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Adaptive Sensory-Motor Encoder for Neural Prostheses.

The invention concerns an adaptive sensory-motor encoder having the characteristics of the superordinate concept described in Claim 1 as well as a spinal implant and a cranial implant.

There are several precursor systems of spinal implants known, that, for example, are employed in cases of transverse lesions of the spinal cord with paraplegia for control of urinary tract functions and for guidance of ambulating movements or grasping movements that work by means of stimulation contacts in the form of implants or that work transcutaneously (see Eckmiller and colleagues., Neurotechnology Report, 1994 and 1995).

The spinal implant precursors currently available or those in development have diverse limitations, for example, no adaptation, no functional increase of number of microcontacts and no bi-directional, perception-based control by the implant carrier.

In particular, the currently developed microcontact structures and signal and energy transfer systems operate unidirectionally from the external encoder to the implanted stimulator and therefore offer no possibility of ongoing monitoring of neural impulse activity of the stimulated neurons. Thus, the stimulation pulse sequence cannot be adapted to the spontaneous activity of the neurons. Furthermore, triggering of neurobiological impulses by stimulation pulses can not be monitored directly. Moreover, an assured impulse monitoring opportunity for possible temporal tuning and synchronization of the impulse sequences of multiple neurons is also lacking.

There are isolated rationales for development of implanted, active substance applicators that are controlled by need, for example for insulin, but there have been to date no cranial implants that have been successfully implemented. Cranial implants that, for example, are urgently needed for local, event-triggered administration of active substances for suppression of onset of epileptic events, are not available.

This invention undertakes to eliminate these problems and to create an adaptive, sensory-motor encoder, which with the aid of neural networks in dialogue with the implant carrier or in bi-directional signal and data exchange from implant and addressed nerve tissue, can perform an optimization of the perturbed nervous system functions, functionally increases the selectively reachable stimulation sites, and monitors the neural activity of individual neurons that are to be

stimulated. The invention further seeks to create a process for the operation of an adaptive sensory-motor encoder, and further to provide a spinal implant and a cranial implant.

This problem is solved by an encoder with the characteristics descried in Claim 1. Furthermore, this problem is solved by a process having the characteristics described in Claim 10, by an implant having the characteristics described in Claim 13 and by an implant having the characteristics described in Claim 14.

Because the encoder is bi-directionally coupled with implanted microcontacts, monitoring of the neural impulse activity of individual neurons to be stimulated and other signals and the execution of quasi-autonomous actions can be realized. The functions can be optimized either self-actuating by the neural network or in dialogue with the implant carrier. The number of the selectively addressable stimulation sites can be functionally increased and the neural activity of individual neurons monitored. The implanted structure can operate sensory-motor quasi-autonomously by using appropriate sensory and action components and an adaptive control system. Essential components and processes of the adaptive information processing system are implemented in various combinations, particularly for spinal implants in bi-directional contact with the spinal cord or the peripheral nervous system and for cranial implants in bi-directional contact with the structures of the central nervous system within the cranium.

Furthermore, for the first time an encoder is proposed that allows the number of selectively reachable stimulation sites to be functionally increased and also subsequently to adapt itself to new stimulation conditions. The encoder described herein can (on the basis of its structure and function as a group of adaptive spatio-temporal filters) in addition to the stimulation function, also perform monitoring an evaluation of the neural activity of the neurons to be stimulated.

The spatio-temporal filters associated with the individual microcontacts, to the extent possible, are tuned to optimum function individually in the dialogue between the encoder and the implant carrier.

In contrast with an encoder with static pre-processing; that is, without the possibility of individual adjustment, the present case allows, on the basis of the single relevant criterion; namely the specific functional enhancement of the given area of the nervous system, adjustment of the single spatio-temporal filters as separate encoder channels. This advantage includes the possibility that subsequent function changes, for example, as a result of shift of micro-contacts by corresponding adaptations of the spatio-temporal filter function, can be compensated for. An advantage of the tuning of the spatio-temporal filter function in the dialogue with the implant carrier or with an area of the carrier's nervous system is in the consideration of functional aspects, that only the actual implant carrier can incorporate into the optimization process and only in implicit form; namely, for example, by subjective assessment of his perception or by

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evaluation and function monitoring of his nervous system and their use in the encoder adjustment.

