Experimental Studies in Human Tooth Wear: I

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ABSTRACT The construction of a machine called CANIBAL which is capable of simulating the actions of the human mandible during chewing is reported. Powered by an electric motor, a cam activated rocker arm assembly transmits force by means of wires to each point on the mandible where muscles would be attached. A separately adjustable cam, rocker arm, directional pulley and wire represents each muscle. Models of dental arches cast in dental stone or other materials can be mounted and subjected to extended wear. With different cam settings, wear patterns can be produced which resemble those seen on various fossil and living human dental arches.

Extreme forms of tooth wear, so frequently seen upon examination of the dentitions of skeletal remains of "primitive" peoples, suggest that the teeth are frequently used for purposes other than eating, even though the abrasives in food are probably the major causes of wear (Dahlberg, '63). Studies on both skeletal and living representatives of aboriginal populations describe heavily worn teeth for people subsisting on aboriginal diets (Cambell, '25; Pedersen, '38, '49; Shaw, '31; Snow, '48).

Observations of living populations show that the teeth are used for a variety of purposes such as chewing of hides as part of the tanning process (Pedersen, '38), the chewing of coca leaves or tobacco dipped in lime (Leigh, '28; '37), and, as can be seen in the heavy wear on the front end of the dental arch, for tools in tearing, cutting, or holding and pulling (Falero, '05; Noble, '26; Brace, '62). Though the literature discussing dental caries and attrition is quite extensive, there are very few recorded observations on how the teeth are characteristically used. When questioned on this point, however, a person who has spent some time studying a primitive group will reply that the teeth are frequently used for a variety of functions in place of tools. For example, several persons who have visited the Seri Indians of Northern Sonora, Mexico, over the past few years mention that the Indians are "always putting something in their mouths." The Seri have been observed using their teeth to aid in the making of baskets, splicing rope, untying a difficult knot, and in the manufacture of harpoons. These and other funtions place heavy stress on the dental arches, particularly the forward end (incisors and canines). Unfortunately, there is as yet no report on the dentition of these people.

The various studies reporting the degrees and types of attrition show that not all people wear their teeth in the same way, and the patterns produced frequently are characteristic of certain populations (Buxton, '20; Drennan, '29; Shaw, '31; Steadman, '37; Campbell, '39; Goldstein, '48). These studies deal mainly with the wear planes produced on the molar surfaces. In addition, the edge-to-edge bite, considered characteristic of primitive people, is mentioned as being the result of a wearing down of the cusps and not as the result of some genetic mechanism (Ritchie, '23; Steadman, '37; Emslie, '52; Senyürek, '52). Leigh also ('28) states that the edge-to-edge bite is the result of the function and is not innate. He observes that adolescents and children in an aboriginal population frequently show a labial overlapping of the superior incisors while maintaining a normal position of the first molars. Adults in the same population show an edge-to-edge occlusion.

[1] The senior author would like to express his gratitude to the Research Committee at the University of Calfiornia, Santa Barbara, for granting support from General Research Funds to defray the expenses incurred, starting in 1961 and continuing through 1967. In addition, the junior author gives thanks to the National Science Foundation for awarding an Undergraduate Participation Award in 1962-1963, NSF-G-16128, and to the National Institutes of General Medical Science for awarding a Predoctoral Fellowship, 1-F1-GM-30,609-01, without which the project could not have been completed.

These wear patterns, whether caused by dietary abrasives or through the use of the teeth as tools, are the results of a particular set of movements of the mandible. Years of study by a great many investigators emphasize that the movements of the human jaw are the results of highly complicated, precisely coordinated changes in the forces applied by the masticatory muscles. In order to study the ways in which the various wear patterns are produced and how they affect the occlusion of the dental arches, the movements of the mandible must be thoroughly understood.

A concern for understanding the precise movements of the human chewing apparatus and the problems of dental restoration and prosthesis has produced an interest in mechanical articulators and the problems of masticatory actions which extends back into the nineteenth century — at least on the part of the dental profession (Luce, 1889, 1891, '11; Walker, 1896a,b). The immediately practical significance of such interests has meant that research concerning the actual variations of the human masticatory machinery had little impetus. As a result, theories such as the one suggesting that "spherical articulation" was the human ideal could be offered without contradiction (Needles, '22, '23a,b). and almost no information has been systematically collected on the different ways in which the human dentition is characteristically used. To our knowledge, only one previous attempt has been made to simulate precisely the exact forces which operate the human chewing mechanism, and this was only a demonstration device not designed for active and continued operation (Lord, '13, '37) .

