Gap junction assembly: roles for the formation plaque and regulation by the C-terminus of connexin43

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ABSTRACT Using an established gap junction (GJ) assembly system with experimentally re-aggregated cells, we analyzed “formation plaques” (FPs), apparent sites of GJ assembly. Employing freeze-fracture electron microscopy methods combined with filipin labeling of sterols and immunolabeling for connexin43 (Cx43), we demonstrated that FPs constitute distinct membrane “domains” and that their characteristic 10-nm particles contain connexin43, thus representing precursors (i.e., GJ hemichannels) engaged in assembly. Analysis of FPs in new systems—HeLa and N2A cells—resolved questions surrounding several key but poorly understood steps in assembly, including matching of FP membranes in apposed cells, reduction in the separation between FP membranes during assembly, and the process of particle aggregation. Findings also indicated that “docking” of GJ hemichannels occurs within FP domains and contributes to reduction of intermembrane separation between FPs. Other experiments demonstrated that FPs develop following a major C-terminal truncation of Cx43 (M257), although assembly was delayed. Particle aggregation also occurred at lower densities, and densities of particles within developing GJ aggregates failed to achieve full-length levels. With regard to regulation, inhibition of assembly following protein kinase C activation failed to occur in the M257 truncation mutants, as measured by intercellular dye transfer. However, several C-terminal serine mutations failed to disrupt inhibition.

INTRODUCTION Connexins, which form cell-to-cell channels found in vertebrate gap junctions (GJs), are required for the normal function of virtually all types of cells, tissues, and organs (Locke and Harris, 2009). Fundamental insights have come from studying connexin deletions in mice, as well as connexin mutations that are linked to a number of human diseases (Dobrowolski and Willecke, 2009). This compelling evidence emphasizes how various connexins play different roles. This is partially explained by the fact that channels formed by different connexins or connexin combinations display qualitatively different permeability properties and are regulated differently (Beyer et al., 2001; Burt and Steele, 2003; Weber et al., 2004). Thus connexin diversity provides for important qualitative variations in cell-to-cell communication.

Similarly, quantitative variations in GJ communication also play critical roles, for example, in development (Wei et al., 2004), cell growth (Cronier et al., 2009), and a range of cellular responses (Paemeleire et al., 2000). Some of these variations likely arise from modifications in GJ assembly, a premise that is consistent with the exceptionally short half-lives of connexins (often just several hours) in different cell systems (Fallon and Goodenough, 1981; Beardslee et al., 1998) and the rapid remodeling and reassembly of GJs seen in steady-state cultures (Simek et al., 2009). Accordingly, the regulation of GJ assembly is likely to be an important way for cells to control GJ structure and function.
A long-term goal of our research has been to elucidate the process, mechanisms, and regulation of GJ assembly (Meyer et al., 1992; Lampe, 1994; Paulson et al., 2000; TenBroek et al., 2001; Johnson et al., 2002). Our approach has been to use structural (freeze-fracture [FF] and electron microscopy [EM]) and physiological (electrical coupling and dye transfer) methods to study GJ assembly among dissociated, recovered, and reaggregated cells (Johnson et al., 1974; Preus et al., 1981b). Although the model is generally supported by our earlier studies (Johnson et al., 1974; Preus et al., 1981b) and by others (Decker and Friend, 1974; Risinger and Larsen, 1983; Fujimoto et al., 1997), certain key features remained unclear, and these are emphasized in the first part of the present study. Moreover, we confirmed that the model, based heavily on earlier studies of Novikoff hepatoma cells, is also useful in describing assembly in two new systems—transfected HeLa and N2A cells—and is thus more likely to reflect the essential steps in de novo GJ assembly elsewhere.

In our model, we proposed that formation plaques (FPs) are distinct membrane domains, but this contention was based on subjective rather than molecular evidence. To obtain objective molecular information about FPs, we used two different approaches in the present study. First, we used filipin labeling (Elias et al., 1979) to evaluate hydroxysterol levels (i.e., largely cholesterol) within the membranes of reaggregated Novikoff hepatoma cells, reasoning that changes in membrane lipids in FPs might facilitate or regulate assembly (Malewicz et al., 1990; Meyer et al., 1991). FPs were notably deficient in filipin labeling, suggesting either a deficiency of cholesterol or inaccessibility of the sterol for filipin binding. Second, we used powerful freeze-fracture replica immunolabeling (FRII) methods (Li et al., 2008) to localize connexin43 (Cx43) proteins within developing FPs, taking advantage of large FPs found in Cx43-transfected N2A cells. Together these analyses demonstrate both the specialized nature of FP membranes and the role of FPs as the sites of accumulation of GJ precursors (namely, connexons or GJ hemichannels) during GJ assembly. The larger and/or more distinctive FPs also allowed us to obtain more definitive support for several other key aspects of our assembly model, including the matching of FPs in apposed cells, the enrichment of 10-nm particles, the depletion of smaller particles in FPs, the steps in the aggregation of 10-nm particles ultimately into GJs, and the progressive reduction of the distance between FP membranes. Moreover, quantitative FF analysis of other FP parameters, such as FP area and the number, degree of aggregation, and density of 10-nm particles, provided more, sometimes unexpected, information on the processes of initiation, maturation, and growth of FPs.

In the next part of our study, we turned our attention to the role of the cytoplasmic C-terminal tail (CT tail) of Cx43, first in basal and then in negatively regulated assembly. Previous studies showed that cells without the CT tail could still form GJs and develop dye permeability but at an apparently slower rate (TenBroek et al., 2001; Maass et al., 2004, 2007; Simek et al., 2009). However, none of these earlier studies used FF to study the development of FPs in the absence of the CT tail. Using N2A and HeLa cells expressing a truncated version of Cx43 (M257), we compared FP development with that in full-length Cx43 transfectants during basal GJ assembly. We found only very limited FP development in the N2A-M257 cells but detected most assembly steps in the HeLa-M257 cells. However, a more detailed quantitative comparison of the HeLa-M257 and HeLa-Cx43 cells showed more complex results and revealed important new features of FP development. Although the M257 cells had an apparent delay in the overall development of FPs, the aggregation of particles appeared to occur at a lower density of unaggregated particles than in the HeLa-Cx43 cells, implying a higher efficiency of aggregation in the M257. Yet the resulting aggregates were less tightly packed (i.e., lower particle density within the aggregates) than in the HeLa-Cx43 cells and did not show a gradual increase in density with assembly time, in contrast to that seen in the HeLa-Cx43 cells.

The quantitative differences in assembly by the Cx43 and M257 cells suggest that FP development and GJ maturation may require interactions of the CT tail of Cx43 with other connexin moieties or other protein(s) (Laird, 2010). Interactions with other proteins have been postulated to affect many features of Cx43 function, including GJ assembly (Hunter et al., 2005) and may be the focus of regulation, occurring, for example, through phosphorylation of various sites on the CT tail (Solan and Lampé, 2009). Earlier work demonstrated that the CT tail is required for the positive regulation of GJ assembly—the “enhanced assembly” that is mediated by cAMP (Paulson et al., 2000; TenBroek et al., 2001). In addition, phosphorylation of Cx43 by casein kinases at sites within the CT tail has been shown to influence GJ assembly (Cooper and Lampé, 2002). However, it was not known whether the negative regulation of GJ assembly by means of protein kinase C (PKC) activation via the phorbol ester 12-O-tetradecanoylphorbol-13-acetate (TPA; Lampe, 1994) requires full-length Cx43. Our dye injection studies here of assembly by the M257 truncation mutants demonstrate that the CT tail is required for the TPA effect. Moreover, our detailed analysis of various phosphorylation-site mutants raises the interesting possibility that the PKC effect on GJ assembly does not require phosphorylation of Cx43 at a specific site(s) on the CT tail but rather an interaction between the CT tail and another protein affected by PKC, for example, one involved in membrane trafficking.

