General and specialized characteristics of the TMJ

The temporomandibular joint (TMJ) is a cardinal feature that defines the class Mammalia and separates mammals from other vertebrates. As befits its late evolutionary origin, the TMJ also makes a tardy developmental appearance. The TMJ is interesting because its constituent bones, the mandible and the squamous temporal, are intramembranous in origin. Thus, the tissue that covers each articulating surface is a secondary cartilage with a fibrous skin, derived from the periosteum. Another nearly constant feature is the intra-articular disc. The disc, even when incomplete, is associated with the lateral pterygoid muscle, which has led some authors to speculate that it arose as a tendon which became pinched by the new joint.

An additional interesting feature of the TMJ is its role in growth. Intramembranous bones do not have epiphyseal plates, but their growth is effected (or at least affected) by nearby cartilaginous structures. In the cranium, the cranial base cartilages and the nasal septum are thought to be the major drivers of growth at cranial sutures. It seems likely that in most vertebrates, Meckel’s cartilage performs a similar role for the multiple bones of the lower jaw. The evolution of the TMJ accompanied the almost complete removal of Meckel’s cartilage from the sutureless lower jaw of mammals, thus eliminating this mechanism of growth. The substitute is the secondary condylar cartilage, which is a major growth site in addition to being an articular covering.

Despite its status as a mammalian identifier, the TMJ shows remarkable morphological and functional variation in different species, reflecting not only the great mammalian adaptive radiation in feeding mechanisms, but also a freedom from constraints such as bearing body weight. The most extreme evolutionary variants include: (1) loss of the synovial cavity in some baleen whales; (2) loss (or possibly primitive absence) of the disc in monotremes, some marsupials, and some edentates (anteaters and sloths); (3) variations in the orientation of the joint cavity from parasagittal (many rodents) to transverse (many carnivores); and (4) reversal of the usual convex/concave relationship so that the mandibular condyle becomes the female element (many artiodactyl ungulates such as sheep and cattle). In addition, the relative size of the joint is exceedingly variable. Soft tissue details such as capsular ligaments and collagen orientation in the disc are also highly species-specific.

The striking anatomical differences in TMJs are clearly tied to biomechanics. The features mentioned above are either correlates of loading (e.g., size of articular surfaces) or movement (e.g., orientation of the joint) or both. Loading of the TMJ is a reaction force arising from the contraction of jaw muscles; its magnitude depends strongly on the position of the bite point relative to the muscle action line. The evolution of the TMJ is thought to have coincided with a period of low reaction loads, with higher loading having evolved repeatedly in different lineages, including our own. Many commonly used laboratory animals, especially rodents, fall in the category of minimal TMJ loading, especially during chewing. In contrast, carnivores such as dogs probably sustain TMJ loads that are higher than those in primates. Complex movement in three planes of space is also a primitive characteristic of the TMJ, at least if embryology is any indication, but there is no uniformity in how movements are accomplished. Opening of the jaw usually involves a combination of forward sliding and rotation around a transverse axis, but some carnivores have lost the ability to slide and some specialized anteaters instead use a rotation around the long axis of the curved mandible. Similarly, transverse movement is usually accomplished by moving one condyle forward and the other one backward, but carnivores use a combination of lateral sliding and rotation around the long axis of the mandible.

Animal models for TMJ research - a literature survey

TMJ research on animal models has not lagged in com-
A May, 2003 Medline search for "TMJ and animal" yielded 952 hits overall, a distant second place to the number of citations for the knee but well ahead of those for other body parts (Table 1).

In the last 20 years, animal-based publications on TMJ research have increased from 17 papers per year in 1968-82 to an average of over 80 per year in 2000-02. At the same time, there have been striking changes in the species used. Interestingly, the genetic revolution has not revolutionized TMJ research. The proportion of TMJ publications using mice has remained steady at 6-7% over the entire time period. Probably this reflects the physical difficulty of working on tiny mouse joints, but in addition it surely points to a lack of interest in the TMJ on the part of geneticists.

What has changed the most is use of primates. In 1973-82, monkey studies accounted for 37% of animal TMJ work, but in 1998-2003 this percentage dwindled to 6%. Work on dogs and cats also declined, from 18% to 6%. The slack has been taken up by rats (from approximately 22% to 37%), rabbits (from 6% to 22%), and surprisingly, artiodactyl ungulates (pigs, sheep, goats and cattle, increasing from approximately 10% to 24%). The most likely reason for this changeover is pressure from animal protection groups.

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Table 1. Results of a Medline search.