Some statements concerning mandibular function were simply speculations based on the assumed logic of the human chewing apparatus (Keith, '20; Gysi, '21; Brace, '62) to which some insight was contributed from histological studies (Robinson, '46; Rees, '54) and from clinical cases (Root, '46; Cobin, '52). From another direction, information has accumulated from the experimental modification of the chewing machinery, although this has been directed more towards elucidating the relationship between the growth of the masticatory apparatus and the form of the skull than towards demonstrating the actual functioning of the muscles involved (Anthony, '03; Anthony and Pietkiewicz, '09; Baker, '22, '41; Pratt, '43; Washburn, '46, '47; Horowitz and Shapiro, '51.

More recently, the development of electromyographic techniques has led to the discovery of the precise sequence of muscle action required to produce specific mandibular movements (Moyers, '49, '50; Neumann, '50; Carlsöö, '52, '56; Pruzansky, '52; MacDougall and Andrew, '53; Latif, '57). While great insights have been gained through the use of electromyography, a number of limitations are also present. Insertion of the electrodes causes a certain amount of pain which may modify normal activity, and as yet these is no way to determine the extent of this possible inhibition (Carlsöö, '52, '56; Moyers, '50). Furthermore, in experiments with the living, it is impossible to eliminate at will the contributions of specific muscles in order to determine either their functions or the functions of others which tend to contract at the same time, although some of this has been demonstrated in the clinical literature (Root, '46; Cobin, '52).

In addition, electromyographic analysis requires the cooperation of the subject, and it is not always possible to obtain this. In this latter regard, some of the dental conditions of greatest interest to the anthropologist occur among people in remote parts of the world far from the appropriate laboratory facilities, and, finally, some of the most interesting problems are presented in the jaws and teeth of skeletal remains, both recent and ancient, where no possibility for active cooperation by the subject exists.

With this as a background, it would seem that a logical approach would be the construction of a machine which would simulate the human chewing mechanism and which would allow the variation and control of each significant element separately. An attempt to reproduce the full amount of pressure capable of being generated at each point on the dental arcade of the living would be desirable, but so far the expense of construction and instrumentation has proved prohibitive. While this approach has had to be postponed, it is our hope to be able to pursue it further if funds become available.

Although is has been demonstrated that the force exerted by the human bite can exceed 100 kg (Black, 1895; Klaffenbach, '36; Warner, '39; Howell and Manly, '48; Anderson, '56), the forces normally generated during the mastication of foods characteristically encountered in the "civilized" diet are below 10 kg, averaging in the neighborhood of 3 to 4 kg (Neumann, '50). Our intent, then, was to build a machine which was at least capable of generating normal chewing pressures and which could simulate by homologous means all of the actions of which the human dental apparatus is capable. The mental image created by a machine which wears itself down by chewing — in fact, eats itself — led us to refer to it as the CANIBAL, which we rationalize to Cam Actuated NIBbling AppLiance.

In the course of producing a device which was actually able to carry out our intent, preliminary models were made which served to test the practicality of the basic approach and give us some idea concerning strength of materials and magnitude of power source required. For instance, CANIBAL II, the immediate predecessor of our present model, was constructed of odd pieces of aluminum door frame with cam and dentition mounting plates of three-quarter inch plywood, but the bend in these elements produced by even a moderate application of force (barely enough to make impressions on dental wax) was sufficient to demonstrate the need for much stouter construction.

In anticipating the dimensions which such a machine should have, it was noted that there are five sets of muscles which are of primary importance in producing mandibular movements:

1. Temporals.
2. Masseters.
3. Internal pterygoids.
4. External pterygoids.
5. Digastrics.

Actually, the masseters (both superficial and deep portions) and the internal pterygoids produce effects upon the mandible which are so nearly identical that, for purposes of our model, one component was regarded as being sufficient. On the other hand, electromyographic work has shown that the temporalis should not be represented by a single direction of pull (Latif, '57). Because of the variety of directions in which the temporalis can pull, provision was made for three components: an anterior component which pulls vertically; a posterior component which pulls back about 15° above the horizontal; and a middle component which pulls back and up, halfway in between the directions of the other two components.