RESULTS

Molecular evidence that formation plaques are distinct plasma membrane domains

Probing FP membrane cholesterol: filipin labeling. The relatively flat, apparently rigid topology of FPs suggests that the composition or structure of membrane lipids may be altered and somehow contribute to early steps in FP assembly (Johnson et al., 1974). Prompted by early findings of significant cholesterol levels in isolated GJ fractions (Henderson et al., 1979) and evidence that cholesterol can affect membrane fluidity (Malewicz et al., 1990), we sought to determine whether FPs have different levels of membrane cholesterol than the surrounding, nonjunctional plasma membrane. We applied a convenient FF-EM method for mapping the distribution of cholesterol in membranes, using the polyanionic antibiotic filipin, which is known to bind specifically to β-hydroxysterols and to be useful in probing membrane domains (Elias et al., 1979).

In FF replicas of reaggregated Novikoff hepatoma cells (Johnson et al., 1974), filipin-induced F-face protrusions were distributed widely throughout the plasma membrane (Figure 1 and Table 1). However, unexpectedly, filipin-based protrusions were totally missing from FP membranes, whether or not they contained aggregated particles, that is, small, immature GJs (Figure 1, A and B). In this regard, they behaved similarly to mature GJs, which also excluded filipin (Figure 1C), as reported earlier (Elias et al., 1979; Risinger and Larsen, 1983). However, recent studies revealed filipin labeling of a subset of GJs in the lens (Biswas and Lo, 2007), reinforcing the concept that filipin can be used to probe GJs and FPs for cholesterol. Of importance, filipin treatment in the present study did not appear to alter the proportion of FPs containing particle aggregates, the mean number of aggregated particles per FP or the mean area of FPs (Table 1). This makes it unlikely that filipin treatment obscured or altered the nature of FPs, causing a certain class of FPs to be overlooked during
as we propose, these particles are GJ precursors, they should be composed of connexins. To test this idea, we next used FRIL methods (Fujimoto, 1995; Rash and Yasumura, 1999) and transmission EM to study reaggregated HeLa and N2A cells transfected with Cx43 to determine whether Cx43 is enriched in the FPs and associated with the 10-nm particles. With the use of antibodies specific for the C-terminal tail of Cx43, which resides on the cytoplasmic side of the membrane, along with secondary gold-labeled antibodies, Cx43-containing GJs can be labeled on the surface that underlies the P-fracture face (Rash et al., 2005). Our results with this approach are illustrated in Figure 2A, which shows several small GJs and FPs immunolabeled with 20-nm gold beads. One FP (Figure 2B, yellow overlay) clearly shows labeling associated with a group of unaggregated particles, most of which measured ∼10 nm in diameter, as well as labeling of a nearby GJ. Other examples are shown in Figure 2, C–E. Thus the Cx43 labeling was associated with both the dispersed and aggregated 10-nm particles within the FPs (also see Discussion).

The specificity of the immunogold labeling was illustrated in several ways. First, the background labeling was exceptionally low (Figure 2, A–E). Second, all of the labeling of the protoplasmic fracture face (P-face) was, in fact, always on the tissue side of the replica, that is, the former cytoplasmic side of the membrane (as predicted based on the location of the epitope, and as confirmed using specimen tilt in the EM along with stereoscopic viewing) and never on the opposite, Lexan-coated surface of the replica. Third, using a primary monoclonal antibody for Cx43, it was possible to use two different secondary antibodies tagged with different sizes of gold to probe the distribution of Cx43. A large FP with multiple particle aggregates was labeled with two sizes of gold beads that localize Cx43 in Figure 2E (blue overlay); note the overlap of the two gold signals. It should also be emphasized that no other membrane specializations bound the antibodies for Cx43. We conclude that the labeling of the FPs was highly specific.

Consistent with the specificity, the extraplasmic fracture faces (E-faces) of junctional membranes were also labeled, including pits derived from small aggregates (Figure 2D), as well as multiple sites within larger FPs. Thus our interpretation is that the unaggregated 10-nm particles found in FPs contain Cx43 and therefore are GJ precursors (connexons or hemichannels).

Phases in the development of formation plaques
Our model for GJ assembly (see Introduction), which emphasizes the role of FPs, was derived almost exclusively from studies of reaggregated Novikoff hepatoma cells (Johnson et al., 1974; Preus et al., 1981b). These early studies provided significant support for certain features of FP development proposed in the model, such as the early appearance of FPs, the increase in numbers of 10-nm particles and particle aggregates with assembly time, and the
progressive decrease in the proportion of unaggregated particles. However, several key features were less well supported, including 1) the matching of FP membranes in apposed cells, 2) the enrichment of 10-nm particles and depletion of smaller particles in FPs, 3) the process of particle aggregation, including the fate of small aggregates, and 4) a reduction in the separation between FP membranes during assembly. Moreover, the applicability of the model to GJ assembly in other cell systems has been uncertain. In the present study, using transfected HeLa and N2A cells, we obtained evidence for important but poorly supported parts of the model while confirming the generality of the model in two additional cell systems.

Matching of FPs. The question of whether an FP membrane in one cell is matched with a similar structure in an apposed cell has been difficult to resolve with confidence. This is because the answer requires a view of both membranes, and with small and infrequent FPs the chance that the fracture plane will skip from one membrane to another in the middle of the FP is exceedingly limited. Thus replicas of N2A and HeLa cells had the potential of providing major insights into the question of whether FPs develop in a coordinated manner between two apposed membranes, an important feature of the FP model. In fact, we found more than 100 examples in which fractures skipped between membranes, often multiple times within an FP (e.g., Figure 3). In these cases, the specializations in one FP membrane were consistently found to be similar to those in the apposed membrane, with regions of clustered E-face pits adjacent to regions of clustered P-face particles or aggregated E-face pits continuous with aggregated P-face particles. All of these observations support the idea of matched FP membranes, although the basis for this cooperative interaction between membranes in early FPs remains unclear.

**Enrichment of large and depletion of small FP particles.** Two fundamental features of the assembly model are the accumulation in FPs of 10-nm particles, which, according to our FRIL studies (discussed earlier) contain Cx43, and the depletion of smaller particles. Figure 3 shows several large FPs with different densities of uniformly sized 10-nm particles, both unaggregated and aggregated, and variable loss of smaller particles. The images are consistent with differing stages in 10-nm particle enrichment (cf. Figure 3, A and B) and small-particle depletion (Johnson et al., 1974). However, to add new quantitative support for these subjective interpretations, the numbers of both 10-nm particles and smaller particles were determined in a series of plaques at different stages in development, as well as in nonjunctional membranes. The results from one method are illustrated in Supplemental Figure S1. Similar results were obtained with a second method, which evaluated entire FP membranes. Whereas 10-nm particles were found to comprise from 6 to 27% of the particles in nonjunctional membranes, they represented 76–94% of the particles in FP membranes, both per unit area, an “enrichment” of up to ~12-fold in FPs of higher density. There was also a “depletion” of smaller particles, down to as few as 6% of the FP particles. Both features underscore the fact that FP membranes represent specialized domains.

