 trp1-1 ura3-1</td>
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<tr>
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<td>MATα bar1Δ::ADE2 HIS3:SPA2-YFP scw11Δ::HphMX4 ade2-1 can1-100 leu2-3,112 trp1-1 ura3-1</td>
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<tr>
<td>LBHY153</td>
<td>MATα bar1Δ::ADE2 HIS3:SPA2-YFP scw4Δ::KanMX6 scw11Δ::HphMX4 ade2-1 can1-100 leu2-3,112 trp1-1 ura3-1</td>
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<td>SLY412</td>
<td>MATα ade2-1 can1-100 his3-11,15 leu2-112 trp1-1 ura3-1 (W303 wildtype)</td>
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References


CHAPTER 4

Conclusions, discussion, and future directions
ABSTRACT

Mating in the budding yeast is a complex, highly regulated process that mirrors many of the processes in the cell biology of higher eukaryotes. The studies presented in this thesis serve to elucidate several aspects of intercellular communication and fusion. However, they also bring to light additional questions and possible future directions for research. These include further characterization of the biological and biochemical functions of the a-factor barrier protein, Afb1, and further investigation of the differences in the regulation of gene expression in MATα and MATα cells as well as more studies on how robust the process of intercellular communication and fusion is. Additionally, while we have provided support for the hypothesis that cell wall dissolution occurs through contact-limited diffusion of cell wall remodeling enzymes, we have not negated the possibility that additional signaling pathways are involved, and additional experiments could be done to provide further support for our hypothesis. Through the future directions described here and elsewhere, we can hope that eventually the complex process of the mating of the budding yeast will be completely elucidated.
INTRODUCTION

The study of mating in the budding yeast, *Saccharomyces cerevisiae*, is an excellent model system for many of the processes we see in higher eukaryotes. Signaling through G-protein coupled receptors and subsequent activation of a mitogen-activated protein (MAP) kinase signaling cascade is relevant to intercellular communication that regulates growth and division\(^1\). Cell polarization in an external gradient of signaling molecules is similar to the maturation of neuron axons in the development and maintenance of the nervous system\(^2\). The process by which yeast cells arrest the cell cycle in response to pheromone can tell us more about the control of the cell cycle in general.

Budding yeast cells are also capable of differentiating into three different cell types: \(MATa\), \(MATα\), and \(MATa/α\) ref.\(^3\). This process is one of the simplest and most easily controllable examples of cellular differentiation, making it an excellent model system. Studying the differentially expressed genes in these different cell types is a useful way to determine which genes are necessary to define a cell type. Since the differentiation between \(MATa\) and \(MATα\) cells mainly concerns differences necessary for mating\(^4\), investigating how the careful regulation of these genes controls mating efficiency can also inform us about the robustness of intercellular communication in this system. In Chapter 2, I discussed the characterization of transvestite yeast: yeast cells whose mating type-specific transcription is under the control of one set of transcription factors at the \(MAT\) locus but express the mating type-specific genes of the other mating type. The transvestite yeast enabled us to identify the long sought-after α-factor barrier protein, \(AFB1\). We also observed that pheromone-stimulated \(MATa\) cells expressing the α-factor receptor, Ste2, shmoo but arrest in G1 only transiently. It is possible that this indicates a novel mechanism through which \(MATa\) cells attenuate the cell cycle in response to pheromone-
stimulation either in general or specifically through Ste2. With respect to MATa cells, we gave further evidence to support the hypothesis that all of the MATa-specific genes have been identified since it was possible to achieve mating efficiencies at near wild-type levels in the a-playing-α PTDH3-MFα1 cells. Additionally, the transvestite yeast give us a tantalizing view into the robustness of the intercellular communication in budding yeast mating.

Once two haploid cells have successfully signaled and polarized towards each other, they must go through cell fusion to form a single diploid zygote. This process has relevance to the fertilization of an egg by sperm as well as formation of muscle cells, osteoclasts, giant cells, and placental cells5-8. Since the budding yeast nucleus is incased in a series of 3 concentric envelopes, generation of a diploid cell requires a series of three types of fusion: cell wall fusion, plasma membrane fusion, and nuclear fusion9. Each of these is a tightly regulated process ensuring that the various compartments of the cell stay isolated from each other and from the extracellular environment. In Chapter 3 we provided support for the hypothesis that yeast cells limit cell wall dissolution to the point of contact with a fusion partner via contact-limited diffusion of cell wall remodeling enzymes. We hypothesize that pheromone-stimulated cells secrete cell wall remodeling enzymes to remodel their cell walls and enable polarized growth of a shmoo. When cells are unattached, these cell wall remodeling enzymes can diffuse into the extracellular environment, weakening but not breaching the cell wall, and thus allowing its continuous expansion as two partner cells grow towards each other. However, when two shmoo tips are attached to each other in preparation for fusion, the cell wall remodeling enzymes are trapped between the shmoo tips, increasing the concentration of cell wall remodeling enzymes, and leading to cell wall dissolution. Cell death due to cell wall dissolution has previously been seen in populations of pheromone-stimulated cells10, and we showed that this is likely due to
tight apposition of shmoo tips to non-permeable surfaces such as another cell of the same mating type or a glass coverslip, resulting in an increase in the concentration of cell wall remodeling enzymes at the shmoo tip.