All together, for the forces acting on the mandible, provisions had to be made for three temporal components, a masseter component, and external pterygoid component, and a digastric component. Taking both sides of the mandible into account, the machine had to be able to pull in 12 different directions at once. This was coordinated by deriving movement from a set of cams mounted on two cam-shafts. Power was provided by a one-third horsepower A. C. motor operating through a worm gear transmission which achieved a 14:1 reduction. A "V" belt and pulleys completed the transmission of power to the cam assembly. Different speeds could be produced by varying the pulley diameters.

The overhead cam-shaft and rocker-arm assembly transmitted vertical forces to stainless steel cables, with changes in the directions of pull being determined by variously placed guidance pulleys. In order to minimize the power lost to friction which had plagued CANIBAL II, bearings were used wherever possible.

The framework of CANIBAL III was welded from one inch angle iron. This serves as support for the maxilla and the cam assembly mounting plates which were cut from three-quarter inch aluminum jig plate. The cam assembly includes a drive shaft mounted on one-half inch sealed ball bearings, one at each end, and two cam shafts mounted at both ends and in the middle by similar one-half inch bearings. The "V" belt and pulley turn the drive shaft which imparts motion to the cam shafts by means of one and one-half inch spur gears, three-eighths inch thick, and with a pitch of 24 teeth to the inch. There are eight cams per shaft, cut from one and one-half inch bronze round stock, giving a total of 16 possible sources of power appli-

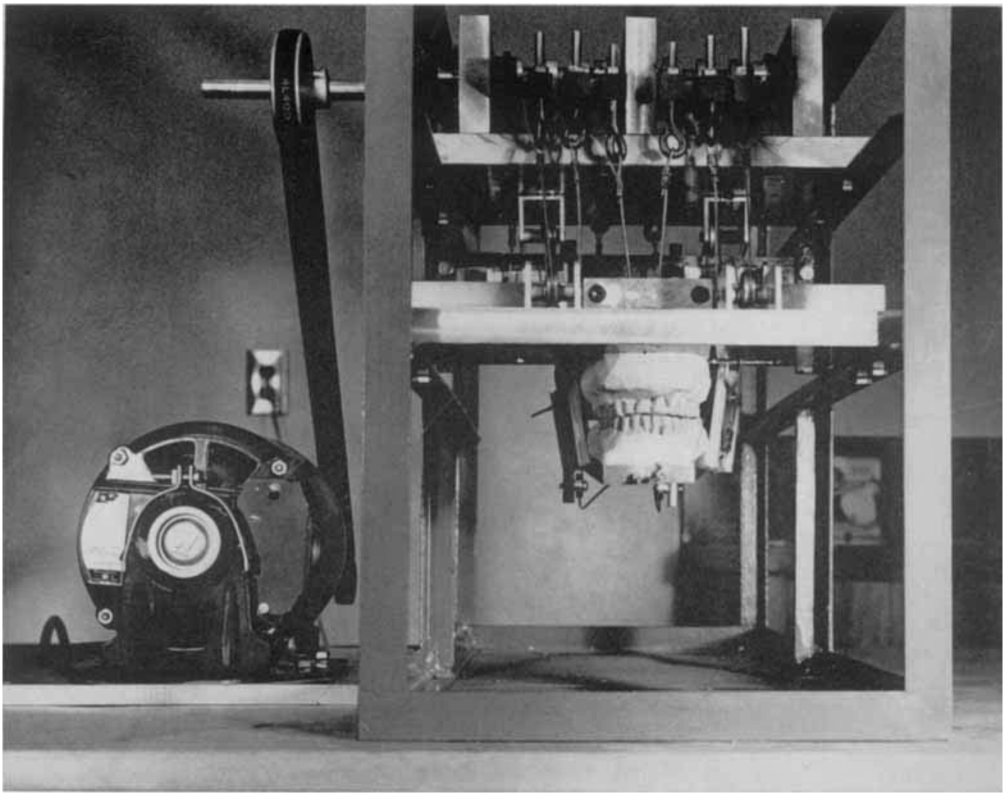

Fig. 1 The CANIBAL, front view.

cation. Each cam has two Allen-head set screws which enable each one to be separately adjusted so that the timing action of the "muscle" represented could be changed. Calibrated discs fixed on the cam shafts enabled us to quantify the variations in cam settings from an arbitrary zero point.