**Aggregation of 10-nm particles.** Another important feature of the assembly model is the aggregation of 10-nm particles in FPs, as illustrated in Figure 3. Aggregates took a variety of shapes, often elongated (Figure 3, A and B), and sometimes lacy (Figure 3C), which may represent an early stage of particle aggregation. E-Face fractures of other lacy aggregates (Figure 3D) provide insight into the topography of the developing FPs. In other FPs (Figure 3E), large numbers of aggregates were observed, implying many different nucleation sites for aggregation. In some cases, particle-free areas were found within the larger networks of aggregated particles (e.g., Figure 3, B and C), consistent with the idea that unaggregated 10-nm particles have been incorporated into the aggregates. Of interest, membrane invaginations have been detected within particle aggregate regions (Figure 3E, inset), representing membrane vesicles either fusing with the FP membrane or pinching off, as in exocytosis and endocytosis, respectively. This constitutes the FP version of membrane trafficking, described previously for GJ membranes (Gaietta et al., 2002; Shaw et al., 2007).

In addition, earlier reports provided evidence for the lateral fusion of small-particle aggregates, thereby reducing their number and increasing the number and size of larger aggregates and creating more mature GJs (Preus et al., 1981b). Our analysis of the much larger FPs in the N2A system provided a second important line of support for the fusion hypothesis. In a number of cases, developing FPs each displayed several dozen particle aggregates

### Table 1: Quantitative analysis of formation plaques in filipin-treated samples.

<table>
<thead>
<tr>
<th>Plaques examined (n values)</th>
<th>Control</th>
<th>Filipin-treated samples</th>
<th>t test</th>
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<tbody>
<tr>
<td>NA</td>
<td>25 (100%)</td>
<td>51 (100%)</td>
<td>NA</td>
</tr>
<tr>
<td>FP(−)s</td>
<td>19 (76%)</td>
<td>35 (68%)</td>
<td>NA</td>
</tr>
<tr>
<td>FP(+)s</td>
<td>6 (24%)</td>
<td>16 (31%)</td>
<td>NA</td>
</tr>
<tr>
<td>Area of FP(−)s</td>
<td>0.087</td>
<td>0.073</td>
<td>0.33</td>
</tr>
<tr>
<td>(geometric mean in μm², ± SEM)</td>
<td>0.078–0.098</td>
<td>0.065–0.081</td>
<td>Not significant</td>
</tr>
<tr>
<td>Area of FP(+)s</td>
<td>0.133</td>
<td>0.123</td>
<td>0.84</td>
</tr>
<tr>
<td>(geometric mean in μm², ± SEM)</td>
<td>0.102–0.170</td>
<td>0.100–0.151</td>
<td>Not significant</td>
</tr>
<tr>
<td>Mean area of all FPs</td>
<td>0.096</td>
<td>0.086</td>
<td>0.51</td>
</tr>
<tr>
<td>(geometric mean in μm², ± SEM)</td>
<td>0.085–0.107</td>
<td>0.076–0.096</td>
<td>Not significant</td>
</tr>
<tr>
<td>Number of aggregated</td>
<td>25</td>
<td>27</td>
<td>0.90</td>
</tr>
<tr>
<td>particles/FP(+)</td>
<td>14–44</td>
<td>21–33</td>
<td>Not significant</td>
</tr>
<tr>
<td>(geometric mean)</td>
<td>NA</td>
<td>155 ± 9 (n = 6)</td>
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</table>
It seems highly unlikely that each of these aggregates would develop into an individual GJ, because we never observed more than a few large, mature GJs in a single N2A cell expressing Cx43. These findings complement fluorescence studies on the lateral mobility of connexins within the plasma membrane (Simek et al., 2009). Aggregate fusion is consistent with a biophysical model for GJ structure, which emphasizes the minimization of the repulsive forces between apposed membranes through the side-by-side aggregation of docked channels (Braun et al., 1984).

Reduction of intermembrane space between FPs. FF analysis also validated another key feature of the assembly model—a progressive reduction in the distance between matched FP membranes. These separations appeared to fall into three classes. Early FPs (defined by smaller areas and lower particle densities) exhibited a rather broad separation, with an intermembrane distance interpreted as 10–20 nm and approaching that of apposed, nonjunctional membranes; we found 33 examples of this class. The aggregates of particles in FPs displayed a second class. Whenever the fracture planes skipped between these membranes (63 examples), the separations were much reduced, as in a mature GJ where the distance measures ~2 nm (Figure 3, E and F). Finally, images were also obtained of a third type of separation (Figure 3C), involving a reduced extracellular space (comparable to a mature GJ), but in FP areas containing unaggregated particles, with no evidence of aggregates (18 examples). We believe that these less frequent images represent an intermediate in the process by which the intermembrane space is reduced. In no instance did we observe an aggregate with a broad membrane separation. Thus our interpretation is that FP development clearly includes a process that reduces the intermembrane distance found in early FPs.

Hemichannel docking would provide a logical mechanism for converting the broad class of membrane separations to the narrow class associated with particle aggregates and GJs. Strong support for this idea comes from E-face views of lacy particle aggregates (Figure 3D and Supplemental Figure S2), which reveal grooves or valleys, indicating that the intermembrane separation is sharply reduced and precisely at the site of particle aggregation. In addition, small numbers of hexagonally arrayed pits (reflecting small aggregates) were found in depressed sites on E-faces, densities. Note that with the two antibody steps used here (primary and secondary antibodies), gold particles were found within 28 nm (most within 15 nm) of the labeled antigenic sites (Fujimoto, 1995; Fujimoto et al., 1997; Kamasawa et al., 2006). Small calibration bars, 0.1 μm.
indicative of reduced separation (Supplemental Figure S2). Large, highly prominent pits on the E-face (Figure 3D) could conceivably represent dimples left by a single pair of docked particles; pits from these 10-nm particles would lie at the bottom of the dimple. If this is correct, particle aggregation would then follow docking, possibly very close in time due to biophysical considerations (Braun et al., 1984).

Role of the C-terminus of Cx43 in the process of GJ assembly

Because the C-terminus is a critical regulatory region in Cx43 (Ek-Vitorin et al., 1996; Sorgen et al., 2004; Solan and Lampe, 2009) and the major region engaged in binding different partner proteins (Laird, 2010), it can be envisioned as playing a key role in executing and regulating GJ assembly. In previous electrophysiological studies (Maass et al., 2007), it was shown that a truncation mutant of Cx43 (M257) lacking residues 258–383 can assemble into a smaller number of functional GJ channels. Other, dye transfer studies raised the possibility of a reduced rate or efficiency of assembly (TenBroek et al., 2001). Immunolocalization studies also revealed reduced numbers of GJs with the truncation (Maass et al., 2007). However, it was not known whether or how the deletion specifically affects FP structure, either qualitatively or quantitatively, during the assembly process. Thus we next sought to determine with FF methods and EM how development of the FP is affected by deleting the C-terminus of Cx43.