The experiments described in this thesis present several important conclusions about the mating of budding yeast and strive to further elucidate the process by which the two haploid cell types communicate and fuse to form a single diploid. However, the conclusions drawn also bring to light the need for future experiments to provide additional information about the mechanisms involved in budding yeast mating.

**DISCUSSION and FUTURE DIRECTIONS**

*Further characterization of AFB1*

In Chapter 2 we identified the novel, MATα-specific a-factor barrier protein, AFB1. When expressed under the endogenous promoter in α-playing-a cells, Afb1 causes decreased a-factor secretion. We hypothesize that this protein is secreted due to its ability to also block a-factor expressed from MATα cells in mixtures of MATα and α-playing-a cells, and identified the gene as the uncharacterized open reading frame (ORF) YLR040C. Since the activity of Afb1 is active in α-playing-a cells and in MATα cells expressing Afb1 under a constitutive promoter, it is unlikely that Afb1 acts to increase endocytosis of a-factor receptors bound to a-factor. Although we were able to see biological activity of this protein, the specific biochemical activity is still unknown. In 1991, Marcus et al. reported the biochemical activity of a MATα-specific a-factor endopeptidase\(^{11}\). However, the gene encoding this endopeptidase has not been identified\(^{12}\).

It is possible that Afb1 is the endopeptidase seen by Marcus et al.\(^{11}\). If so, cells expressing Afb1 should be capable of a-factor degradation and cells lacking Afb1 should not. If Afb1 does not show endopeptidase activity, it is also possible that it acts in some other way –
perhaps either by cleaving the farnesyl moiety or by somehow sequestering a-factor away from Ste3 receptors.

While we did see an increase in the mating efficiency of α-playing-a cells lacking Afb1 compared to α-playing-a cells that express Afb1 under the endogenous promoter, we did not detect a difference in the mating efficiency of wild-type MATα cells expressing and lacking Afb1. It seems likely that Afb1 would have an effect on mating efficiency under certain conditions, and it would be interesting to identify these. Since Afb1 is hypothesized to have a glycophasphotidylinositol (GPI) anchor keeping it associated with the plasma membrane of MATα cells, perhaps, like Bar1 trapped in the cell walls of MATα cells, Afb1 increases the ability of MATα cells to choose between two nearby potential partners by inhibiting saturation of the pheromone receptors and increasing the ability of cells to identify the specific location of the pheromone source. For example, in an ascus the distance between a given germinating MATα spore and the two germinating MATα spores may be close to equidistant, so identifying the exact location of each cell as opposed to an average of the two point signals, resulting in polarization of the MATα cell between the two MATα cells, would be extremely important. It is also possible that, like Bar1 for MATα cells, Afb1 creates a-factor sinks around MATα cells in dense mating mixtures, causing MATα cells to polarize away from each other and increasing the likelihood of MATα cells polarizing towards different potential MATα partners. Modeling the effect of Afb1 on mating in the ascus and in dense mating mixtures could shed some light on these possibilities.

Another way to investigate the effects of Afb1 on mating efficiency would be to look into whether MATα cells lacking Afb1 are as capable of distinguishing between potential MATα partners as wild-type MATα cells. Jackson and Hartwell, 1990 observed that MATα cells have a preference for MATα cells that produce more a-factor. It is possible that while MATα cells
lacking Afb1 do not have a mating defect in standard mating assays, they are deficient in partner discrimination. Further elucidation of the role of Afb1 in mating will serve to paint a more complete picture of intercellular communication in the mating of budding yeast.