The asynchronous impulse sequences of the individual spatio-temporal filter outputs of the functionally separated encoder channels, as stimulation signals, selective stimulation sites are selectively tuned to one another in the dialogue with the implant carrier, in consideration of the of the neural impulses recorded at the stimulation site.

Because it is presumed that time courses and locale distributions of the stimulation signals that have been reciprocally tuned by superposition, have been suitably selected by an adaptation process and their field distributions effected at several microcontacts will, as stimulation foci, trigger local and temporal selective neural impulse excitations, the number of selectively addressable stimulation sites and their definition or cross-talk suppression will be functionally enhanced with fixed number of implanted microcontacts.

With a given, relatively low number of implanted and permanently functional microcontacts, whose position relative to the neurons can not be modified, it is of particular advantage, functionally; that is, by generation of suitable signals, to increase the number of selectively reachable stimulation sites or neurons and thus, at the same time, increase the number of separately accessible encoder channels with an adequate reserve of spatio-temporal filters. This advantage effects an improvement of the quality of the respective function.

The control or relief of defective functions of the spinal cord or peripheral nervous system with the aid of a partially implanted neuroprosthesis in the closest possible sensory and motor coupling with the implant carrier and by using quasi-autonomous sensory-motor functions of the implanted structure is thus made possible.

Using adaptive spinal implants the quality of the relief from functional impairments in the spinal cord or peripheral nervous system fundamentally improved and, with respect to diverse applications, is possible for the first time.

Alleviation of neural functional impairments of the central nervous system within the cranium is made possible, particularly for the purpose of reducing undesirable sensory, motor, or cognitive effects for a number of groups of neurological or psychiatric patients using an implanted structure with an active substance applicator and quasi-autonomous, sensory-motor functions in coupling with control and monitoring functions of the implant carrier.

For the first time, using adaptive cranial implants the quality of the relief of neural functional impairments in the central nervous system within the cranium is possible in diverse applications.

These beneficial forms are derived from the characteristics of the subordinate Claims. Examples of applications of the present invention are described using the drawings. Shown in:

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Figure 1.: An example of a design form of a spinal implants in the area of the nerve tissue with a control unit and a command module activated by head movements.

Figure 2.: A schematic illustration of an implanted microcontact structure for stimulation of nerve tissue not directly contacted; and

Figure 3.: A schematic illustration of a cranial implant with the various modules in a block circuit diagram.

A cranial implant used as a grasp prosthesis is illustrated in Figure 1. This prosthesis is used when arm movements can still be performed in a paraplegic, but gripping movements with the hand are not possible.

The grasp prosthesis includes an implant (1), that communicates with a transcutaneous module (2). The module (2) in turn is in bi-directional, wireless connection with an adaptive central control unit (3). The control unit receives commandos from a command module (4), that is guided by a head movement sensor (5).

The implant (1) is in contact with nerve tissue (8) via micro-contacts (6, 7). In addition, several sensors (9), that pick up measurement values for the grip process in the area of the terminal thumb and one other finger, are connected to the implant (1).

The system described so far operates in the following manner to produce and control a grip process. Initially the user moves the hand in the direction of an object that he intends to grasp. For example, the object can be a glass. When the hand is in the right position for grasping the glass, the grasp process is triggered by a particular head movement that is recognized in the head movement sensor (5). Then the head movement sensor (5) communicates its signals to the command module (4). The command module generates the appropriate control commands, which are then communicated to the control unit (3) either wireless or by signal conduction. The command interpreter (11), which also provides movement monitoring, is situated in an initial area (10) of the control unit. A second area (11) of the control unit (3) includes the position and strength control. The "grasp" command coming from the command module (4) is interpreted in the unit (10) and an appropriate movement stimulation pattern is determined for the action. The unit (11) in the central control unit (3) then issues positioning commands to the transcutaneous module (2), which then issues the command to the implant (1) and in particular to a stimulation unit (12) therein for stimulation of the appropriate neural pathways (8) via the micro-contacts (6, 7). The neural pathways (8) control the electrical stimulation of the hand muscles required for the grasping process, which then contract and triggers the grasping process.