We began with N2A cells transfected with Cx43 or with M257 in order to build on our earlier dye transfer studies (TenBroek et al., 2001). We chose a single assembly time (3 h) for the initial analysis, reasoning that this would allow the M257 cells ample time to assemble GJs, even if more slowly. Our results are summarized quantitatively in Table 2, which shows the full spectrum of junctional structures in the Cx43 transfectants, but, surprisingly, no FPs and only three GJs in the M257 sample. This meant that the N2A system, although useful for qualitative analysis of the Cx43 transfectants (see earlier discussion and Figure 3), was unsatisfactory for a detailed quantitative comparison of the Cx43 and M257 cells.

Thus we switched to HeLa cells transfected with either Cx43 or M257, to continue our comparative studies. The two transfectants showed similar qualitative features of FP and GJ development. Plaques without aggregates, termed FP(–)s (Figure 4, A and B), and those with aggregates, termed FP(+)s (Figure 4, C and D), were found in both cell lines. Nearly mature GJs were also observed...
GJs in FF samples of HeLa Cx43 and M257 transfectants assembled

unaggregated particles in FPs from the two different transfectants.) On the basis of such images of 10-nm particles was impaired in the M257 cells. (Similar images seen at 3 h (consistent with aggregate fusion over time), whereas for full length versus 33 for M257. However, cells expressing full-length Cx43 had 25% fewer total aggregates (including GJs) than seen at 3 h (consistent with aggregate fusion over time), whereas the M257 cells had more than double the number of aggregates (including mature GJs) from 3 to 6 h. Finally, there was not a significant difference in the areas of mature GJs at 6 h between the Cx43 and M257 cells (p = 0.06).

Thus there are two observations that seem hard to reconcile. First, in cells expressing the truncated form, there appeared to be a delay in the development of FP(+)s and GJs continuing even to 6 h. Second, however, the actual process of particle aggregation, which was initially delayed, appeared to accelerate between 3 and 6 h of assembly. This might all be explained by a slower rate of accumulation of particles in FPs in the M257 cells, along with an enhanced aggregation of the particles that do accumulate. This interpretation is consistent with differences seen in the densities of unaggregated particles in FPs from the two different transfectants.

### TABLE 2: Freeze-fracture EM analysis of reaggregated N2A cells expressing Cx43 or M257.

<table>
<thead>
<tr>
<th></th>
<th>Cx43</th>
<th>M257</th>
</tr>
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<tbody>
<tr>
<td>Initiation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total number of FPs plus mature GJs</td>
<td>47</td>
<td>3</td>
</tr>
<tr>
<td>Plaque area/FP (geometric mean, μm²)</td>
<td>0.49 (SEM 0.37–0.63)</td>
<td>0 (SEM 0.03–0.12)</td>
</tr>
<tr>
<td>Maturation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of FPs (with countable particles or pits) + mature GJs</td>
<td>40 (100%)</td>
<td>3 (100%)</td>
</tr>
<tr>
<td>Number (%) of FP(−)s</td>
<td>1 (2.5%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Number (%) of FP(+) s</td>
<td>26 (65%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Number (%) of mature GJs</td>
<td>13 (32.5%)</td>
<td>3 (100%)</td>
</tr>
<tr>
<td>Plaque area/GJ (geometric mean, μm²)</td>
<td>0.008 (SEM 0.006–0.01)</td>
<td>0.006 (SEM 0.003–0.012)</td>
</tr>
<tr>
<td>Growth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unaggregated particles/FP (geometric mean)</td>
<td>160 (SEM 118–215)</td>
<td>0</td>
</tr>
<tr>
<td>Aggregated particles/FP(+) (geometric mean)</td>
<td>146 (SEM 111–192)</td>
<td>0</td>
</tr>
<tr>
<td>Total particles/FP (geometric mean)</td>
<td>354 (SEM 270–463)</td>
<td>0</td>
</tr>
<tr>
<td>Aggregated particles/GJ</td>
<td>56 (SEM 43–74)</td>
<td>36 (SEM 23–57)</td>
</tr>
</tbody>
</table>

N2A cells stably transfected with full-length Cx43 or truncated M257 were dissociated, recovered, and then reaggregated for 3 h. All samples were processed for routine freeze-fracture analysis. Comparable numbers of replicas were studied for a similar time on the EM for each different sample. Substantial assembly was detected with freeze-fracture Cx43 but very little with M257, as documented here earlier. The data are based on four different experiments each, with multiple samples.

*Only these FPs were used for data derived from particle counts.

(Number of aggregates plus mature GJs) / 100, using only FPs with countable particles and/or pits.

The most obvious measure of initiation is the total number of FPs and mature GJs seen at the end of an assembly period. As shown in Table 3, the total gradually decreases with time for the Cx43 cells, suggesting a possible net loss of some FPs (chiefly FP(−)s) between 1 and 6 h; the total increases with time for the M257 cells. The total for the Cx43 cells is greater at all times (15x at 1 h, 4x at 3–3.5 h, and 1.7x at 6 h). These results suggest that FP initiation by the M257 cells is delayed, with the large discrepancy fading by 6 h; connexin expression levels may also contribute.

Another measure of initiation is the mean area of observed FPs, presumably reflecting the extent of recruitment of lipids to the plaques, along with any proteins that might underlie the newly differentiated plaque membranes, as well as the loss of nonplaque components. The mean area per FP was not significantly different between the Cx43 and M257 cells at either of the first two time points (p = 0.92 at 1 h and p = 0.96 at 3–3.5 h) but was greater for the M257 at 6 h (p < 0.0009). The lack of a difference at 1 and 3–3.5 h is consistent with the general qualitative similarities described here earlier for the two transfectants. The significant difference at 6 h is unexplained.

### Maturation during assembly.

The aggregation of 10-nm particles, a distinctive feature of GJ assembly, is central to the maturation phase. According to our model, FP(−)s initially develop without aggregates, they mature as aggregates appear (FP(+)s), and, as further aggregation ensues, they eventually develop into mature GJs. Thus the extent of maturation should be reflected in the proportions of the three junctional forms (shown graphically in Figure 5, A and B) and in the number of aggregates/FP (see Table 3, Maturation). By both measures, at 1 h of cell reaggregation, maturation has apparently occurred faster in the Cx43 cells than in the M257 cells, that is, in the Cx43 cells the percentage of FP(+)s and GJs is greater (64 vs. 25%) and, of most significance, there were many more aggregates (49 vs. only 1). By 3–3.5 h, although there remained four times as many FPs plus GJs in the full-length transfectants as with the truncation, the percentages with FP(+)s and GJs were similar, and the number of aggregates per FP(+) was comparable (1.31 vs. 1.57, respectively; not significantly different, p = 0.6). After 6 h of reaggregation, the total number of FPs plus mature GJs was higher in the full-length samples (24 vs. 14), but the number of aggregates (including mature GJs) was comparable in the two samples, that is, 34 for full length versus 33 for M257. However, cells expressing full-length Cx43 had 25% fewer total aggregates (including GJs) than seen at 3 h (consistent with aggregate fusion over time), whereas the M257 cells had more than double the number of aggregates (including mature GJs) from 3 to 6 h. Finally, there was not a significant difference in the areas of mature GJs at 6 h between the Cx43 and M257 cells (p = 0.06).