**How robust is mating?**

The experiments described in Chapter 2 mainly focused on the mating of the transvestite yeast to wild-type partners and what that can tell us about the different cell types and mating in yeast. However, the low mating efficiency of the two transvestites to each other indicates that defects in mating are synergistic. This result was supported by the fact that crossing the α-playing-α cells with “pseudo”-α-playing-α cells (MATα mfa1Δ cells) resulted in similarly low mating efficiency. Perhaps it is not surprising that affecting the regulation of the approximately 130 genes that are differentially regulated in MATα and MATα cells would cause such a large decrease in mating efficiency, but it raises the question of how robust the process of mating is. It is clear that yeast have evolved an efficient mechanism for mating. It has also been shown that sterile cells can outcompete cells capable of mating when competed for purely vegetative growth\(^\text{17}\). It would be interesting to continue to investigate whether yeast have evolved to be the best maters possible or if the regulation of sexual and asexual genes is a tradeoff between mating efficiency and asexual generation time. It has been shown that it is possible to evolve cells with faster asexual growth rates\(^\text{17}\), but is it possible to engineer a super-mater?

Investigating strains of yeast that produce differing amounts of pheromone would be a simple way to begin to untangle the tradeoffs inherent in sexual and asexual reproduction. We demonstrate in Chapter 2 that cells are capable of producing more α-factor than is typically produced in wild-type MATα cells. This increase in α-factor production did result in an increase in the mating efficiency of the α-playing-α cells. However, the α-playing-α cells started with
lower than normal α-factor production, they may have additional complexities that affect their mating efficiency, and they did not improve their mating efficiency above typical wild-type levels. This leaves the question of whether additional α-factor production in wild-type MATα cells would improve mating efficiency in traditional mating assays. MATα cells are capable of discriminating between MATα cells that produce differing amounts of α-factor and prefer wild-type MATα cells to MATα cells deleted for one of the α-factor genes18. Will MATα cells with higher than normal α-factor production be able to outcompete wild-type MATα cells for a MATα partner or will the increased α-factor production of these strains overwhelm the ability of MATα cells to distinguish between potential partners? If MATα cells do prefer MATα cells with higher than normal α-factor production, it would also be informative to investigate whether this increase in mating efficiency causes a decrease in asexual fitness. Either way, it will be interesting to investigate the tradeoffs inherent in sexual versus asexual reproduction.

**How different is the pheromone response in MATα and MATα cells?**

The response of MATα cells to pheromone has been extremely well characterized through the investigation of the MATα transcriptome under the influence of differing α-factor concentrations and incubation times19. Because of the hydrophobicity of a-factor the intense reciprocal investigation of the pheromone-stimulated MATα transcriptome has not been done. The engineering of α-playing-a cells makes it possible to perform a close comparison of the response of MATα and MATα cells to pheromone over time and pheromone concentration. Even under the single pheromone concentration and time point tested in Chapter 2, we saw evidence of differential expression in over 100 genes. It is possible that a more thorough investigation of the pheromone-stimulated α-playing-a transcriptome will identify additional evidence of differential regulation of the pheromone response between MATα and MATα cells.
When investigating the phenotypic differences between *MAT*<sub>a</sub> and α-playing-*a* cells, we also saw a difference with respect to pheromone-stimulated G1 arrest. While *MAT*<sub>a</sub> *bar1Δ* cells shmoo and arrest in G1, α-playing-*a* *bar1Δ* cells shmoo but arrest only transiently. We were unable to identify a single gene responsible for this effect and showed that cells expressing both *MAT*<sub>a</sub> and *MAT*α specific genes (aside from *BAR1, STE3, MFα1*, and *MFα2*) are capable of arresting in response to pheromone. A possible explanation for this is that the lack of G1 arrest in pheromone-stimulated *MAT*<sub>a</sub> cells is actually due to a complex interaction of the many differentially regulated genes in *MAT*<sub>a</sub> and *MAT*α cells. These many small changes in gene expression could act together to lead to continued budding during pheromone stimulation either in *MAT*α cells in general or only in those *MAT*α cells expressing the α-factor receptor, Ste2.

It is also, of course, possible that this effect is due to a gene we did not investigate. In 1989, Steden *et al.* identified a mutation that causes increased pheromone-sensitivity specifically in *MAT*α cells exposed to α-factor and mapped it to a 125 kilobase region on Chromosome XII<sup>20</sup>, which contains 72 ORFs, none of which are differentially expressed between pheromone-stimulated *MAT*<sub>a</sub> and α-playing-*a* cells. However, perhaps one of these genes interacts with a differentially regulated gene in a way that allows *MAT*α cells to continue budding even while pheromone-stimulated. Whether a specific gene is responsible for the lack of enduring cell cycle arrest in α-playing-*a* cells or whether it is the combination of a complex network of differentially expressed genes, a careful investigation of the differences in the transcriptomes of *MAT*<sub>a</sub> and α-playing-*a* cells throughout a variety of times and pheromone-concentrations could be extremely enlightening.