The sensors (9) now detect the grip of the hand around the objects by picking up information regarding the position, the pressure applied, and slippage of the object. The goal of a grip

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process is exertion of pressure that is as slight as possible in order not to damage the objet (e.g., a raw egg), on the other hand, however, also to provide a grasp that is slippage free and so prevent dropping the object.

The sensor (9) signals are transferred to a sensor unit (13) of the implant (1). The signals received are transferred by the sensor unit (13) to the transcutaneous module (2), which then delivers the values determined after signal processing to the checking unit (11) of the control unit (3), where position and strength regulation for the grasping process is done. In the individual case the stimulation of the nerve tract (8) via the micro-contacts (6) is guided in such a manner that an optimal grasp event results. The user can, for example, after grasping the glass, issue the information, by another head movement, to the head movement sensor (5) and thus to the command module (4), that the grasp process can now be sustained independently. The control unit (3) then effect the autonomous control of the grasp process. As an adaptive control unit (3) the stimulation is retro-coupled on a regular basis by way of the micro-contacts (6, 7) in the area of the nerve tract (8) in that the activity of the nerve tract (8) via the sensors (9) is picked up in the sensor unit (13) of the implant (1). The control unit (3) integrates this adaptability via a neural network that so regulates the site, the strength and the time course of stimulation of the nerve tract (8) that those nerve tracts are stimulated as precisely as possible and in the appropriate strength that is required for the grasp process. Thus, after an adaptive phase, an optimal grasp process is possible.

Figure 2 shows an illustrative example of micro-contacts (6) that impinge into nerve tissue (8). In the present example three micro-contacts (16, 17, 18) are implanted into the nerve tissue (8) and are positioned more or less randomly near certain nerve cells. The micro-contact structure (6, 16, 17, 18) is in each case essentially coarser than the matrix of the nerve cell (8). The micro-contacts (16, 17, 18) are supplied with signals (S2, S2 and S3) via the stimulator (12).

In order to create a targeted neural stimulation, for example, a stimulation focus F must be attained that can not be directly affected by a micro-contact. The stimulation focus F can, however be attained, by conducting the signals (S1, S2, and S3) using different strengths, time courses and, above all, temporal intervals to the electrodes (16, 17, 18). The overlap of the signals generated can then be so arranged that the convergence of the signals in the area of the intended stimulation focus F exceeds the stimulation threshold of single or a few nerve cells, while the addition of signal progressions in the remaining area of the nerve tissue remains below the excitation threshold.

By changing the temporal sequence and the temporal signal progression of the various reciprocally tuned signals the stimulation focus can also be shifted from F to F'. For balancing of the stimulation functions that reach a stimulation focus which is not directly in conjunction

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electrodes, an adaptive process is required. Since it is not exactly known which stimulation focus F, F' must be addressed for a particular neural stimulation, the adaptive sensory-motor control unit can offer only a certain signal pattern which the implant carrier then assess via a sensory perception or another sensor data evaluation. A second signal pattern, which is modified with respect to the first, is then likewise evaluated as to whether the intended neural stimulation is reached or not. The user needs only to say whether the later signal pattern better or worse suited is than the previous one. Using the check mechanism of a neural network and in the course of the checking process, an optimal signal time function is determined for the electrodes (16, 17, 18) for the purpose of excitation of the stimulation focus F.

In Figure 3 depicts a cranial implant for monitoring and influencing a region of nerve tissue in the cortex. A neural tissue (20) that is to be monitored is provided with micro-contacts (20) in the area of a region (21). The region (21) can, for example, be that region whose impaired function results in epileptic events. In such a case, a micro-contact structure (22) includes both the micro-contacts for stimulation of the nerve cells and also microsensors fur monitoring the nerve cell activity and other biophysical parameters. The micro-contact structure (22) itself is connected to a signal path (23) with an adaptive processor (24) that has available to it a bi-directionally operating transmission and reception system. Otherwise, the micro-contact structure (22) is in contact with a signal tract (25) with an active substance reservoir (26). The active substance reservoir (26) is prepared for controlled local release of small quantities of active substance, for example in the nanoliter range. Finally, the processor (24) is connected via another signal tract (27) directly to the active substance reservoir (26).