Thus there are two observations that seem hard to reconcile. First, in cells expressing the truncated form, there appeared to be a delay in the development of FP(+)s and GJs continuing even to 6 h. Second, however, the actual process of particle aggregation, which was initially delayed, appeared to accelerate between 3 and 6 h of assembly. This might all be explained by a slower rate of accumulation of particles in FPs in the M257 cells, along with an enhanced aggregation of the particles that do accumulate. This interpretation is consistent with differences seen in the densities of unaggregated particles in FPs from the two different transfectants for three different time periods. We organized the data in Table 3 according to the three different phases of GJ assembly in our model: initiation, maturation, and growth (Johnson et al., 2002).
That is, the average densities of unaggregated particles in FP (+)s at 1, 3, and 6 h for the Cx43 cells (606, 480, and 559 respectively) are significantly higher than those for the M257 cells at those times (117, 151, and 180). Lower connexin levels in M257 cells could contribute to the slower rate of accumulation but not to the different densities of unaggregated particles. If densities of unaggregated particles are considered measures of the “concentration” of particles required to initiate aggregation (Johnson et al., 1974; Preus et al., 1981b), then it appears that particle aggregation can occur more readily, that is, at a lower concentration of unaggregated particles, in the M257 than in the Cx43 cells. Note that the densities of unaggregated particles in the FP(−)s are higher than those for FP(+)s, a possible reflection of a “super saturation” effect reported earlier for FPs in Novikoff cells (Preus et al., 1981b).

Our analysis of GJ aggregates and maturation in reaggregating cells also revealed three novel and significant findings on a new parameter—packing density in aggregates. First, in cells expressing full-length Cx43 the densities of particle packing in aggregates were found to increase significantly with reaggregation time (Table 3), from a mean of 6569 particles/μm² at 1 h to 8952 particles/μm² at 6 h (with p < 0.0005). Particle densities for Cx43 at 1 h are also different from those at 3 h (p < 0.007), and those at 3 h are different from those at 6 h (p < 0.05).

Second, we found that cells expressing the truncated connexin M257 failed to exhibit the same progressive increases in packing density with reaggregation time seen in Cx43 cells; for example, there was no increase from 3 to 6 h (p = 0.57). As a result, M257 cells displayed significantly lower particle densities at 6 h than did Cx43 cells (p < 0.05), with means of 7576 and 8952 particles/μm², respectively. This indicates that the packing of 10-nm particles is impaired with the truncation.

Third, within individual FPs, the particle packing densities of aggregates were more uniform than expected from the variation of mean densities among FPs from the same assembly sample. (See Supplemental Table S1 and Supplemental Figure S3 for regression analysis and determination of SD/mean.) Cx43 FPs exhibited this uniformity more than M257 FPs. These results suggest that for the Cx43 cells, and less often for the M257 cells, the packing density is somehow “coordinated” among aggregates within an FP. N2A-Cx43 cells also showed the same

FIGURE 4: Images from FF replicas of HeLa cells, expressing either full-length Cx43 (clone Cx43-F) or the truncation mutant (clone M257-2.2), reaggregated for 1–3 h. (A) Two FPs (yellow overlays) without particle aggregates in HeLa-Cx43-cells. (B) Possible small FPs (yellow overlays) without particle aggregates in HeLa-M257-cells, particularly in the lower right corner, all containing very few unaggregated particles. Moderately sized FP(+)s (yellow overlays) with particle aggregates (blue overlays), in HeLa-Cx43-cells (C) or HeLa-M257-cells (D). (E) Modest, hexagonally packed GJ (blue overlay) in cells expressing full-length Cx43, with a ring of unaggregated particles (yellow overlay) surrounding it. (F) Fracture face skips from one FP membrane to another in the middle of the plaque from HeLa-Cx43 cells. Different intermembrane separations are shown: 1) highly irregular cell apposition outside the FP (upper left), 2) closely apposed membranes, but still exceeding 10 nm (yellow arrow), and 3) a reduced separation as found in mature GJs (blue arrow). (G) Large FP (measuring ~1.3 μm in length, yellow overlay) strikingly devoid of unaggregated particles in this HeLa-M257 cell. Several small aggregates (blue overlays) are present. Calibration bars, 0.1 μm.
phenomenon, although they were studied only at one time point (data not shown).

Thus the packing parameter appears to provide a quantitative measure of a previously unrecognized maturation process, which is dependent on or affected by the CT tail. The changes in particle packing within aggregates could depend on interactions between connexin hemichannels and/or between Cx43 and its binding partners. The data are consistent with a model in which low-density aggregates form first, perhaps based on a biophysical mechanism for GJ stability (Braun et al., 1984). Aggregation of this type is found in both the Cx43 and M257 cells. Subsequently, interacting proteins, including scaffolding proteins like ZO-1 (Hunter et al., 2005), could link connexins laterally to produce high-density aggregates. Aggregation of this second type appears to be defective in M257 cells.

Growth during assembly. We examined the number of 10-nm particles in order to focus on the recruitment of Cx43 to developing FPs (Table 3, Growth). It was clear that recruitment was well developed in the Cx43 cells over the initial 3 h but had begun to plateau by 6 h. Total number of 10-nm particles/FP (including mature GJs) at 3 h was almost twice that at 1 h (significantly different, p < 0.02) but did not increase significantly at 6 h. However, recruitment in M257 cells over the 6-h time period did not match that in the full-length cells. Cx43 cells had nearly twice as many total particles/FP at 1 and 3 h than the M257 cells, (p < 0.04 and p < 0.05, respectively) but no significance difference at 6 h. Of interest, unlike the Cx43 cells, the M257 cells did show an increase in the total number of 10-nm particles/FP from 3 to 6 h, indicating that recruitment had continued. This comparison over time of total particles in both FPs and mature GJs is found in Table 3 and shown in histogram form in Figure 5C.

<table>
<thead>
<tr>
<th></th>
<th>Cx43 cells</th>
<th>M257 cells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 h</td>
<td>3–3.5 h</td>
</tr>
<tr>
<td>Initiation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total number (%) of FPs plus mature GJ</td>
<td>64 (100%)</td>
<td>36 (100%)</td>
</tr>
<tr>
<td>Plaque area/FP (geometric mean, in μm², with SEM)</td>
<td>0.054</td>
<td>0.061</td>
</tr>
<tr>
<td>Maturation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number (%) of FP(−)s</td>
<td>23 (36%)</td>
<td>3 (8%)</td>
</tr>
<tr>
<td>Number (%) of FP(+)</td>
<td>39 (61%)</td>
<td>26 (72%)</td>
</tr>
<tr>
<td>Number (%) of mature GJs</td>
<td>2 (3%)</td>
<td>7 (19%)</td>
</tr>
<tr>
<td>Total number of aggregates in FP(+)s</td>
<td>49</td>
<td>38</td>
</tr>
<tr>
<td>Area/mature GJ (μm², geometric mean, with SEM)</td>
<td>0.068</td>
<td>0.008</td>
</tr>
<tr>
<td>Packing density of aggregated particles in FP(+)s (geometric mean, per μm², SEM)</td>
<td>6569</td>
<td>7780</td>
</tr>
<tr>
<td>Density of unaggregated particles/FP(−) (geometric mean, per μm², SEM)</td>
<td>904</td>
<td>1051</td>
</tr>
<tr>
<td>Density of unaggregated particles/FP(+) (geometric mean, per μm², SEM)</td>
<td>606</td>
<td>480</td>
</tr>
<tr>
<td>Growth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unaggregated particles/FP (geometric mean, SEM)</td>
<td>37</td>
<td>32</td>
</tr>
<tr>
<td>Aggregated particles/FP(+) (geometric mean, SEM)</td>
<td>32–46</td>
<td>46–99</td>
</tr>
<tr>
<td>Total particles/FP (geometric mean, SEM)</td>
<td>63</td>
<td>119</td>
</tr>
<tr>
<td>Total particles/mature GJ (geometric mean, SEM)</td>
<td>446</td>
<td>70</td>
</tr>
<tr>
<td>Total particles/FPs plus GJs (geometric mean, SEM)</td>
<td>67</td>
<td>107</td>
</tr>
</tbody>
</table>

See Materials and Methods for details related to EM sampling. The three GJ assembly parameters evaluated here are described in the Results section. Because the values for the areas of FPs and mature GJs, the numbers of particles found within them, and densities are skewed, the mean values for these features are expressed as geometric means (see Materials and Methods). Statistical values derived from t tests for various parameters are found in the Results section.