*Artificial cell fusion*
In order for two haploid cells to fuse to form a single diploid, they must polarize towards each other, attach to each other at their shmoo tips, and dissolve their cell walls specifically at the point of contact. This is an extremely dangerous task because if the cell wall is dissolved at the wrong time or in the wrong location the cell wall will no longer be able to resist the turgor pressure of the cell leading to lysis\textsuperscript{9,21}. In Chapter 3, we present data supporting our hypothesis that cell wall dissolution is the result of the limited diffusion of secreted cell wall remodeling enzymes when a shmoo tip is attached to a non-permeable surface such as another cell or a glass coverslip.

It is possible to imagine other hypotheses for cell wall dissolution during mating that include additional signaling or regulation, but these additional signaling molecules have yet to be identified. For instance, another hypothesis that fits our data is that pheromone-stimulated cells are able to sense that they are physically touching a non-permeable surface, causing an increase in the secretion of cell wall remodeling enzymes at the point of contact.

A possible future experiment that would provide additional support for our hypothesis would be to artificially fuse two unstimulated cells. One way to do this would be to artificially polarize isotropically growing cells, perhaps using a protein involved in bud polarity, such as Bud\textsuperscript{522}. Mating agglutinins from both mating types and cell wall remodeling enzymes thought to be involved with mating could be placed under an inducible promoter, and their transcription could be activated as the cells were stimulated for artificial polarization. Since secretion would be polarized to this site, the agglutinins would preferentially be sent here, thus, causing cells to attach specifically by their sites of artificial polarization. The secretion of the cell wall remodeling enzymes would also be polarized to this location, so it might be possible to see cell wall dissolution by looking for the absence of fluorescently labeled cell wall separating two
fluorescently labeled cytoplasms. The ability to fuse the cell walls of cells in the absence of pheromone would argue strongly that additional signaling beyond the pheromone response pathway is unnecessary for cell wall dissolution.

If it is possible to induce yeast cells to fuse their cell walls in the absence of pheromone, it could also be elucidating to ask whether it is possible to artificially induce plasma membrane fusion. Although additional proteins may still need to be identified, it would be interesting to observe the effect of inducing expression of proteins known to be involved in plasma membrane fusion, such as Prm1 ref. 23, Fig1 ref. 24, Kex2 ref. 25, Erg2, Erg3, and Erg6 ref. 26. It has been reported that strong pheromone induction is not necessary for plasma membrane fusion ref. 26, indicating that if the proteins necessary for fusion were induced, artificial plasma membrane fusion could potentially be possible. If so, artificial plasma membrane fusion could serve to demonstrate that all of the pheromone-induced proteins necessary for plasma membrane fusion had been identified.

CLOSING REMARKS

Our results serve to fill in some of the gaps in our knowledge of the mating of the budding yeast. We have identified a novel a-factor barrier protein, Afmb, which may serve to clarify the process by which MATa and MATα cells successfully communicate in both a dense mating mixture and when cells are relatively isolated. We have also provided further evidence that all of the MATa-specific genes have been identified and that the process of intercellular communication requires careful regulation of multiple genes to proceed efficiently.

Additionally, we have put forth a hypothesis for the mechanism by which mating partners safely proceed through cell wall fusion. Learning more about how budding yeast cells are able to communicate and eventually fuse is applicable to similar processes in higher eukaryotes as well.
as to the mating and fusion of other fungi. Future studies will serve to further elucidate this process, perhaps eventually culminating in a complete understanding of all of the complex interactions surrounding the mating of the budding yeast.
References


APPENDIX

Supplemental movies
Movie A1. MATa cells are capable of enduring arrest in response to pheromone stimulation. MATa bar1Δ cells were grown in a flow chamber for 8 hours perfused with rich media with 10nM α-factor and imaged with DIC every 10 minutes using 60x magnification. The scale bar indicates 10µm.

Movie A2. α-playing-a cells arrest only transiently in response to pheromone stimulation. α-playing-a bar1Δ cells were grown in a flow chamber for 8 hours perfused with rich media with 10nM α-factor and imaged with DIC every 10 minutes using 60x magnification. The scale bar indicates 10µm.

Movie A3. Pheromone stimulated cells lyse when tightly apposed to a non-permeable surface. MATa bar1Δ cells were grown in a flow chamber for 5 hours perfused with rich media with 50nM α-factor and imaged every 10 minutes using 20x magnification. The scale bar indicates 10µm.

Movie A4. 1M sorbitol protects cells from pheromone-induced cell lysis. Cells were grown in a flow chamber for 7 hours. For the first 5 hours the chamber was perfused with rich media with 1M sorbitol and 50nM α-factor. At the end of 5 hours, the media in the chamber was replaced with rich media with 50nM α-factor and no sorbitol. Cells were imaged every 10 minutes using 20x magnification. The scale bar indicates 10µm.