The three modules (22, 24, and 26) of the cranial implant function cooperatively to prevent epileptic events in the following way: The microsensors monitor the spontaneous nerve cell activity in the region (21) and communicate their measurement signals over the signal tract (23) to the processor (24) which then on the one hand evaluates the signals itself and, on the other hand, communicates a status report to an external encoder. With the occurrence of suspect characteristic nerve cell activity, which can, for example, be expressed in synchronous, neural activity within the region (21), the processor (24) identifies the existence of a stimulation pattern that can result in an epileptic event. It can then communicate on the one hand over the signal tract (23) stimulation pulse sequences to the micro-sensor (22), which counteract such synchronous, neural stimulation. When this purely electrical intervention is inadequate, the processor (24) can communicate an instruction over the signal tract (27) to the active substance reservoir (26). The reservoir administers a precisely metered dose of a pharmacological active substance, which in turn is capable of lowering the synchronous nerve cell activity to a normal level.

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dialogue with the encoder, the perceptual comparison between the desired pattern and the actual pattern; for example, by using as the evaluation input unit a row of several sliding controls or in the form of particular encoded head movements, communicates with a technical neural network with non-monitored adaptation rules and that the neural network establishes the next parameter vector for the spatio-temporal filters as well as the next desired value, with the goal of reducing the perceived pattern difference in the next dialogue step. An advantageous form of the search for the optimal parameter vectors for the spatio-temporal filters is where, in the dialogue module either from a neural network with non-monitored adaptation parameter vectors are produced that result in a particular perception for a given pattern presented and are correspondingly subjectively evaluated or, where in a dialogue module with another parameter adjusting system sequences of parameter vectors are used for the production of virtual motion in the function space of the spatio-temporal filters; for example, as continuous trajectories depending on the type of scanning or sweep processes, or as non-regular sequences, or as sequences of neurophysiological, particularly typical filter functions. In the course of this suitable timed sequence, the user casually reports the "sensible" perceptions produced by the collaboration of the given pattern, the pre-processing module, the following spatio-temporal filters and that part of the nervous system coupled to the associated micro-contact and, then, in the region of the function space determined in this process, a more precise parameter optimization can be undertaken based on perception.

An exemplary form of the generation of asynchronous impulse sequences is where the output signals of the individual spatio-temporal filters are transformed into asynchronous impulse sequence, relevant to the activity of the neurons, by using suitable converter algorithms of the quasi-continuous time functions of the spatio-temporal filters and where impulse sequence – time courses and points in time of the occurrence of single impulses can be shifted in the dialogue phase by using variable time delay elements.

An exemplary form of the process for temporal coupling of the asynchronous impulse sequences generated by several spatio-temporal filters of the encoders for the purposes of triggering nerve cell impulses is where the transmission time point of the individual impulse signals are varied by controllable time delay elements in such a way that temporal coupling up to precise asynchronous occurrence results, wherein the variation of the time delay is regulated by the implant carrier. Or, in the dialogue this occurs based on perception via a neural network, or is externally regulated, in that the selection of the impulse groups that are to be temporally coupled can take into consideration the impulses coming both from the spatio-temporal filters and those recorded in the interface and that, in view of the very different momentary impulse rates of the different spatio-temporal filters, suitable criteria are established for inclusion of individual impulses in the impulse groups that are to be coupled.

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An exemplary example of the process for functional increase of the number and definition of the selectively addressable stimulation sites in the case of a given number of stationary implanted micro-contacts is where the impulse signals from a given spatio-temporal filter are conducted to several, locally adjacent micro-contacts, whereby the characteristic time courses — that have been established for each micro-contacts and corresponding to current amplitude, polarity, and phase length in the interface — of the electromagnetic field in the area of the neurons to be stimulated have the effect that said stimulation signals, which have been tuned to each other by superpositioning, trigger locally and temporally selective neural impulse excitations in the field distributions at several micro-contacts and that the selective stimulation sites can be rapidly changed by suitable variation of the superpositioned stimulation signals and that the respective variation of diverse parameters of the reciprocally tuned stimulation signals results in the perception–based dialogue with the implant carrier via a neural network, or other signal variation process for the determination of as many as possible simulation sites leading to selective and defined neural excitation. Further, this advantageous form consists in the optimization of the stimulation-time functions is improved with respect to intended single cell selectivity and lasting biocompatibility through the comparison of recorded neural impulses to the stimulation signals.