<table>
<thead>
<tr>
<th>Search Term</th>
<th>Number of Citations</th>
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<tr>
<td>Knee Joint and Animal</td>
<td>3649</td>
</tr>
<tr>
<td>TMJ and Animal</td>
<td>952</td>
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<tr>
<td>Hip Joint and Animal</td>
<td>800</td>
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<tr>
<td>Tarsus and Animal</td>
<td>728</td>
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<tr>
<td>Ankle Joint and Animal</td>
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<tr>
<td>Shoulder Joint and Animal</td>
<td>310</td>
</tr>
<tr>
<td>Intervertebral Joint and Animal</td>
<td>198</td>
</tr>
</tbody>
</table>

Are rats, rabbits, pigs, sheep, goats and cattle adequate as TMJ models?

Whether or not a given animal model is appropriate obviously depends on what problem the model is supposed to address. On a basic biological level, for example, the response of mesenchymal cells to a certain type of loading or a certain cytokine, the species may not matter. Indeed, for such general problems, one might not need a TMJ. Despite their unusual origin, it has not been demonstrated that TMJ cells are physiologically different from cells of other joints. Some "TMJ research" could probably be conducted using more conveniently located joints such as the knee. For more specific questions, however, the joint and the species clearly do matter.

One might ask, in view of my earlier comments on mechanics, whether a switch from primate and carnivoran models to rodents, lagomorphs and artiodactyls has been wise. These species have emerged as preferred TMJ models for practical reasons, not because their TMJs are particularly similar to those of humans. I would argue, however, that we are better off with these diverse groups. The relative proximity of the monkey and human lineages is no guarantee of similarity in TMJ function. If representatives of three different mammalian orders (Rodentia, Lagomorpha and Artiodactyla) all support a given finding, the chances are good that the finding will be valid for humans too. A comparative approach will be especially useful to determine the generality of genetic influences, pain mechanisms, and inflammatory responses.

The one area which remains a problem is function, because muscles, movements, and joint loads are so species-dependent. A perfect animal mimic of human function is an impossibility, because the human TMJ is unique in several features, such as the comparatively enormous lateral pterygoid muscle. However, it will clearly help if researchers have a good understanding of how the TMJ functions in their model organisms. Thus, I will conclude with short descriptions and key references for the TMJs of the currently most popular species.

Sheep, goats and cattle are closely related ruminant artiodactyls and have essentially identical TMJs. This group of ungulates has a distinctive jaw apparatus specialized for an herbivorous diet. As mentioned above, the condyle is the concave element. The TMJs are specialized for great mobility in the transverse plane but limited opening. The mandibular symphysis is patent and flexible, permitting long axis rotation of the mandible. Although the TMJ has not received much attention, muscle activity patterns and loading of facial bones have been well described.

Despite belonging to the same order (Artiodactyla) as the ruminants, pigs have a totally different TMJ, actually surprising similarity to that of higher primates. For this reason, their jaw joint anatomy and function have been well investigated. Moderate movements in all planes are permitted, and the symphysis is fused, as in humans. The condyle is compressed and probably twisted during chewing, whereas the lateral surface of the temporal bone is bent. More general features of pig oral behavior and muscle contraction are known as well.

Rabbits have converged with the ruminants in terms of their occlusal pattern and masticatory movements but the condyle is rounded (more so than in primates and pigs) and the symphysis is immobile (but unfused). Rabbit TMJs have a pronounced antero-posterior component which is utilized in certain masticatory movements. There is a rich literature...
on masticatory function in rabbits\textsuperscript{27-30}, including calculations of TMJ loads based on muscle activity\textsuperscript{26,31}. Interestingly, the working side condyle may be completely unloaded during the power stroke of chewing in rabbits\textsuperscript{26}.

The rat (and mouse) TMJ is highly specialized for extensive protrusive movements, much more so than the rabbit. The rounded condyle travels in a trough-like temporal fossa and the power stroke is in the protrusive direction with only a minor medial component\textsuperscript{32}. Long-axis rotation can occur around a mobile symphysis. Calculations indicate that neither the working nor the balancing side TMJ is loaded during mastication\textsuperscript{19}. Although rat masticatory mechanics are a far leap from those of primates, practical considerations have led to a database which is both deep and broad\textsuperscript{34-37}.

### Summary

The TMJ is unique to mammals, but among different mammalian groups its morphology and function vary enormously. Practicality dictates that animal models will not be the closest mimics of the human condition. Currently, the most used species are rats, rabbits, pigs, and ruminant ungulates. Each has distinctive TMJ adaptations. Except for pigs, it is likely that these species show less loading of the jaw joints during chewing than do humans.

### References

28. Langenbach GEJ, Wejs WA, Brugman P, Van Eijden