The motion of the cam shafts is picked up by cam follower arms, or rocker arms, mounted one-fourth inch roller bearings on one-fourth inch rods, one parallel to each cam shaft. The rocker arms were made from five-eighth inch cold rolled key stock, and in the ends which ride on the revolving cams were set three-eighth inch sealed ball bearings (this had been a major area of friction in CANIBAL II). The motion of the outer ends of the rocker arms is transmitted to the mandible by 6 mm diameter stranded stainless steel cable. Changes in the direction of pull were accomplished by running the wires over variously placed pulleys made from three-quarter inch brass round stock mounted in one-quarter inch roller bearings.

Although many refinements can be made, the machine is now reliable enough to run untended for periods of half a day or more, and some tentative insights can already be reported. Among these is a possible function for the digastric muscle which has been generally overlooked. It has usually been assumed that this is of importance mainly in the opening of the mandible and primarily in the later phases of opening. The CANIBAL shows, however, that it can also play a role in the distal shifting of the mandible. This is only a tentative suggestion, however, since we do not have any data relating to the possible differences in function of the anterior as contrasted with the posterior belly of the digastric. As yet, electromyographic studies have been confined to the anterior belly (Moyers, '50). If our surmise concerning

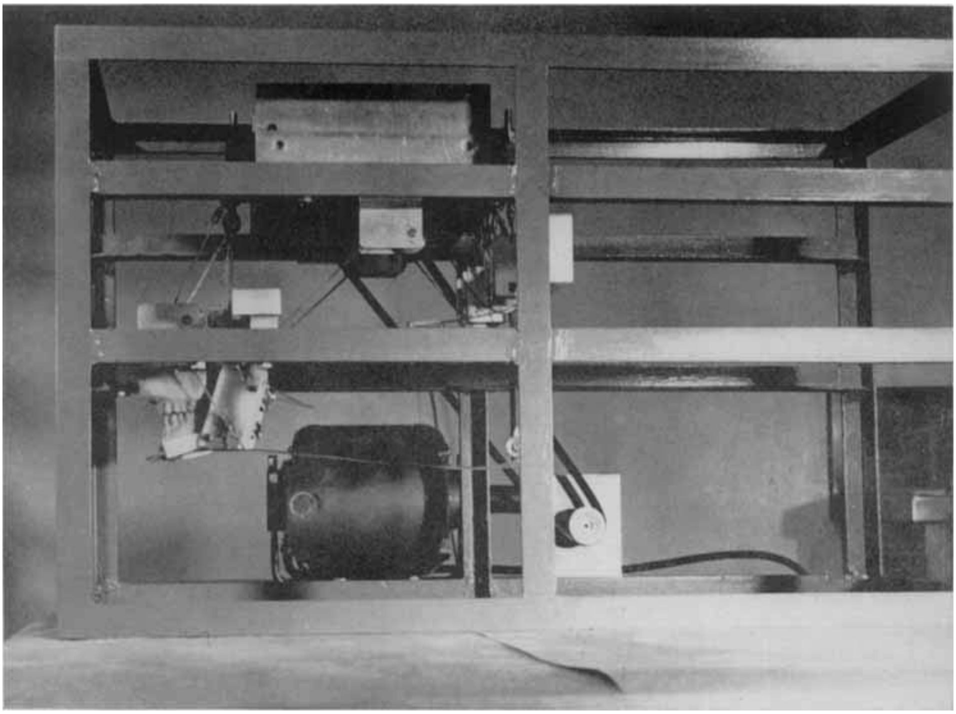

Fig. 2 Side view of the CANIBAL showing how pulleys change the direction of force application from the vertical pull of the rocker arms.

the possible listo-shifting function of the digastric is correct, then it might be a first step to explaining why the digastric impressions of Palaeolithic mandibles are so marked. Perhaps the digastric played a part in the fixing of the mandible against the forward pull exerted when an object held between the incisors was pulled by the hands. With the heavy wear so characteristic of the forward end of the dental arch during the Palaeolithic, it seems evident that the manipulative function of the anterior dentition was of survival value, and it is possible to speculate concerning this and the apparently great development of the digastrics.