A exemplary form of the monitoring system for a partially sensory-motor autonomously functioning implanted structure of the encoder is where the implanted micro-contacts are used both for stimulation and for recording of neural impulses, in that the recorded impulses and other physical or chemical signals from the implanted structure are reported through suitable pre-amplifiers and optical or electromagnetic transmitters to the encoder and there, the recorded neural signals are further processed for the various purposes of the encoder function.

An exemplary form of the partially autonomous sensory-motor actions of the implanted structure is where, by the use of various sensors accessible in the implanted structure that detect physical or chemical values, or using various actors such as, for example, electrical stimulation electrodes, mechanical micro-actors, chemical active substance applicators, or thermally acting probes for healing or micro-surgical purposes, structures for the performance of chemical analysis and processes within the implanted structure and using a partially neural, adaptive control system in communication with the encoder, quasi-autonomous, diverse sensory-motor actions can be executed, for example, rapid response effects on the local tissue can be executed in response to the sensory data just detected. In this case, the bi-directional coupling with the encoder can be used as control or checking.

An exemplary form of the adaptive spinal implant, for example for use in paraplegics for neural modulation of the urinary tract, for guidance of the grip or walking movements, or for the reduction of phantom pain following amputation is where the implanted microstructure is situated in the spinal cord, the peripheral nervous system or in muscle groups, whereby

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external adaptive encoder in bi-directional communication with the implanted structure is carried on the body of the user as a portable unit and is in bi-directional communication with the user for signal reception and functions to a large degree autonomously or can be controlled by the user through manipulation or, for example, through head or eye movements. An exemplary form of the implanted structure is where quasi-autonomous sensory-motor actions such as, for example, a need-driven administration of growth hormone or thermal effects are performed.

An exemplary form of the adaptive cranial implant, for example, as need-triggered local administration of active substance for epileptic patients, parkinsonism patients, or psychiatric patients, is where the implanted structure — including local detectors of physical, neurophysiological and ionic, molecular, and active substance concentrations, and also active substance depots with the possibility of simple external replenishment, local active substance dosers with control and adaptive information processing module — is situated intracranially and communicates bi-directional with an external encoder, whereby a medically and technically specially qualified team, after informed consent of the patient, similar to, for example, prior to the decision regarding micro-surgical intervention by using implanted thermally acting probes, not only monitors but also checks the individual functions and that the individual functions of the patients in perception-based dialogue can be optimized and monitored. An exemplary example of the implanted structure is where the quasi-autonomous sensory-motor actions, such as, for example, need-driven administration of growth hormone or locally deficient neurotransmitter for synaptic functions; in other words, the biological contacts between nerve cells that are fundamentally involved in learning and adaptation and, for example, the need-driven suppression of epileptic events or thermal effects are effected.

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Patent Claims

1. An adaptive, sensory-motor encoder for a neuroprosthesis in the central nervous system within the cranium, the spinal cord or in the peripheral nervous system and equipped with a central control unit (3) for signal processing functions, monitoring functions, checking functions, and or external interventional functions as well as with a group of adaptive spatio-temporal filters for sensory and/or motor functions **characterized by the fact that** a bi-directional interface (2) for the coupling of the encoder with an implanted microstructure (6, 7) is provided for stimulation of nerve or glial tissue and for function monitoring of brain function.

2. An encoder as described in Claim 1 and **characterized by the fact that** the control unit (3) is adaptive and is provided for the purpose of checking an at least quasi-autonomously operating sensory-motor implanted structure (1, 6, 7; 22, 24, 26).

3. A process as described in one of the foregoing Claims and **characterized by the fact that** by means of the checking function, a substance or a form of energy can be applied at the site of the implanted structure (22, 24, 26).