*In these samples, there were small numbers of FP(+)s, including one large outlier in each case. When this value is not included, the geometric mean for the sample is shown in parenthesis.

*Only one FP(+) in this sample.

**TABLE 3:** Freeze-fracture EM analysis of HeLa cells in an assembly assay versus reaggregation time.
with full-length Cx43 was lacking. There were also significant effects on growth, which could be attributed to truncation effects and/or expression levels in the two lines. However, what is striking is that the areas of developing FPs, a measure of initiation, were not affected, in spite of reduced numbers of 10-nm particles at 1 and 3 h.

Role of the C-terminus of Cx43 in the inhibition of GJ assembly by PKC

Here we used dye transfer to determine whether the C-terminus of Cx43 is also required for the dramatic inhibition of assembly seen following PKC activation (Lampe, 1994). Results of dye injection experiments on reaggregated HeLa-M257 cells are shown in Figure 5D. When HeLa cells (three clones) expressing full-length Cx43 were treated with TPA to activate PKC immediately prior to and during reaggregation in 1 h GJ assembly assays, the development of dye transfer was completely inhibited (Figure 6A), regardless of the baseline level of communication. Because established cultures of the HeLa-Cx43-K clone maintained significant communication for at least 1 h following TPA treatment (Supplemental Figure S4A), the TPA inhibition of assembly by this clone was

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**FIGURE 5:** Analysis of GJ assembly in stable transfectants expressing either full-length Cx43 or M257. For HeLa-Cx43-F cells (A) or the M257 truncation (B), percentages of the three classes of junctional structures (FPs without aggregates, FPs with aggregates, and mature GJs, as noted) are plotted vs. reaggregation time. (C) Histogram summarizes differences between the two lines in terms of total 10-nm particles displayed on a per plaque basis vs. reaggregation time; includes both FPs and mature GJs. Error bars are asymmetrical for geometric means (see Materials and Methods). (D) Examples are given of results from Lucifer yellow injection experiments following reaggregation with M257-2.2 cells. Calibration bar, 15 μm.
Role of specific C-terminal serines in the regulation of GJ assembly

Having shown that the C-terminus of Cx43 is required for inhibition of GJ assembly by TPA, we next asked, using dye transfer, whether specific serine residues, either directly or indirectly phosphorylated following activation of PKC, play a role in this inhibitory response. We used transfectant clones that in established cultures showed no rapid TPA inhibition and thus no gating effect (e.g., Supplemental Figure S4C). Serines 255, 262, and 368 on Cx43 are known to be phosphorylated following the activation of PKC (Sirisakuldee et al., 2009; Srisakuldee et al., 2009). We first evaluated the role of S368 phosphorylation in the regulation of assembly by testing stable transfectants of S368A in assay essays (Figure 6B). As was seen with cells expressing full-length Cx43, two of these S368A transfectants showed complete inhibition of assembly by TPA (as measured with dye transfer). Because the mutation failed to block inhibition in these clones, one can conclude that phosphorylation of S368 is not required to inhibit GJ assembly following the activation of PKC. Experiments on a third clone, however, revealed that GJ assembly was inhibited, but by only ∼70%, suggesting that S368 may contribute to the inhibition of assembly or that subcloning of stable transfectants may select for differing enzyme activities/isozyme profiles.

To analyze the role of other potential PKC phosphorylation sites, both an S262A site mutation and an S262A/S368A double mutation were stably transected into HeLa cells. Assembly was analyzed in different clones, and results indicated that neither the S262A mutation nor the double mutation (S262A/S368A) significantly altered the inhibitory effect of TPA on assembly (Supplemental Figure S4, D and E). TPA continued to induce a marked inhibition in these site mutants.

Because MAP kinase can be activated by PKC (Leithe et al., 2009), PKC could indirectly block assembly via Cx43 phosphorylation. However, inhibition still occurred with a triple mutant replacing serines 255, 279, and 282 (Supplemental Figure S4F), sites possibly phosphorylated by MAP kinase when activated by PKC (Warn-Cramer et al., 1996). The results suggest that none of these sites, alone or in combination, is sufficient for the inhibition of assembly.

DISCUSSION

In the present study, we analyze the role of the FP in GJ assembly and identify specific regulatory functions of the Cx43 C-terminus in assembly. We demonstrate here that 1) the FP is a distinct membrane domain, characterized by 10-nm particles containing connexins, 2) the defined steps in GJ assembly involve changes both within and between membranes, including docking and particle aggregation, 3) in the absence of the C-terminal tail of Cx43, there is a delay in FP development and several aspects of particle aggregation are altered, and 4) negative regulation of GJ assembly by PKC requires the C-terminal tail.

Formation plaques are membrane domains involved in GJ assembly

Filipin labeling. There are two interpretations of the filipin labeling; both indicate that FPs are distinct membrane domains. First, FPs could have lower levels of β-hydroxysterols, most likely cholesterol, compared with surrounding membranes. This would be interesting, as different cholesterol levels have been shown to affect the activity of connexin hemichannels (Locke and Harris, 2009). Second, a protein network could underlie the FP membrane.
interfering with filipin binding, as occurs with the cholesterol-rich membranes of clathrin-coated pits or viruses (Steer et al., 1984). In certain EM preparations, GJ membranes display distinctive coats on the cytoplasmic surface (Sotelo et al., 1974; Sotelo and Korn, 1978; Manjunath et al., 1987; De Zeeuw et al., 2003). Whether FP membranes involve similar protein complexes is not known, but such specializations could also explain the stiff or rigid appearance of FP membranes. Thus proteins underlying the FP membrane (i.e., not in the bilayer), such as ZO-1 or adhesion-related proteins, could be implicated (Hunter et al., 2005).

**Connexin immunolabeling.** A large body of FRIL data demonstrate that all mature GJs, composed of different connexins, contain membrane particles ~8–10 nm in diameter, depending on various factors (Rash and Giddings, 1989), findings consistent with analysis of isolated GJs formed by Cx43 (Unger et al., 1999). Thus we know what to look for in FF replicas in terms of identifying the membrane particles (i.e., the connexons or GJ hemichannels) from which GJs will be constructed. The 10-nm particles are the only membrane particles of an appropriate size and sufficient number in the FP to represent connexin hemichannels and contribute to GJ assembly, and it is these particles that are labeled with Cx43 antibodies in the FRIL studies. Thus we have a second line of support for the idea that FPs are membrane domains, which is further strengthened by our analysis of the enrichment of 10-nm particles and the depletion of smaller particles.