Among the various other insights which the CANIBAL has yielded is one which is of importance in understanding the means whereby a biting force is transmitted to the forward end of the dental arch. Keith ('20) considered this to occur mainly as a result of the action of the masseter, evidently envisioning the mandible as a second class lever. More than 20 years ago, however, it was demonstrated that the glenoid fossa was not a stress bearing joint (Robinson, '46; Rees, '54). Robinson showed that the resultant of the directions of the temporal and masseter pull would produce vertical force in the region of the molars without any lever action, although this does not explain how force is transmitted to the incisors.

In order to study the ways in which the forces could be transmitted through the forward part of the dental arch, the mandible was first treated as a moving body free of bony articulation. Varying the applied forces one by one, it was shown that incisor biting can be produced by the masseter (and presumably the internal pterygoid) and the posterior component of the temporal alone. Basically, this can be considered as the action of a first class lever, with the angle of the mandible held by the masseter (and internal pterygoid) acting as the fulcrum, while the ascending ramus, powered by the posterior component of the temporal, acts as the power

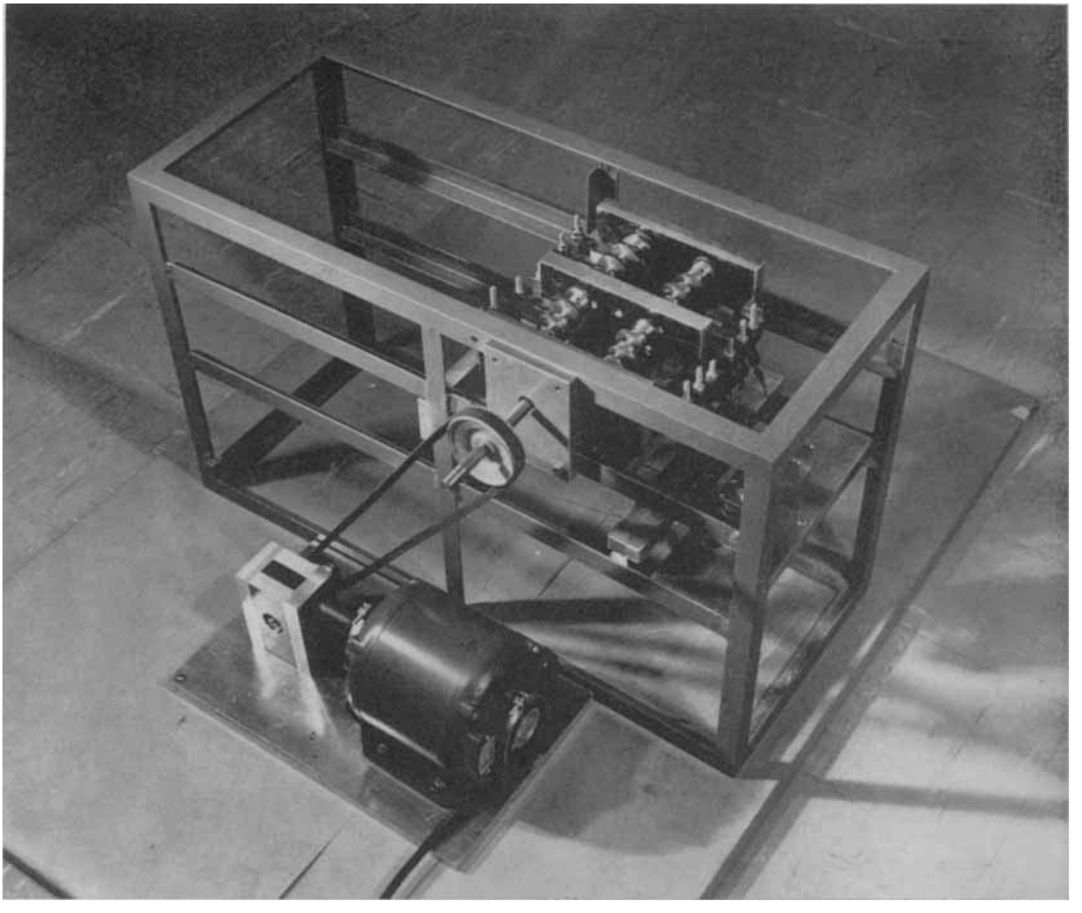

Fig. 3 View of the CANIBAL from three-quarters above, showing the details of power transmission and the cam and rocker arm assembly.

arm. This may offer a possible explanation for the results reported by Latif ('57) who, in an electromyographi study, found that 22% of the subjects showed greater activity of the posterior region of the temporal than in other parts of the muscle during edge-to-edge biting.

