CHAPTER III

Remodelling of the Internal Architecture and External Shape of Bones

During normal growth, the skeleton continuously undergoes typical modifications of its external shape (see Chap. VI, Sect. 1). They result from the different requirements of mechanical performance from the individual bones at different ages.

These typical modifications in shape are of course accompanied by growth changes of the internal architecture, which take place at many points, although the normal architectural picture of each bony area remains grossly the same throughout life (see Chap. VI, Sect. 1).

Determining exactly these typical growth changes of the internal architecture in each bony area at different ages remains an enormous task for the anatomists.

I do not discuss these modifications in shape and architecture of the bones in the present work.

I shall only consider the alterations in shape and architecture which occur when the bones of young or adult individuals work in circumstances different from normal.

I shall thus discuss:

1. remodelling of the internal architecture of bones when their external shape is disturbed pathologically,
2. secondary changes of the external shape of bones following primary alterations of their shape,
3. modifications in architecture and shape of bones after pathological disturbances of their static stressing and
4. changes in architecture and shape of bones after intentional modifications of their stressing.

We shall successively see evidence of remodelling in specimens of pathological and experimental bones, and in clinical observations, discuss the development of each remodelling theoretically and follow the histological process of the bone remodelling.

1 Remodelling of the Internal Architecture of Bones After Pathological Alterations of Their External Shape

Following the discovery of Culmann, important conditions can be predicted mathematically not only for normal bones but also for bones altered pathologically. Elementary graphic statics demonstrate that any change in the external shape of a loaded beam provokes an alteration in the directions of the maximum tension and compression and, therefore, a modification in the stressing of all the elements of the beam in compression, tension and shear.

Applied to bone this means that, when a bone altered in shape starts to function again, the initial trabeculae which were adapted to the earlier normal shape may be useless. They are no longer able to withstand the maximum tension and compression due to loading. After the alteration in shape, the shearing effects of loading which were previously eliminated in the trabeculae become effective. The directions of the maximum tension and compression resulting from the altered shape often coincide with holes between the original trabeculae and with the medullary cavity, where earlier the presence of bony material was superfluous. As soon as its external shape has been altered, the bone no longer matches its mechanical requirements. Even for relatively slight external assaults it will break or collapse.

These mathematical considerations suggest that a bone altered in shape can be functional again only after its trabeculae, which were adapted to the earlier normal shape may be useless. They are no longer able to withstand the maximum tension and compression due to loading.

Again I can write that either Culmann's discovery is illusory or, if not, that every pathological change in the shape of a bone must entail a corresponding remodelling of its trabeculae.

Based on preliminary thinking in 1870 I published the guidelines of "The law of remodelling of the internal architecture of bone after pathological alteration of its external shape". Thus "It seems almost doubtless that the bony trabeculae disappear where, as a result of a
curvature, they are no longer stressed. New bony elements must develop where the material is stressed as a result of bony regeneration or of curvature of the bone” [23].

I added that I was analysing a bone bent by rickets and predicted that research into the architecture of rickety bones would provide us with essentially new insights into the process of the condition.

Only in 1871 was I able to demonstrate on specimens of pathological bones the correctness of the law which I had suggested.

The mathematical assumption was again verified in these specimens.

In many specimens of fractures I observed that, every time the fracture had healed with an angulation of the fragments, a new bony architecture had developed which matched the new static circumstances. The architectural modifications extended to areas some distance from the fracture site. For example, they were observed at the articular extremities of a long bone after a fracture of its shaft. This phenomenon obviously confirms the mathematical considerations.

Similarly the study of bones bent by rickets showed that a new architecture adapted to the new mechanical circumstances had developed in the section along the neutral fibre layer as well as in that perpendicular to it.

I delivered the first communications about this discovery in September 1871 to the surgical and to the anatomical section of the Meeting for Nature Researches in Rostock 10.

Confirming my arguments, Martini 19 presented to the surgical section the development of a new architecture in the specimen of an ankylosed hip.

The demonstration by Martini was suggested by myself after I had found that Martini was "enthusiastic", as he wrote later [31], "about von Meyer’s, Culmann’s and my own works" and became involved in the analysis of bony architecture.

Using interesting material which had accumulated in the meantime, I demonstrated the exact conditions of the law of these remodellings at the session of the Berlin Medical Association on 15 May 1872 and I discussed the consequences of this law on fracture healing.20

This communication, abundantly complemented, was published soon after in Archiv für klinische Chirurgie [35]. The publication was illustrated by the first photographic pictures of Fournier sections representing the internal architecture of bones broken and malunited [35, Table V] and by the first schematic picture of a rickety bone [35, Table VI, Fig. 5].

In my communication I also showed for the first time the secondary modifications of the external shape of the bones resulting from primary alterations in shape.

I spoke about what Roux would call later the theory of the "functional shape of the bones" [35, p. 310, fn. 1] and about what Roux would call the theory of the "trophic stimulation of function" [35, pp. 301, 311]. Finally I mentioned certain bone remodellings induced experimentally during my study of bone growth [35, p. 293] (see Chap. III, Sect. 5).

Koester confirmed my theory in an excellent, although fragmentary, communication which he had delivered on the architecture of ankyloses on 15 July 1872 at the Association for Physics and Medicine in Würzburg [36].

Koester had found that "as soon as a mass of cancellous bone has developed after an ankylosis, this bone mass presents – as does normal cancellous tissue – a well-defined structure of curved lines intersecting each other which correspond to the theoretical lines of graphic statics. This structure always appears in similar instances. This architecture is most obvious in ankylosis of the knee and hip. The bony trabeculae pass from the normal bone through the newly built bone mass without interruption or angulation. The appropriate shape here is also restored with a minimum expenditure of material. The functional capacity or at least the impression of security progresses with the development of these compression and tension lines".

A second confirmation followed in Hamburg on 30 July 1872 when Martini delivered a communication on the architecture of bones and joints pathologically deformed [31].

As mentioned above, this author had studied the ankyloses before Koester and continued his researches using the abundant material of the Institute of Anatomopathology of the Hamburg General Hospital.

He was able to show that, in ankyloses in abnormal positions, "there exists a new architecture adapted to the new static circumstances, without any visible limit between the bones thus united". His analysis of specimens of fractures led him to confirm what I have mentioned briefly above. Moreover, he described the ap-

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18 Dr. Gies from the surgical section briefly commented in the proceedings of the Rostock meeting (p. 126): "Wolff (Berlin) presents specimens of united fractures of the neck of the femur and of rickets from which it appears that in pathological circumstances a new architecture of the bone develops which is adapted to the altered mechanical circumstances". Messrs. Zuntz and Flemming made similar comments on my lecture to the anatomical section of the Rostock meeting.

19 About the demonstration of Martini, Dr. Gies wrote (Rostock meeting, p. 126): "After Wolff's lecture, Martini (Hamburg) presented a specimen of ankylosis of the hip in which a new architecture had also developed corresponding to the new mechanical circumstances".

20 See my own short comment about this lecture in [32, 33]. See also my remark concerning my priority claim on the law of remodelling [34].