When combined with the shift in junctional structures over time (Figure 5A) and the present analysis of dynamic changes within and between FP membranes, a compelling case is made for FPs serving as sites of GJ assembly, where the 10 nm particles are incorporated into GJs. An alternative interpretation—that FPs are not sites of assembly but instead sites of disassembly linked to junctional degradation—is not supported by the time-course analysis. Identifying the FP as a site of GJ assembly provides an important framework for future assembly experiments.

**Membrane interactions, docking, and aggregation in formation plaques**

Analysis of FP structures and dynamics during the GJ assembly process provided important support for the apparent matching of FP membranes and the progressive reduction of the intermembrane separation proposed in our assembly model. We documented that well-developed FPs involve matched membranes, seen most convincingly when P-face particle aggregates are found to be continuous with arrayed pits on an adjacent E-face. However, matching of the earliest FPs, although likely, remains uncertain. In addition, as suggested by images of relatively empty FP membranes, sparsely populated with 10-nm particles, the earliest FPs may involve few, if any, 10-nm particles.

Substantial support was also obtained for a progressive reduction of the intermembrane distance during assembly, illuminating what had been a poorly understood concept. Broad separations between membranes are clearly found in undeveloped FPs, and aggregates in FPs display intermembrane separations indistinguishable from those in GJs. The interesting question is what drives this reduction. Strong support is presented here for the role of GJ hemichannel docking in bringing membranes together, involving significant reductions of the intermembrane separation at precisely the sites of particle aggregates. Provocative images of what could be single docked particles serve to strengthen the case. The significance of this role for docking is twofold. First, it answers a long-standing question, indicating that docking occurs in the FP, in contrast to the nonjunctional membrane. Second, it would mean that docking precedes particle aggregation.

**Role of the C-terminal tail of Cx43 in GJ assembly and regulation**

Experiments comparing assembly with full-length Cx43 versus the truncation mutant identified several aspects by which connexin-interacting partner proteins could be envisioned to play critical roles. First, the apparent delay in assembly in M257 cells can logically be interpreted as a suppressed trafficking to the plasma membrane and/or to the FP, although we cannot rule out some contribution by lower expression levels in the M257 cells. It is possible that multiple regions within Cx43, including sequences found in M257, bind to multiple interacting proteins to facilitate recruitment to the plasma membrane and/or FP domain. Loss of the C-terminus might then affect recruitment but not exclude it. Second, the absence of high-density particle aggregates could also reflect the essential role of a binding protein that links particles together but is compromised in M257 cells. Finally, it is important to recognize that the number of unaggregated particles in M257 cells never exceeded that observed with full-length Cx43; in fact they were significantly reduced. This would support the idea that there is not an essential defect in docking and/or initial aggregation of hemichannels in the truncation mutant, because this would lead to a large excess of unaggregated particles (i.e., assembly precursors). Instead of an excess, however, the aggregation of particles in M257 cells occurred at a lower density of unaggregated FP particles than with full-length Cx43.

Other experiments demonstrated that the loss of the CT tail of Cx43 dramatically reduced the inhibition of GJ assembly mediated by PKC. These observations further emphasize the critical role of the C-terminus of Cx43 in regulating communication in a range of cell systems (Solan and Lampe, 2009) and highlight a role for kinases in modulating GJ assembly (Solan and Lampe, 2005).

Given the role of the C-terminus in regulating GJ assembly, we also sought to identify specific PKC phosphorylation sites required for the negative regulation. Five sites were evaluated. Mutating none of these sites, however, appeared to be sufficient to block the inhibition of assembly triggered by activation of PKC with TPA. The possibility remains that all three PKC sites (255, 262, and 368) must be phosphorylated for complete inhibition of assembly. Cell-specific differences in kinase profiles may also play a role in these responses. Finally, another possibility is that direct phosphorylation of Cx43 is not essential for the inhibition of assembly. Instead, an interaction could be involved between the CT tail of Cx43 and another protein affected by PKC, for example, one participating in membrane trafficking. Other studies reported PKC-mediated effects on Cx43 trafficking that occur over a time course that is consistent with the inhibition of assembly as described here (Leithe et al., 2009).

**MATERIALS AND METHODS**

**Cells**

Novikoff cells, grown as reported earlier (Johnson et al., 2002), were used for filipin studies. N2A cells transfected with wild-type connexin43 and M257 were kindly provided by Steve Taffet (SUNY Health Science Center, Syracuse, NY) and used for initial FF-EM studies on GJ assembly. They were maintained at 37°C in a standard incubator with 5% CO₂ in high-glucose DMEM containing 10% fetal calf serum (FCS), 100 U/ml penicillin/streptomycin, and 800 μg/ml gentamicin (G418; Life Technologies, Carlsbad, CA). HeLa cells, used for FF-EM and dye injection, were kindly provided and transfected with Cx43 by Klaus Willecke (University of Bonn, Bonn, Germany; HeLa-Cx43-K) and Bonnie Warn-Cramer and Alan Lau (University of...
Hawaii, Honolulu, HI; HeLa-Cx43-F, clone 4) or were generated in house via transfection (HeLa-Cx43-A), using connexin-deficient HeLa cells (American Type Culture Collection [ATCC], Manassas, VA).

For generation of clone HeLa Cx43-A, a cDNA insert containing the complete coding region of Cx43 (a generous gift from Eric Beyer, University of Chicago, Chicago, IL) was subcloned into the phagemid vector, pBluescript SK+ (Stratagene, La Jolla, CA), amplified, and then further subcloned into a pZipSV2 vector with zeocin resistance (Invitrogen, Carlsbad, CA) for introduction into HeLa cells (ATCC). A Cx43 insert containing a stop codon at serine 257 (M257), generously donated by Mario Delmar (University of Michigan, Ann Arbor, MI), was similarly subcloned and then transferred into a pIREs expression vector (GenBank U89672) possessing hygromycin resistance. A number of stable HeLa transfectants (including HeLa-M257 clones 2.2, 2.4, and 2.5) were generated from connexin-deficient HeLa cells (ATCC) using this expression vector. These cells were maintained in low-glucose DMEM containing 10% FCS, 100 U/ml penicillin/streptomycin, and 500 μg/ml hygromycin.

Paul Lampe (Fred Hutchinson Cancer Institute, Seattle, WA) kindly donated a pIREs-puroycin resistance pCDNA construct for expression of Cx43-S368A, Cx43-S262A, and a double mutant expressing both mutations. These were used to generate stably transfected HeLa cell clones (using ATCC cells), which were maintained in low-glucose DMEM, 10% FCS, and 0.5 mg/ml puroycin. The triple MAP kinase mutants transfected into HeLa cells were kindly donated by Bonnie Warn-Cramer and Alan Lau (University of Hawaii).