Other force combinations are also capable of producing a resultant at the forward end of the dental arch. The anterior and middle regions of the temporal, with the addition of the masseters and internal pterygoids, will exert considerable force through the incisors if the condyles are held in a fixed position on the inclined plane formed by the posterior slope of the articular eminence. This points out the importance of this region as compared to the glenoid fossa, and, if the condyles are held against it so that it can act as a fulcrum, then the mandible *can* be regarded as a second class lever powered by the vertical pull of the major masticatory muscles — biting force being exerted through the incisors.[2] While the glenoid fossa proper is a non-stress bearing structure,

[2] In an earlier version of this paper, delivered at the annual meetings of the American Association of Physical Anthropologists at Mexico City, June, 1964, we had stressed the fact that removal of the glenoid fossa assembly had no effect on the motions of the mandible or on the forces generated. While strictly speaking we *were* able to make this demonstration, we are indebted to Dr. E. L. DuBrul for pointing out that this would require exertion on the part of the posterior component of the temporal which is out of all proportion to the size and indicated power of that muscle section in living human beings. As a result of DuBrul's suggestions, we were stimulated to construct a more adequate glenoid assembly than that which was present in the earlier versions of the machine.

the articular eminence has a compact bony surface which, with the histologic analysis of the overlying tissue, indicates that it is fully capable of stress bearing functions (Root, '46; Rees, '54; Symons, '54). Recognizing the importance of the articular eminence (c. f. Angel, '48), efforts were made to manufacture an effective mechanical counterpart. This was accomplished by covering a flat strip of metal with a polyethylene pad, running it from one side of the machine to the other, and fixing it to the frame by means of an adjustable bracket which allows alterations both in the angle of inclination and the height. Using this, it has been possible to demonstrate the inadequacy of considering the mandible solely as a free moving body, which while it will serve to show the production of resultant forces through the molar part of the dental arch, will not fully account for the pressures which members of some populations regularly exert on the forward part of the dentition.

Further manipulation of the forces applied has shown that the masseter and the anterior region of the temporal provide the most efficient means of applying a biting force to the incisors. While these two muscles furnish the main biting power, the external pterygoids are also brought into play in holding the condyle fixed in position on the articular eminence. Others have noted that even at the rest position the condyles are more on the slope of the eminence than in the fossa (Hildebrand, '31; Angel, '48; Sicher, '52; Choukas and Sicher, '60). In addition, the functional significance of this structure is further indicated by observations made on skeletal material where it has been noted that, in Eskimo skulls with heavily worn dentitions, the eminence is greatly modified and the fossa is rather shallow (Buxton, '20; Richie, '23), and observations also made on California Indian skulls (Leigh, '28). It is hoped that future studies will help to illuminate the relationship between eminence form, tooth wear, and muscle action. Since a major consideration in any vector system is magnitude as well as direction, appropriate instrumentation is being designed for installation on the CANIBAL so that exact measurements of the force magnitude can be made in future experiments. This will lead, with allowance for losses due to friction and mechanical inefficiency, to a description of the activity of each muscle as the type of occlusion is altered to correspond with those observed in the various fossil and recent populations.

In addition to the study of the forces of mastication, the major concern is to reproduce the different kinds of wear commonly found on fossil and recent dentitions. Numerous runs have been made with the machine adjusted to various cam settings, and several casts were worn down into patterns resembling those characteristic of certain populations. The major difficulty at present, however, is that the material used to make the casts — dental stone, dental plaster, or a variety of resins — either chips and cracks easily or wears too slowly to be of practical value. We entertain the hope, at least, that an experimental approach such as this can cast some light on the nature of the selective forces which have been important in influencing the course of the evolution of the human dentition. To this end, work is continuing (a) to find a suitable casting material, (b) to refine various mechanical features of the CANIBAL, and (c) to design instrumentation capable of measuring all the forces and pressures involved. A summary of the results together with photographs will be presented in future papers.

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