4. A process as described in one of the foregoing Claims and **characterized by the fact that** the monitoring function picks up the activity of neurons or glial cells and ionic, molecular, or active substance concentrations.

5. A process as described in one of the foregoing Claims and **characterized by the fact that** for the purpose of functional increase of the number and definition of the selectively addressable stimulation sites with a given number of stationary implanted micro-contacts (6) the impulse signals (S1, S2, S3) can be conducted both at single and at several, locally adjacent micro-contacts (16, 17, 18) and that the decoded stimulation-time functions — based on the encoder commands individually established precisely for each micro-contact (16, 17, 18) corresponding particularly with respect to time course, current strength, polarity and phase length in the interface (12) — effect characteristic time courses and local site distributions of the electromagnetic field in the area of the neurons to be stimulated.

6. A process as described in one of the foregoing Claims and **characterized by the fact that** the time courses and local distributions, selected or determined by an adaptive process, of the various reciprocally tuned stimulation signals trigger local and temporally selective neural impulse stimulations in field distributions effected at several micro-sensor (16, 17, 18) as stimulation foci (F, F').

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13. An adaptive spinal implant for alleviation of neural functional impairment in the spinal cord or peripheral nervous system, in particularly with respect to motor aspects of the extremities, the urogenital tracts and undesired pain sensations or phantom perceptions, equipped with an adaptive encoder, a quasi-autonomously functioning sensory-motor implanted structure (1, 6) and a bi-directional signal and energy transfer system (2, 12, 13), whereby the encoder is in bi-directional contact with parts of the spinal cord, the peripheral nervous system or muscle groups.

14. An adaptive cranial implant for alleviation of neural functional impairments of the central nervous system with undesired sensory, motor, or cognitive effects, including memory defects and personality changes, equipped with an adaptive encoder having a central control unit for signal processing functions, monitoring functions, checking functions and/or external intervention functions of a quasi-autonomously functioning implanted structure (22, 24, 26) having microcontacts (16, 17, 18, 22), detectors, active substance depot, and active substance administration (26), whereby the encoder is in bi-directional contact with regions of the brain (21) via a signal and energy transfer system (24).

15. A process as described in one of the foregoing Claims and **characterized by the fact that** a quasi-autonomous monitoring system undertakes an evaluation of the signals recorded at the implant by using a locally available adaptive checking system and converts them into physical or chemical local action commands.

16. A process as described in one of the foregoing Claims and **characterized by the fact that** corresponding functions of the adaptive encoder (3) are used for perception-based, automatic or externally checked function adaptation as well as sensory spatio-temporal filters for sensation optimization and motor spatio-temporal filters, or other checking modules for optimization of the progress of movement, need-driven administration of active substances, or micro-surgical or curative effects.

17. A process as described in one of the foregoing Claims and **characterized by the fact that**, in the case of spinal implants, measurement systems (5) for eye and head movements or other articulations are used and are available for the purposes of checking/controlling implant functions and for purposes of reporting the intentions or perceptions of the implant carrier and that the corresponding processes for selection of different function proceedings by a portable command input unit as well as for ongoing transmittal of selected conditional parameters with respect to the implant carrier and the implant with the aid of a suitable sensory organ, for example, the tactile sense, or use an attendant and can be adapted to the patient and implemented

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18. A process as described in one of the foregoing Claims and **characterized by the fact that** an adaptive checking system is provided for evaluation of the signals recorded at the implant site, including chemical analysis and production of chemical reactions within the implanted structure and that the evaluation is converted into physical or chemical local action commands such as, for example, local electrical stimulation, administration of active substances or thermal effects for surgical or curative purposes.

19. A process as described in one of the foregoing Claims and **characterized by the fact that** the implanted local active substance depots (26) are addressed in dependence on an pathophysiological condition or status space — in an adaptive phase evaluated with respect to necessity of action — captured by suitable implanted detectors (22), for example for neural or glial cell activity, physical parameters and ionic, molecular, or active substance concentrations for locally limited and temporally synchronized dispensing of metered quantities of active substance and that subfunctions of this locally status-based dosing of active substance can be controlled autonomously in the implanted structure or in bi-directional communication with the encoder external to the cranium, directly by the implant carrier and/or by an attendant.



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