The choice of cell lines and transfecant clones for the various experiments was based on the following considerations: 1) Novikoff cells, in which FPs have been characterized quantitatively in previous studies (Johnson et al., 2002), were used for the filipin experiments as part of an earlier set of assembly studies only now being reported. Repeating these experiments with N2A and/or HeLa transfectants was not considered necessary, given the clear results with the Novikoff cells. 2) N2A transfectants (expressing either Cx43 or M257) were used for some of the qualitative studies and for an initial quantitative EM/FF comparison with results from our previous dye injection studies on assembly by these cells (TenBroek et al., 2001). Because the Cx43-N2A cells developed very large and numerous FPs, they were especially useful in studying certain FP features, such as matching of FPs in adjacent cells, width of intermembrane separation, organization of 10 nm particles, and so on. However, the re-aggregated N2A-M257 cells exhibited only a very small number of junctional structures (either FPs or GJs), making it impractical to compare the Cx43 and M257 FPs in quantitative detail. 3) HeLa cells were therefore chosen for comparing Cx43 and M257 transfectants by means of EM/FF. The HeLa-Cx43-F clone was selected, except where noted, because these cells displayed rapid assembly and allowed for sampling from numerous, actively assembling interfaces. The HeLa-M257-2.2 clone was chosen for comparison because, based on dye transfer, it was representative of several clones expressing the Cx43 truncation. However, the Cx43-K clone was the primary “control” for the dye injection studies of TPA-induced inhibition of assembly. In contrast to the Cx43-F clone (results not shown), the Cx43-K clone in established cultures continued to display substantial communication after 75 min in the presence of TPA (Supplemental Figure S4A), that is, only partial inhibition of permeability (gating), and thus provided the most unambiguous comparison with TPA effects on assembly by the M257 transfectants and CT site mutants.

Assembly protocol
Novikoff cells were reaggregated according to established methods (Johnson et al., 2002). Both N2A and HeLa cells were passaged 2 d prior to an experiment, and a change of fresh medium occurred 24 h prior to the experiment. To achieve complete confluence following assembly, 100-mm dishes of cells at 80–100% confluency were dissociated and then reassembled in 35-mm culture dishes. Cells were dissociated with 1 ml of 0.25% trypsin-EDTA (Life Technologies) for 1.5 min at 37°C, the trypsin neutralized with complete DMEM medium containing FCS, and the cell suspension centrifuged to remove the neutralized trypsin. Cells were then gently resuspended in fresh medium containing 12.5 mM 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid buffer and transferred to adhesion-blocked poly-2-hydroxyethyl methacrylate–coated centrifuge tubes for a recovery period of 90 min on a shaker platform in a 37°C incubator with rotation at 200 rpm. During this period, cells internalize disrupted GJs from the cell surface (Preus et al., 1981a). The suspension was passed through a sterile 35-μm filter to remove any large clumps of cells. The final cell preparation was plated onto 35-mm dishes by gentle centrifugation at 750 rpm for 10 min. Cell reaggregation and subsequent assembly of junctions was allowed to proceed by placing the dishes in a standard CO2 incubator at 37°C for 3 h in the case of N2A cells and for 1–1.5 h with HeLa cells. For the time-course evaluation of GJ assembly in HeLa cells with FF-EM, at least two experiments were evaluated for each of the two samples (full-length and truncated Cx43) at each time point.

Fixation
For filipin-labeling studies, Novikoff cells were prefixed for 15 min in 2% glutaraldehyde, 0.05% CaCl2, and 1% dimethylsulfoxide in a 0.1 M sodium cacodylate buffer (Johnson et al., 2002). Then control samples were treated with fresh fixative of the same type, typically for 3 h at 25°C. Experimental samples were treated with the control fixative to which had been added 300 μM filipin (Upjohn, Kalama-zoo, MI). For conventional FF work, assembled monolayers of N2A or HeLa cells were rinsed with Hank's buffered saline containing calcium and magnesium and were then fixed in 2% glutaraldehyde in 0.1 M sodium cacodylate buffer overnight at 4°C. For FRIL studies, cells were fixed for 1 h in 4% formaldehyde in 0.15 M Sorenson's phosphate buffer at pH 7.4.

Sample freezing
For the conventional freeze-fracturing and for the filipin work, after three washes in 0.1 M cacodylate buffer to remove fixative, the cell cultures were scraped with a rubber policeman and transferred to a 1.6-ml Eppendorf tube. Following short centrifugations to produce loose pellets of cells, the supernatants were removed and replaced with fresh cacodylate buffer containing 20% glycerol cryoprotectant, and this was allowed to infiltrate for 1–2 h at room temperature. Samples were briefly centrifuged, transferred to gold FF “hats,” and then frozen by plunging into liquid propane cooled to −190°C and stored in liquid nitrogen until fracturing. For FRIL, samples were cryoprotected with 30% glycerol and plunged-frozen into liquid propane/ethane cooled with liquid nitrogen.

Fracturing
For the filipin studies and for the conventional freeze-fracturing, samples were fractured in a Balzers BAF 060 FF apparatus (Bal-Tec; now Leica Microsystems, Buffalo Grove, IL). They were shadowed with a platinum/carbon source at a 45° angle and then carbon coated. For FRIL studies, samples were fractured in a JEOL 9010c freeze-fracture machine (RMC/Boeckler; JEOL, Akishima, Japan), rotary coated with 1 nm of carbon, and unidirectionally shadowed (60°) with 1.0–1.5 nm of platinum/carbon, followed by 20 nm of carbon (Rash...
expression levels. For these assembly experiments, individual FP parameters and all 10-nm particles were enumerated (Johnson et al., 2002), as well as the areas and particle numbers for the mature GJs.

Following the analysis of the assembly experiments, images were scanned (Umax MagicScan), transferred to a computer, and subsequently examined and analyzed with Image Pro, version 4.0 (Media Cybernetics, Bethesda, MD), software. Magnifications were confirmed by calibrating the microscope using a standard diffraction grating replica (Ernest F. Fullam, Ted Pella), and measurements were then converted to pixels for data collection and comparison. FRIL negatives were scanned and digitized using an ArtixScan 2500f digital scanner (Microtek, Carson, CA) and processed using Photoshop CS2 (Adobe Systems, San Jose, CA).

Dye injection
Injection of Lucifer yellow into various HeLa transfectants was used to monitor GJ communication between cells as reported previously (TenBroek et al., 2001) by assaying for the number of recipient cells detected 5 min after injection (or as noted in the figure legends). In most cases, recipient cells were counted by eye at the 5-min point, although digital images were collected in some later experiments. Parental HeLa cells used for the transfections displayed little to no dye transfer (based on three experiments; data not shown); the occasional limited transfer was presumably due to a low level of expression of a native connexin. For the studies of the effect of TPA on assembly, TPA was present during the last 15 min of the recovery period and throughout the assembly period. The average number of cells receiving dye with TPA was normalized to the average number of cells receiving dye in the untreated cells.

Statistical analysis
For the GJ assembly analysis, since it has been shown that the developing FPs and GJs exhibit a skewed distribution (Preus et al., 1981b), the data on particle numbers and FP areas were presented as geometric means, and standard errors were determined. The latter values, which incidentally are not symmetrical, were then back-transformed for presentation in the tables. Statistical significance was determined by t tests on the transformed data, with p < 0.05 considered significant. For the dye injection experiments, numbers of recipient cells were expressed as arithmetic means ± SEM and evaluated with t tests; p < 0.05 was considered significant. For presentation of dye transfer data, samples treated with TPA were normalized to the untreated controls.

ACKNOWLEDGMENTS
We are grateful to James Nagy and Alberto Pereda for fruitful discussions related to the manuscript, to Mario Delmar and Steve Taffet for N2A cells, to Klaus Willecke for HeLa cells expressing Cx43, to Alan Lau and Bonnie Warn-Cramer for cells expressing the MAP kinase mutations, and to Paul Lampe for constructs. The work was supported by National Institutes of Health Grant GM-46277 to R.G.J. and J.D.S. and by National Institutes of Health Grant NS-44395 to J.E.R.

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